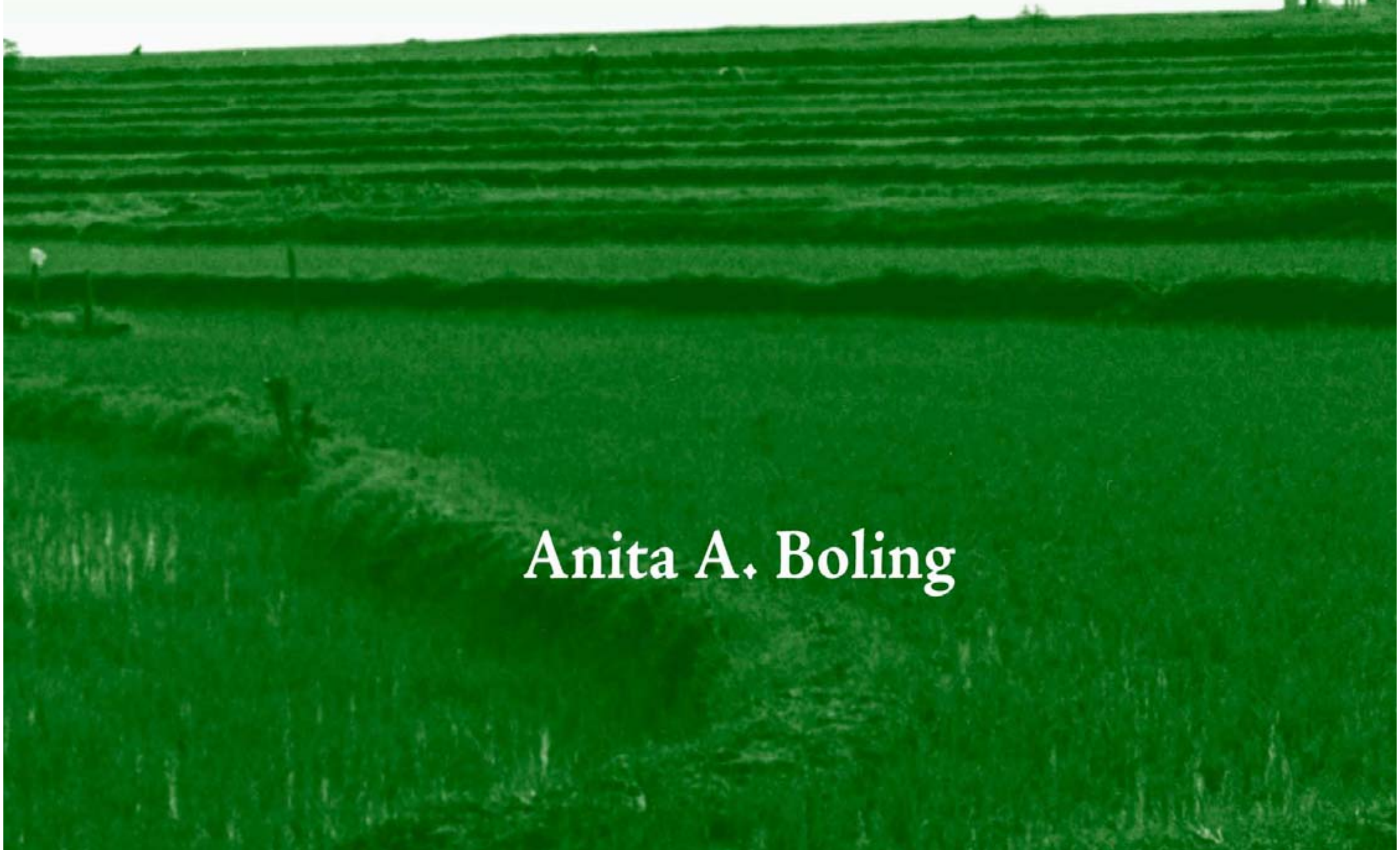
Yield Constraint Analysis of Rainfed Lowland Rice in Southeast Asia



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Dit onderzoek is uitgevoerd binnen de C.T. de Wit onderzoekschool: Production Ecology and Resource Conservation.

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. dr. M.J. Kropff
in het openbaar te verdedigen
op maandag 12 november 2007
des namiddags te half twee in de Aula

Anita A. Boling (2007)
Yield constraint analysis of rainfed lowland rice in Southeast Asia

Boling, A.A. – [S.l.: s.n.]. Ill.
PhD thesis Wageningen University. – With ref. –
With summaries in English, Bahasa Indonesia, Thai, Filipino and Dutch.
ISBN: 978-90-8504-799-5

Abstract

Boling, A.A., 2007. Yield constraint analysis of rainfed lowland rice in Southeast Asia. PhD thesis, Wageningen University, Wageningen, The Netherlands. With summaries in English, Bahasa Indonesia, Thai, Filipino and Dutch, 140 pp.

Rainfed lowland rice yields are low and unstable due to uncertain water supply, low soil fertility, and pest infestation. To design management interventions aimed at increasing rainfed rice production, the magnitude of and variation in yield gaps associated with various constraining factors need to be assessed.

This study aimed at improved understanding of spatial and temporal variations in water status and nutrient availabilities, and their effects on crop growth and yield for rainfed rice along toposequences in SE Asia, as a basis for the design of improved crop management strategies. To realize these objectives, statistical and systems analyses were used to quantify the effects of yield-determining, yield-limiting, and yield-reducing factors and to identify management options along toposequences in sloping rainfed rice areas in Indonesia and Thailand. Field experiments were conducted from 1995–2000 at Jakenan Experiment Station, Indonesia and from 2000–2002 in farmers' fields in rainfed rice areas in Indonesia and Thailand. These areas have similar rainfall levels and represent the common single rainfed rice system (in Thailand) and the (one) more intensive double rainfed rice system (in Indonesia)

The ORYZA2000 crop growth simulation model adequately simulated rice yields at various levels of fertilizer N under irrigated and rainfed conditions in the study area in Indonesia. Simulated potential yields ranged from 3.74 (for crops sown in October) to 5.53 Mg ha^{-1} (for crops sown in July). Groundwater depth had a significant impact on the effects of establishment date, deep tillage, fertilizer application, and supplementary irrigation performance of on rainfed rice sown towards the end of the wet season.

In farmers' fields in Indonesia and Thailand, substantial differences were recorded in field hydrology, exchangeable K, organic C and clay content among different toposequence positions. Differences were also observed in yield and in the magnitude of yield increase due to intensive weed control and/or application of recommended fertilizer doses, but these differences were not consistent across countries, seasons, and years.

In Indonesia, the yield constraints of rainfed lowland rice in the research station and in farmers' fields were identified based on analyses of yield gaps associated with the interactive effects of water and nutrient stress, taking into account the incidence of rice pests. There were consistently wide yield gaps due to water, N and K limitations, and pest infestations. These results indicate substantial scope for increasing rainfed rice yields through timely establishment, deep tillage, supplementary irrigation, application of N and K fertilizers and pest control.

Combining various methodologies in estimating reference yields provided increased understanding of the constraints to rainfed lowland rice production and this set of tools could be applied to other locations to identify yield constraints and management options to increase production, provided that the necessary experimental data required for such a comprehensive analysis are available.

Keywords: Fertilizer application, field hydrology, plant nutrient uptake, toposequence, weed control, yield loss.

Preface

This book illustrates the application of different methods in identifying the yield constraints and the magnitude of exploitable yield gaps in rainfed lowland rice ecosystems. It was written based on theoretical knowledge of rice systems from a researcher's perspective and on observations and experiences on low and unstable rainfed rice yields from a farmer's experience.

Many institutions and individuals have contributed to this research and I am grateful for their support. I am thankful to the International Rice Research Institute (IRRI) for the full support given during the implementation of experiments, data analysis, and preparation of the thesis manuscript; Wageningen University and Research center (WUR) for the 12-months support given to develop the research proposal, write one thesis chapter, and fulfil the remaining requirements for the PhD programme in The Netherlands; The National Agricultural Research and Extension Systems (NARES), Jakenan Experiment Station in Indonesia and Ubon Rice Research Center (URRC) in Thailand, for the implementation of collaborative experiments; the Center for Soil and Agroclimate Research and Gadjah Madah University in Indonesia, and Khon Kaen University in Thailand, for plant nutrient analyses and soil chemical and physical analyses.

I benefitted substantially from being able to work with:

- My promotor in the Plant Production Systems Group, Prof. H. van Keulen, who provided scientific guidance during the final and critical stages of this research. Herman, thanks for patiently explaining the interdisciplinary aspects of this research work, extensive review of manuscript drafts, timely words of encouragement, and making the research and learning process both challenging and enjoyable.
- My promotor in the Crop and Weed Ecology Group (CWE), Prof. J.H.J. Spiertz, who helped finalize the research proposal and gave regular reminders and quick comments on manuscript drafts.
- My former promotor in CWE, Prof. M.J. Kropff, who encouraged me to study simulation and systems analysis, helped develop the thesis proposal, and scientifically guided me during the initial stages of this research.
- My co-promotor in the Crop and Environmental Sciences Division (CESD), Dr. T.P. Tuong, who supervised all stages of this research work. Dr. Tuong, thanks for encouraging me to collect primary data from experiments for research and instilling quality assurance (QA) not only during the data processing stage but also during the execution of the experiments and the processing of plant and soil samples. The QA

measures that were adopted in all aspects of this research gave us high confidence in the research results;

- My supervisor in CESD, Dr. B.A.M. Bouman, who provided a conducive work environment to finalize the thesis manuscript and fulfil the remaining requirements of the PhD programme. Bas, thanks for the fruitful discussions, suggestions to improve the manuscript and concern for me to finish my studies.

I am grateful to:

- Ms. H.H. van Laar for her expertise in setting up the input files for the ORYZA2000 model, for the technical and scientific editing of the thesis, and all the efforts in getting this thesis printed. Gon, thanks for the out-of-Haarweg activities to explore interesting places not only within Gelderland and Holland, but also in Manila.
- Mr. J. Lazaro, IV, for the cover design; Engr. D.F. Tabbal for the inset picture.
- My collaborators and farmer cooperators who participated in the field experiments: Ir. H. Suganda, Ir. S.Y. Jatmiko, Mr. S. Mulyono, Mr. A. Pramono, Ms. E.S. Harsanti, Ms. Indratin, and Ms. T. Sopiawati of Jakenan Experiment Station for experiment implementation, data collection and encoding in Indonesia. *Terimah Kasih!* Dr. Y. Konboon and Ms. W. Waraporn of URRC for supervising the experiment, data collection, and encoding in Thailand; and Mr. D. Harnpichitvitaya of IRRI Ubon Ratchathani Office, for his help in soil physical analysis. Dr. G. Pantuwan of the Thai Rice Department, Dr. C. Vejpas and Mr. S. Phuphak of Ubon Ratchathani University, and Ms. S. Sripodok of URRC, for kindly sharing reference data of KDML 105 and long-term weather data; *Khàwp khun khâ!* Dr. D.T. Franco of the University of the Philippines Los Baños (UPLB) for his help in statistical hydrology. *Maraming salamat, po!*

I am also grateful to many past and present staff and scholars in IRRI, who directly and indirectly helped in many aspects of this research: Dr. S. Haefele, Dr. E. Humphreys, Dr. G. Jahn, Dr. D.E. Johnson, Dr. C. Kreye, and Dr. C.P. Mamaril, for their helpful suggestions to improve the manuscript; Dr. M. Mortimer in conceptualization and data analysis of the 2000–02 experiments in farmers' fields in Indonesia; Dr. M.V.R. Murty for supervising the implementation of the 1995–96 field experiment in Jakenan Experiment Station; Engr. R.J. Cabangon for measuring the soil physical properties in Jakenan Experiment Station; Dr. G. McLaren, Ms. V. Bartolome, Ms. M. Dizon, and Dr. A.G. Laborte for statistical analysis; Dr. B. Hardy for scientific editing; Ms. M.C. Alberto, Dr. M. Pampolino, and Ms. M. Samson for fruitful discussions on soil chemistry and site-specific nutrient management; Ms. T. Rola, Ms. R.S. Madamba, Dr. A.K. Makarim, Mr. & Mrs. J. Nieuwenhuis, and Dr.

K.R. Trijatmiko for the translation of the summary in Filipino, Bahasa Indonesia, and Thai languages; Ms. M.A. Burac for preparing the graphs and for helping in data processing; Engr. R. Bayot, Engr. M. Manalili, and Ms. A.J.V. Delos Reyes, for their help in literature search; Mr. F. Corcuera and Mr. A. Madrid, Jr. for preparing the plant and soil samples for chemical and physical analyses; Dr. F.W.T. Penning de Vries and Ms. C. Herrera for giving introductory lessons on Simulation and Systems Analysis for Rice Production; Dr. L.R. Oldeman for the practical lessons in QA quizzes during processing of agromet and crop data; Dr. D.P. Garrity for encouraging me to study crop science, to do independent research, and to publish research results in peer-reviewed journals.

Faculty, staff, and students of the Crop and Weed Ecology and Plant Production Systems Chair groups of WUR, Dr. L. Bastiaans, Dr. F. Ewert, Prof. K. Giller, Prof. J. Goudriaan, Drs C. Langeveld, Dr. P. Leffelaar, Dr. T.J. Stomph, Dr. M.K. van Ittersum, Dr. J. Vos, and Dr. Yin Xinyou, for posing challenging questions that resulted in fruitful discussions.

Dr. R. Cruz of UPLB, Dr. J. Saludadez of UP Open University, Engr. M. Coronado of the Department of Agrarian Reform, Ms. J. Malinao and Ms. A. Apostol of Grace Baptist Church of Los Baños (GBC-LB) for reviewing parts of the thesis manuscript; Many other friends and acquaintances in IRRIHQ, IRRI Outpost offices, Jakenan Experiment Station, Central Research Institute for Food Crops, URRC, WUR, Filipino communities in Belgium, Germany and The Netherlands; and GBC-LB and other parts of the world, with whom I have spent many rewarding hours of discussion and from whom I have learnt so much.

I would also like to thank Dr. M. Syam, Mr. I. Adidharmawan, Ms J. Bawolje, Ms. F. Herjati, and Ms. D.W. Soegondo of IRRI Outpost Office in Indonesia; Dr. B. Jongdee, Ms. P.K. Leelagud, Ms. A. Phuengwattanapanich of IRRI Outpost Office in Thailand; Ms. L. Adriano and F. Javier of IRRI headquarters (IRRIHQ); Ir. J. Sasa, Dr. P. Setyanto, and Ir. A. Wihardjaka of Jakenan Experiment Station; Dr. N. Supapoj, Mr. S. Rajatasereekul, Dr. P. Mekwatanakarn, and Dr. D. Suriya-Arunroj of URRC; and Ir. D. Jansen, Ms. J. Elwood, Ms. A. Looijen, Ms. C. Remoroza, Ms. C. Schilt, Ms. R. van Dijk, and Ms. G. Berkhout of WUR for the logistics; Ms. H. Drenth of WUR for her practical help and advice on Repetitive Strain Injury.

The Nevens-Conte family for sharing their warm home away from home; My parents and my older siblings for their support. Finally, let me praise and thank the Almighty God for His guidance.

I hope that the information contained herein will help researchers, extension specialists, farmers, and other agents of change realize the increase in rainfed lowland rice production.

Contents

CHAPTER 1

General introduction

Overview of previous studies

World trends in rice demand and production

The world's population is 6.5 billion and growing at 1.2% per year (Population Reference Bureau, 2005). More than half of the world's people depend on rice for 80% of their food caloric requirements. Seventy percent of the world's poor live in Asia where the staple food is rice (Maclean et al., 2002).

Population growth rate is relatively higher than the increase in rice yields that has slowed down from an average of 2% per year during 1966–1990 to 0.7% per year in 2004 (Dawe, 2007). Beside the slowdown in yield growth, the proportion of the total cropped area in rice in Southeast Asia decreased from 26% in 1980 to 23% in 2004 (FAO, 2006). The decline in both, yield increase and rice area, increases the pressure to raise crop yields (Dawe, 2007), particularly from crops grown under less favourable, such as rainfed conditions, as these crops could play a significant role in meeting future food demand (Rosegrant et al., 2002).

Rainfed rice area and production

In Asia, rainfed rice is grown on approximately 59 Mha, 44% of the total rice area (Maclean et al., 2002). Average yield of rainfed rice is low at 2.1 Mg ha^{-1}, and productivity is generally constrained by uncertain water supply, low soil fertility, pest (insects, pathogens, weeds) infestations (Wade et al., 1999a) and poverty (Dawe, 2007).

On-station experiments have shown that yield reduction of rainfed rice due to drought may range from 8% in Indonesia (Setyanto et al., 2000) to 50% in Thailand (Fukai et al., 1998). Field experiments have also shown that most soils in Thailand are characterized by limited availability of N and P (Fukai et al., 1999), while soils in Indonesia are low in available K (Mamaril et al., 1995; Wihardjaka et al., 1999). In India, farm surveys in Uttar Pradesh have shown an average yield loss from rice pests of 28% (Savary et al., 1997). Pest infestation, nutrient stress, drought, and their interactions can occur simultaneously in rainfed systems (Khunthasuvon et al., 1998; Wade et al., 1999a). To design management interventions aimed at increasing productivity in rainfed areas, the constraints to rice growth and yield need to be identified and the magnitude of yield gaps assessed.

Farmers' rainfed rice fields along toposequences are characterized by a high degree of heterogeneity in topography and soil conditions (Fig. 1), so that rice crop performance varies from year to year and from location to location. Yield constraints in research stations do not necessarily reflect the soil nutrient (Eshett et al., 1989; Posner and Crawford, 1992; Yamauchi, 1992) and/or water constraints (Hseu and Chen, 2001; Tsubo et al., 2006) that occur along toposequences in rainfed farmers' fields. The magnitude of the spatial and temporal variations in water and nutrient availability and their effects on crop growth, yield, and yield gaps along toposequences are not well understood. Thus, there is a need to also analyse yield constraints in farmers' fields (Cassman and Pingali, 1995; Francis et al., 1995; Mittler, 2006) as a basis for identifying management interventions aimed at increasing the productivity in rainfed lowland rice areas.

Concepts in production ecology

How can rainfed rice production be increased? Production ecological concepts (Van Ittersum and Rabbinge, 1997) offer a useful approach to answering this complex question. The production ecological approach integrates basic information on physical, chemical, physiological and ecological processes at soil, field, and crop levels. It is a theoretical approach that explicitly takes into account the effects of growth-reducing, growth-limiting and growth-defining factors (Fig. 2).

Growth-defining factors are those that, at optimum supply of all possible growth-limiting factors and in the absence of growth-reducing agents, determine potential growth and potential production level, e.g. CO_2, radiation, temperature and crop characteristics. Growth-limiting factors consist of the essential abiotic resources, e.g.

Figure 1. Typical landscapes in rainfed lowland rice ecosystems.

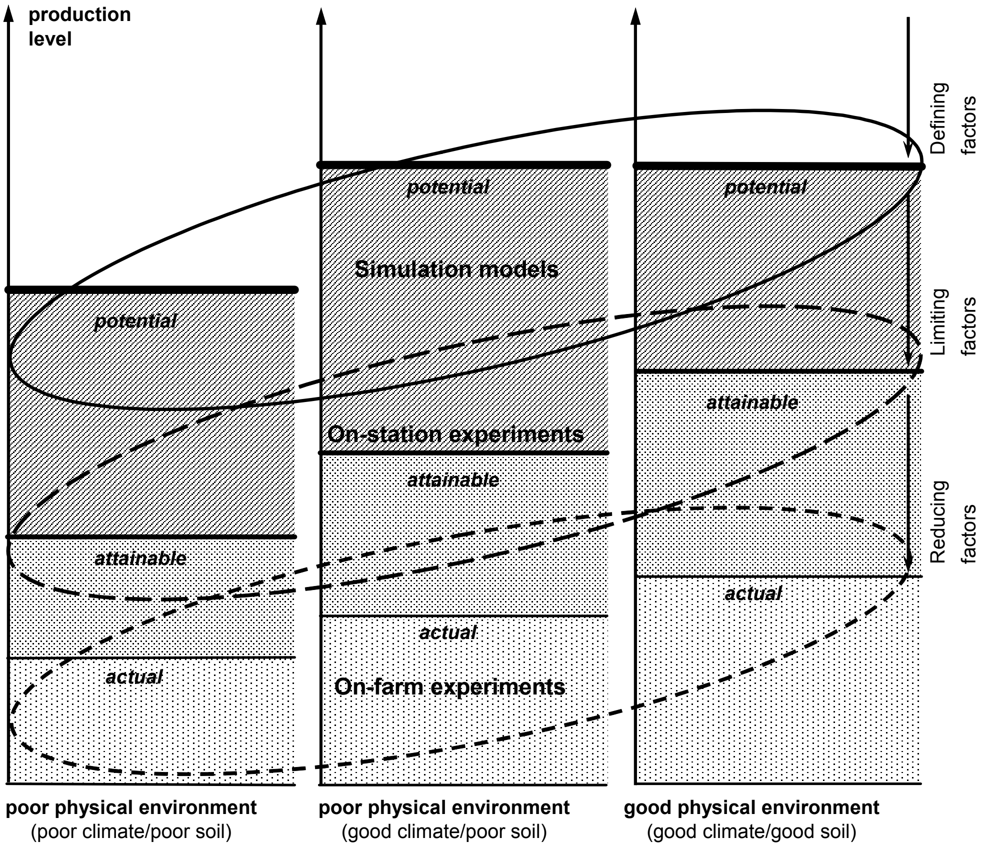

Figure 2. Physical environment, production levels, associated principal growth factors (Van Ittersum and Rabbinge, 1997) and methodologies for estimating yields.

water and nutrients (N, P, K) that, in limited supply, result in crop growth rates deviating from their potential. Growth-reducing factors reduce or hamper growth and consist of biotic factors such as pests (weeds, insects, pathogens) and abiotic factors such as pollutants.

The growth-defining factors determine potential production levels, the growth-limiting factors the attainable production levels and the growth-reducing factors the actual production levels (Fig. 2). With these concepts, the relative importance of various growth factors (from natural sources or as external inputs) can be investigated simultaneously to explain the yield levels (output) and resource-use efficiencies.

Application of production ecological concepts

Potential production levels can be estimated using simulation modelling. Attainable production levels can be directly measured in on-station experiments using best management practices, whereas actual production levels can be measured in on-farm experiments (Fig. 2).

Yield constraints can be investigated, based on either statistical analyses or on observed differences between production levels (input-output combinations, Van Ittersum and Rabbinge 1997). The input-output combinations open possibilities to identify possible management practices to increase yields, based on biophysical, socio-economic, and technical factors. The difference between actual and attainable or potential yields reflects current, often temporary, limitations and constraints associated with farmers' skills, socio-economic factors, occurrence of pests and diseases or available inputs. These constraints could theoretically be (partially) alleviated using the current state of knowledge and techniques.

Yield constraints can be analysed statistically in conventional on-station and on-farm experiments that include treatments with different levels of yield-limiting, and -reducing factors. The influence of treatment factors on the variation in crop, soil, and hydrological characteristics can be determined using analysis of variance, and the performance at any given level of a treatment factor can be compared with a reference value (control treatment). The statistical approach can complement the input-output combination method in identifying yield constraints.

In this thesis, production ecological concepts have been applied to identify gaps between actual, attainable and potential yield levels, as a basis for identification of promising management interventions for increasing yields in rainfed lowland rice systems.

Research objectives and methodology

Objectives

This study aimed at improving understanding of spatial and temporal variations in water status and nutrient availability, and their effects on crop growth and yield along toposequences in rainfed lowland rice ecosystems in Southeast Asia. The improved understanding should provide a basis for the design of improved crop management strategies. The specific objectives were:

- To determine the spatial and temporal variability in water status and nutrient availability at different toposequence positions;
- To quantify the effect of yield-defining, -limiting, and -reducing factors on performance of rainfed lowland rice using experimental data from research stations and farmers' fields;
- To analyse yield gaps at different toposequence positions at various sites in rainfed lowland areas using experimental data from farmers' fields;
- To contribute to the formulation of yield-increasing interventions in rainfed lowland rice systems.

Methodology

This study used statistical and systems analyses based on a combination of field experiments in research stations (on-station experiments) and in farmers' fields (on-farm experiments) and simulation modelling (Fig. 3). Three sets of field experiments were conducted: two sets at a research station in Indonesia (Experiments 1 and 2), and one set in farmers' fields in four toposequences in Indonesia, and four toposequences in Thailand (Experiment 3).

Experiment 1 on water and tillage effects was conducted in 1995–96 at Jakenan Experiment Station, Indonesia (6°47′ S, 111°12′ E, 8 m above sea level). The crop, soil, and hydrological characteristics measured in this experiment were used to calibrate the ORYZA2000 crop growth model. Experiment 2 on water and fertilizer effects was conducted over three consecutive years during 1997–2000, also at Jakenan Experiment Station. The experimental data were used to assess the performance of the calibrated ORYZA2000 model. Statistical analysis of crop, soil, and hydrological characteristics measured in Experiment 2 was used to assess the influence of water, N, P, K, pests and diseases on crop biomass and yield under rainfed and irrigated conditions (yield constraint analysis) in the research station.

Experiment 3 examined the variability in hydrological conditions, soil chemical and physical properties, crop biomass and yields along toposequences. This experiment

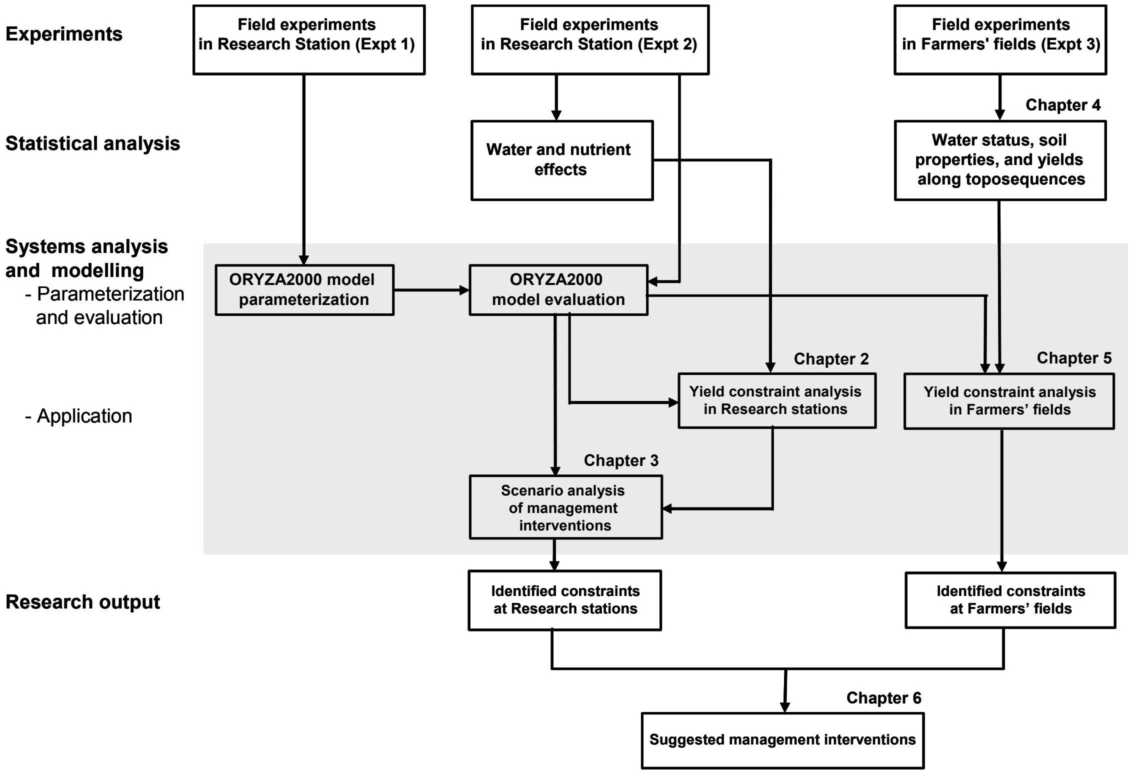

Figure 3. Methodological framework and outline of the study.

was conducted over two consecutive years in 2000–02 in farmers' fields surrounding the Jakenan Experiment Station, Indonesia and surrounding the Ubon Ratchathani Rice Research Center in Thailand (15°19′ N, 104°40′ E, 127 m above sea level). Statistical analysis of measured crop, soil, and hydrological characteristics was used to test the robustness of the relationships between position in the toposequence and hydrological conditions, soil chemical and physical properties, yield, and yield response to nutrient/weed management, superimposed on farmers' practice.

The variations in hydrological conditions, soil properties, and crop developmental stage were used as input in the calibrated ORYZA2000 model for estimating yields under potential and water-limited conditions in the research stations and farmers' fields. These yields were used in analysing yield gaps due to limiting and reducing factors (Fig. 2), and to simulate the effect of different management strategies on yield for shallow, medium, and deep water table scenarios.

Reference yields under nutrient-limited conditions in farmers' fields were estimated from crop nutrient uptake and theoretical physiological efficiencies of the rice crop (Dobermann and Fairhurst, 2000; Van Keulen, 1982, 1986). Identified yield constraints of rainfed lowland rice at the research stations and farmers' fields were used as a basis for suggesting management interventions that could increase yield and yield stability in rainfed lowland rice.

Outline of the thesis

This thesis consists of an introduction (Chapter 1), four research papers (Chapters 2–5), and a general discussion (Chapter 6). The structure of the thesis is illustrated in Fig. 3.

Chapter 2 presents the yield constraint analysis of rainfed lowland rice at Jakenan Experiment Station, which is based on statistical analysis of measurements of crop, soil, and hydrological characteristics as affected by water and fertilizer treatments during pest-free seasons and on systems analysis when pests were not adequately controlled by recommended practices. Chapter 3 covers the ORYZA2000 model parameterization and evaluation, simulation of potential and rainfed rice yields, and scenario analysis of potential yield-increasing interventions in rainfed lowland rice. Chapter 4 presents the spatial and temporal variation in water status, soil chemical and physical properties, rice yield, and attainable yield increase due to nutrient and weed management in rainfed farmers' fields along toposequences. Chapter 5 describes the analysis of yield gaps due to water and nutrient limitations along toposequence positions in rainfed farmers' fields. Chapter 6 compares three methods for determining reference yields. Management interventions for increasing yields are suggested based on identified yield constraints of rainfed lowland rice at the research station and in farmers' fields.

CHAPTER 2

Yield constraint analysis of rainfed lowland rice in Central Java, Indonesia: 1. Research station[1]

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Abstract

The low and unstable yields of rainfed lowland rice in Central Java can be attributed to drought, nutrient stress, pest infestation or a combination of these factors. Field experiments were conducted in six crop seasons from 1997 to 2000 at Jakenan Experiment Station to quantify the yield loss due to these factors. Experimental treatments – two water supply levels (well-watered, rainfed) in the main plots and five fertilizer levels (0-22-90, 120-0-90, 120-22-0, 120-22-90, 144-27-108 kg NPK ha^{-1}) in the subplots – were laid out in a split-plot design with four replications. Crop, soil, and water parameters were recorded and pest infestations were assessed.

In all seasons, rice yield was significantly influenced by fertilizer treatments. Average yield reduction due to N omission was 42%, to K omission 33–36%, and to P omission 3–4%. Water by nutrient interactions did not affect rice yield and biomass production. In two of the three late wet seasons, an average of 20% of the panicles were damaged by pests and estimated yield loss from pests was 56–59% in well-watered and well-fertilized treatments. In one out of six seasons, yields under rainfed conditions were 20–23% lower than under well-watered conditions. Drought, N and K deficiencies, and pest infestation are the major determinants for high yields in rainfed environments in Jakenan. Supplying adequate nutrient and good pest control are at least as important as drought management for increasing crop productivity of rainfed rice-growing areas in Central Java. The relative importance of drought, nutrient and pest management may vary in other rainfed areas. Yield constraints analysis should be systematically carried out to identify appropriate management strategies.

Keywords: Drought, groundwater, perched water, rice pests, nutrient stress, water by nutrient interaction, yield loss.

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[1] Published as:
Boling, A., T.P. Tuong, S.Y. Jatmiko & M.A. Burac, 2004. Yield constraints of rainfed lowland rice in Central Java, Indonesia. Field Crops Research 90, 351-360.

Introduction

Rainfed lowland rice is grown on 46 M out of 132 M ha of rice area in Asia (Maclean et al., 2002). In Central Java, rainfed lowland rice covers about 30% of the 1 M ha rice area (Amien and Las, 2000). In this area, the typical rainfed cropping system includes a dry-seeded rice crop (*gogorancah*) grown from November to February (early wet season), followed by transplanted rice (*walik jerami*) with minimum tillage from March to June (late wet season). Earlier studies have shown that the average rice yield of the wet-season crop is 3.5–6.5 Mg ha^{-1}, while that of the dry-season crop is 1.2–3.0 Mg ha^{-1} (Mamaril et al., 1994; Wihardjaka et al., 1999). To identify management interventions for increasing productivity in this area, the determinants of crop growth and rice yield need to be identified and the magnitude of yield loss assessed.

The low and unstable rainfed rice yields can be attributed to drought, nutrient stress, pest infestations, or a combination of these factors. Field experiments have shown that yield reduction due to drought ranges from 8% in Indonesia (Setyanto et al., 2000) to 50% in Thailand (Fukai et al., 1998). Simulation studies have indicated an average of 30% yield loss due to drought in rainfed lowland rice in Thailand (Jongdee et al., 1997).

Many rainfed lowland rice areas have low soil fertility (Fukai et al., 1999; Wade et al., 1998). Field experiments have shown that most soils in Thailand are characterized by limited supplies of N and P (Fukai et al., 1999), while soils in Indonesia are low in available K (Mamaril et al., 1995; Wihardjaka et al., 1999). Extensive research in various countries has demonstrated the importance of an adequate N-supply to increase grain yields in rainfed lowland areas (Wade et al., 1999b). For Indonesia, the magnitude of yield increase by applying N, P, and K is yet to be determined.

In India, average yield loss from rice pests was 28% (Savary et al., 1997). Pest infestation, nutrient stress, drought, and their interactions can occur simultaneously in rainfed systems (Khunthasuvon et al., 1998; Wade et al., 1999b). There is a need to study the simultaneous yield-reducing effects of nutrient and water deficiencies and the incidence of rice pests in rainfed lowland areas.

In this study, field experiments were conducted in six crop seasons from December 1997 to May 2000 in Central Java to determine the yield losses of rainfed rice caused by interactive effects of drought and nutrient stress, also taking into account the incidence of rice pests.

Materials and methods

Site description

The field experiments were conducted at Jakenan Experiment Station (6°47′ S, 111°12′ E, 8 m above sea level), representative for about 150,000 ha of rainfed lowland areas in Central Java (Mamaril et al., 1995). The landscape is undulating and the soil is Tropaqualf. Table 1 summarizes the soil chemical and physical properties of the site.

Based on historical (1953–1996) records, the rainy season in Jakenan usually starts in October, peaks in January, and ends in May or June. Average annual rainfall is 1550 mm, with 1060 mm falling from November to March. Mean daily solar radiation is low (13 MJ m^{-2} d^{-1}) in January and high (18 MJ m^{-2} d^{-1}) in September. Average maximum temperature is 31.7 °C and average minimum temperature is 23.5 °C.

Experimental treatments and design

Field experiments were conducted in three early wet and three late wet seasons from December 1997 to May 2000. Experimental treatments were laid out in a split-plot

Table 1. Soil physical and chemical properties of 0–20 and 20–40 cm layers in Jakenan Experiment Station.

Soil properties	Units	Soil layer	
		(0–20 cm)	(20–40 cm)
Physical properties			
Soil texture			
sand	%	44	35
silt	%	46	34
clay	%	11	31
Bulk density	kg dm^{-3}	1.46	1.44
Chemical properties			
pH (H_2O)	-	4.7	5.6
Organic C	%	0.39	0.20
N	%	0.04	0.02
Olsen P	mg kg^{-1}	10	4
Bray P	mg kg^{-1}	18	8
Zn	mg kg^{-1}	0.65	0.27
EC	S m^{-1}	0.020	0.018
Exchangeable bases			
K	$cmol_c$ kg^{-1}	0.05	0.05
Ca	$cmol_c$ kg^{-1}	3.87	7.85
Mg	$cmol_c$ kg^{-1}	0.25	0.72
Na	$cmol_c$ kg^{-1}	0.20	0.38

design with four replications with two water treatments (full irrigation (well-watered) and no irrigation (rainfed)) in the main plot and five fertilizer treatments (0-22-90 (PK), 120-22-0 (NP), 120-0-90 (NK), 120-22-90 (NPK, recommended), 144-27-108 (NPK_+) kg NPK ha^{-1}) in the 5 m × 8 m (40 m^2) subplots. In the well-watered treatments, surface irrigation was used to keep the soil at saturated conditions. Plots for the water treatments were lined with polyethylene sheets up to 80 cm depth to minimize subsurface lateral water flow.

The recommended fertilizer (NPK) and well-watered treatments served as a control. The difference in yields of the well-watered treatment and the rainfed treatment was used to estimate production loss caused by possible water deficits. Similarly, the yield difference between the NPK fertilizer treatment and the nutrient omission treatments (PK, NP, NK) was used to determine the production loss caused by elemental N, K, and P deficiency, respectively. A high fertilizer dose (NPK_+) was used to assess the effects of the common farmers' practice of fertilizer inputs exceeding the recommendations.

Cultural practices

For all crop seasons, rice cultivar IR64 was planted. For the early wet seasons, land preparation started at the onset of the rainy season. All plots were hoed twice manually to 30 cm depth, followed by dry land ploughing and harrowing. Five dry rice seeds were dibbled in holes at 15 cm × 15 cm spacing. After complete emergence, the plants were thinned down to three plants per hill. For the late wet seasons, hoeing took place right after the harvest of the wet-season crop. Plots were left fallow under submerged or wet conditions for a week, then harrowed by animal to level the nonpuddled fields and to incorporate basal fertilizer. Three 15- to 21-day-old seedlings were transplanted per hill at 15 cm × 15 cm spacing. Table 2 summarizes the planting (seeding or transplanting) and harvest dates for the six crop seasons.

Micronutrients that included 5 kg Zn ha^{-1} and 20 kg S ha^{-1} were applied in all plots. Fertilizers were applied in three splits: (1) basal – 1/4 N, all P, 1/2 K, all S, and all Zn; (2) at maximum tillering – 1/2 N and 1/2 K; (3) at panicle initiation (PI) – 1/4 N. For dry-season crops, basal fertilizer was applied before transplanting. For wet-season crops, basal N was topdressed at 14 days after emergence (DAE) of the dry seeded crop. The date of fertilizer application in rainfed plots varied within ±7 days around the predetermined dates depending on the occurrence of rainfall to saturate the fields. The farmers' practices of hand weeding and pesticide spraying were used to minimize pest damage.

Table 2. Seeding, transplanting, and harvest dates for the six seasons of field experiments conducted from December 1997 to May 2000 at the Jakenan Experiment Station.

Year and crop season	Crop establishment	Seeding date	Transplanting date	Harvest date
Early wet season				
1997–1998	Dry seeding	2 December 1997	Not applicable	11 March 1998
1998–1999	Dry seeding	31 October 1998	Not applicable	18 February 1999
1999–2000	Dry seeding	25 October 1999	Not applicable	8 February 2000
Late wet season				
1998	Transplanting	30 March 1998	24 April 1998	11 July 1998
1999	Transplanting	23 February 1999	20 March 1999	31 May 1999
2000	Transplanting	11 February 2000	5 March 2000	24 May 2000

Plant sampling and nutrient uptake

Dates of emergence, PI, flowering, and physiological maturity were recorded. At physiological maturity, 22 hills (0.50 m^2) were sampled from each subplot for leaf blade, culm and leaf sheath, and panicle dry weights, nutrient (N, P, K) concentrations, and yield components (panicle density, spikelet number per panicle, % of filled spikelets, 1000-grain weight). Rice yield was determined from 6 m^2 sampling area.

Plant N was determined using Kjeldahl digestion (Varley, 1966). The digest was analysed for nitrogen as indo-phenol blue in the Technicon AutoAnalyzer II (Technicon Instruments Corporation, 1977). P was determined colorimetrically as reduced phosphomolybdate at 625 μ (Chapman and Pratt, 1961; Jackson, 1958; Jones et al., 1990) using the Technicon AutoAnalyzer II. K was determined by soaking with 1N HCl and subsequent analysis of the filtrate (Yoshida et al., 1976) using Atomic Absorption Spectrophotometry.

Water and weather records

Field water depth was measured daily in 40 cm long, 5 cm diameter PVC tubes installed in each subplot to 25 cm below the soil surface. The bottom 22 cm of the tubes was perforated with 3 mm diameter holes at 2 cm intervals. Groundwater table depth was measured daily in each main plot of rainfed treatments, using 5-cm-diameter, 150 cm long PVC tubes, similarly perforated in the bottom 75 cm length, installed to a depth of 100 cm below the soil surface. In the absence of standing water in the rainfed plots, soil water potentials were measured daily from tensiometers installed at 5, 10, and 20 cm depth.

Daily rainfall, solar radiation, maximum and minimum temperature, relative humidity, and wind speed were measured at the Jakenan weather station.

Pest monitoring

In the 1997–1998 early wet season, any panicle damage caused by pests was not recorded. From the 1998 late wet season onward, the proportion of panicle damage was recorded at physiological maturity, following visible pest incidence.

Insect species were identified using a combination of sweepnet and random sampling of plant hills from crop establishment to harvest. For adult insects, 10 sweeps of the sweepnet in a 40 m^2 area were taken thrice a week from 8:00 to 11:00 AM. Similarly, 10 hills in a 40 m^2 area were randomly sampled thrice a week to identify immature insects.

Plant height and colour and lesions in the leaf blade and sheath were monitored in 10-hill samples for disease symptoms. The organisms were identified using the standard procedure for identifying rice pests (International Rice Research Institute, 1983).

Data analysis

Rice biomass, yield, and yield components were analysed with standard split-plot analysis of variance techniques. When the analysis of variance showed significant differences among treatments, Duncan’s multiple range test (DMRT) was used for pair-wise comparison.

In pest-free conditions, grain yields for well-watered NPK treatments were considered ‘potential’. Under potential production situations, water and nutrients are non-limiting so rice growth and yield are determined by weather conditions and crop genetic characteristics only. In seasons that are affected by pests, the crop growth and yield of rice cultivar IR64 in well-watered NPK treatments were simulated using an ecophysiological model, ORYZA2000 (Bouman et al., 2001). This model was extensively evaluated for potential production situations in Jakenan (Boling et al., 2007a) and in other areas (Kropff et al., 1994; Matthews et al., 1995). Yield losses due to drought, nutrient stress, and pests were estimated using the difference between potential and actual yields.

Exceedance probability of rainfall was estimated using the rank-order method (Doorenbos and Pruitt, 1977). In this method, rainfall was assumed to follow normal distribution. Cumulative rainfall amount for two crop periods (November–February and March–June) were calculated from 1953 to 1996. For each period, the cumulative rainfall records were arranged in decreasing order. Each record was assigned a ranking number (m) and a corresponding probability level ($P(m)$):

$$P(m) = 100\, m/(n+1)$$

where, n is the number of records.

Results and discussion

Rice pests and their effects on rice yield

The proportion of damaged panicles was negligible (< 1%) in all early wet seasons and in one (2000) dry-season crop (data not shown). In the 1998 and 1999 late wet seasons, however, on average 20% of the panicles were damaged. The extent of panicle damage was similar for the two water treatments but varied among the fertilizer treatments (Fig. 1). The panicle damage in NP treatments was similar to NK, NPK, and NPK$_+$ plots but was more severe than the PK plots.

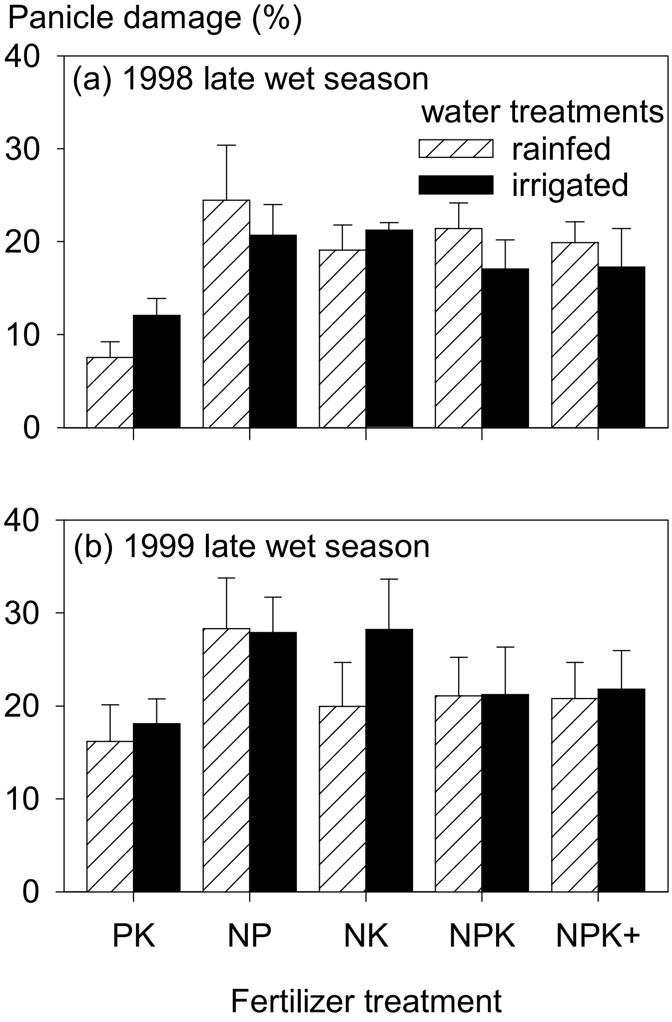

Figure 1. Proportion of damaged panicles in five fertilizer treatments and two water treatments in 1998 (a) and 1999 (b) late wet seasons at the Jakenan Experiment Station. Panicle damage in four other seasons was lower than 1%. Fertilizer treatments are PK=0-22-90 kg NPK ha^{-1}, NP=120-22-0 kg NPK ha^{-1}, NK=120-0-90 kg NPK ha^{-1}, NPK=120-22-90 kg NPK ha^{-1}, and NPK$_+$=144-27-108 kg NPK ha^{-1} Vertical and capped bars represent the standard errors of the mean.

The severe panicle damage in the 1998 and 1999 late wet seasons was associated with the occurrence of deadhearts and whiteheads caused by *Scirpophaga incertulas.* In addition, leaf damage caused by *Helminthosporium oryzae* (leaf brown spot) and *Cercospora oryzae Miyake* (narrow brown leaf spot) also occurred.

Except for the 1998 and 1999 late wet seasons, the simulated potential yields using the ORYZA2000 model agreed well with the measured grain yields under well-watered NPK treatments (Fig. 2). Simulation of grain yields has a root mean square error of prediction of 10–20% (Boling et al., 2007a), which is considered good by Jamieson et al. (1991). This indicates the adequacy of this model to simulate the rice yield in pest-free seasons when water and nutrient are non-limiting. Rice yields under well-watered NPK treatments in the 1998 and 1999 late wet seasons were lower than those in the other four crop seasons (Fig. 2). These yield levels were significantly lower than the potential yield estimated using the ORYZA2000 model. The lower yields in the 1998 and the 1999 late wet seasons were associated with high proportions of panicles damaged by pests (Fig. 1).

If the potential yield estimates were used as a reference, the yield loss due to pests in well-watered NPK treatments was estimated at 2490 kg ha^{-1} (56%) and 2290 kg ha^{-1} (59%) in the 1998 and 1999 late wet seasons, respectively. Yield loss was relatively higher in plots with low K levels (Figs 2b, 2d), which is consistent with the findings of Wihardjaka et al. (1999). The yield losses in this study are comparable with the maximum levels measured in India (Savary et al., 1997).

Severe pest infestation in the 1998 and 1999 dry-season crops in the experiment may be related to their late establishment compared with the surrounding farmer's crops. High pest infestation of late wet season rice crops in the study area was earlier reported (Mamaril et al., 1995; Wihardjaka et al., 1999). Late planting of late wet season crops may have exacerbated the pest infestation due to higher insect densities that tend to congregate on remaining host plants (Gary Jahn, personal communication). The high yield losses indicate the need for crop protection, particularly for late-sown dry-season crops to increase crop productivity in these rainfed lowland areas.

Weather and water conditions

Table 3 summarizes the solar radiation and rainfall for the six crop seasons. Cumulative radiation from PI to physiological maturity was high in the 1997–1998 early wet season, low in the 1998–1999 early wet season and 1999 late wet season, and moderate in other seasons. Compared with historical records, rainfall in the 1997–1998 early wet season was below normal ($P > 0.80$), while that in the 1999–2000 early wet season and 1999 late wet season was above normal ($P < 0.20$). Rainfall in the other three seasons was normal. Rainfall of a normal late wet season (1998 late wet

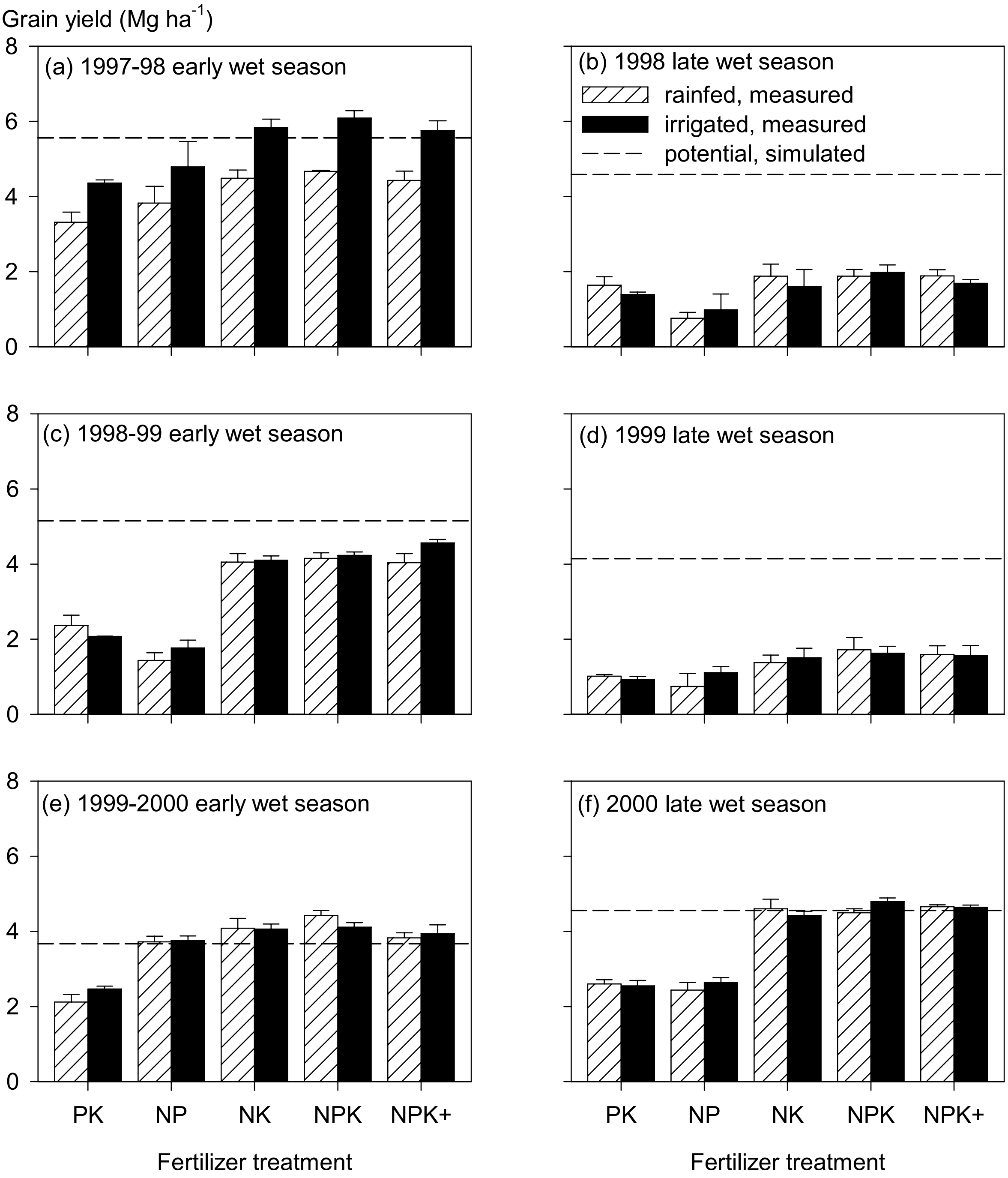

Figure 2. Grain yield of five fertilizer treatments and two water treatments in 1997–1998 early wet season (a), 1998 late wet season (b), 1998–1999 early wet season (c), 1999 late wet season (d) 1999–2000 early wet season (e), and 2000 late wet season (f) at the Jakenan Experiment Station. Fertilizer treatments are explained in Figure 1. Vertical and capped bars represent the standard errors of the mean. Dotted line represents the simulated yield potential using the ORYZA2000 model.

season, P = 0.44) was slightly higher than a below normal early wet season (1997–1998 early wet season, P = 0.99), indicating favourable late wet season conditions during the study period.

Table 3 also shows the number of days without standing water, groundwater below 50 cm (which is beyond the rooting depth of most rainfed lowland rice (Lilley and Fukai, 1994; Pantuwan et al., 2002; Tuong et al., 2002), and surface soil water potential levels below −45 kPa (corresponding to water stress causing a 50% reduction in leaf growth (Boling et al., 1998)) in rainfed treatments. The below-normal rainfall in the 1997–1998 early wet season concurred with an absence of standing water and receding groundwater starting at 32 days after sowing (DAS, Fig. 3). From 40 DAS until harvest, groundwater depth was below 100 cm, indicating drought during the vegetative to reproductive stages of the rice crop. Soil water potential in the surface layer during the crop's reproductive stage was below –45 kPa for 42 days (Table 3). The soil water potential, the groundwater and the field water levels in the 1997–1998 early wet season were significantly lower than in the other two early wet seasons and even in three late wet seasons (data not shown). The below-normal rainfall and prolonged periods of deep groundwater levels and of low soil water potentials indicated that drought was most severe in the 1997–1998 early wet season.

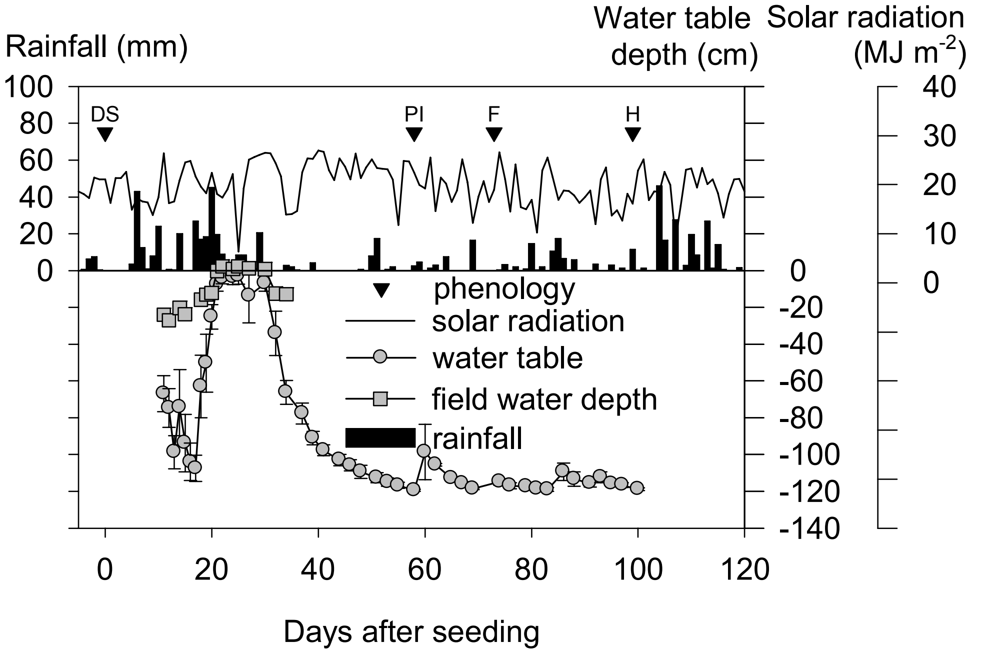

Figure 3. Rainfall, solar radiation, crop phenological stages, field water depth, and water table depth in a representative crop (1997–1998 early wet season) at the Jakenan Experiment Station. DS=direct seeding; PI=panicle initiation; F=flowering; H=harvest. Vertical and capped lines represent the standard errors of the mean.

Table 3. Rainfall, solar radiation, and number of days without standing water, groundwater depth below 50 cm, and surface soil water potential below –45 kPa for the six seasons of field experiments conducted from December 1997 to May 2000 at the Jakenan Experiment Station.

	Rainfall[1]		Solar	Number of days[3]		
Year and crop season	Amount (mm)	Exceedance probability (*P*) (-)	radiation[2] (MJ m^{-2})	Without standing water (d)	Groundwater water below 50 cm (d)	Surface soil water potential ≤ –45 kPa (d)
Early wet season						
1997–1998	432	0.99	781	42	42	42
1998–1999	692	0.71	705	0	0	0
1999–2000	1061	0.08	730	0	0	0
Late wet season						
1998	456	0.44	722	16	16	8
1999	658	0.08	681	0	0	0
2000	510	0.38	732	25	0	0

[1] Cumulative value during the crop season.

[2] Cumulative value during the crop's reproductive stage.

[3] Cumulative number of days during the crop's reproductive stage for rainfed treatments.

Drought effects on rice biomass and yield

Water treatments significantly influenced rice yields and biomass only in the 1997–1998 early wet season, when severe drought at 0.99 probability level was experienced. In the 1997–1998 early wet season, yields for all fertilizer treatments under rainfed conditions were significantly lower than under well-watered conditions (Fig. 2). The direction and magnitude of treatment differences in above-ground biomass (data not shown) were similar to those for grain yield. The lower biomass and yields in the rainfed treatment were associated with a lower proportion of filled spikelets and a lower 1000-grain weight (Fig. 4). These were attributed to the severe drought that occurred from PI to physiological maturity (Fig. 1), which is consistent with the findings of Yoshida (1981).

In the 1997–1998 early wet season, yield loss due to drought ranged from 1000 kg ha^{-1} (20%) in PK and NP plots to 1400 kg ha^{-1} (23%) in the NPK fertilizer treatments. The 20–23% yield losses were lower than those measured in the same experiment area in 1996 late wet season (Boling et al., 2000) but were higher than the maximum yield loss measured over seven crop seasons in an adjacent area (Setyanto et al., 2000). The

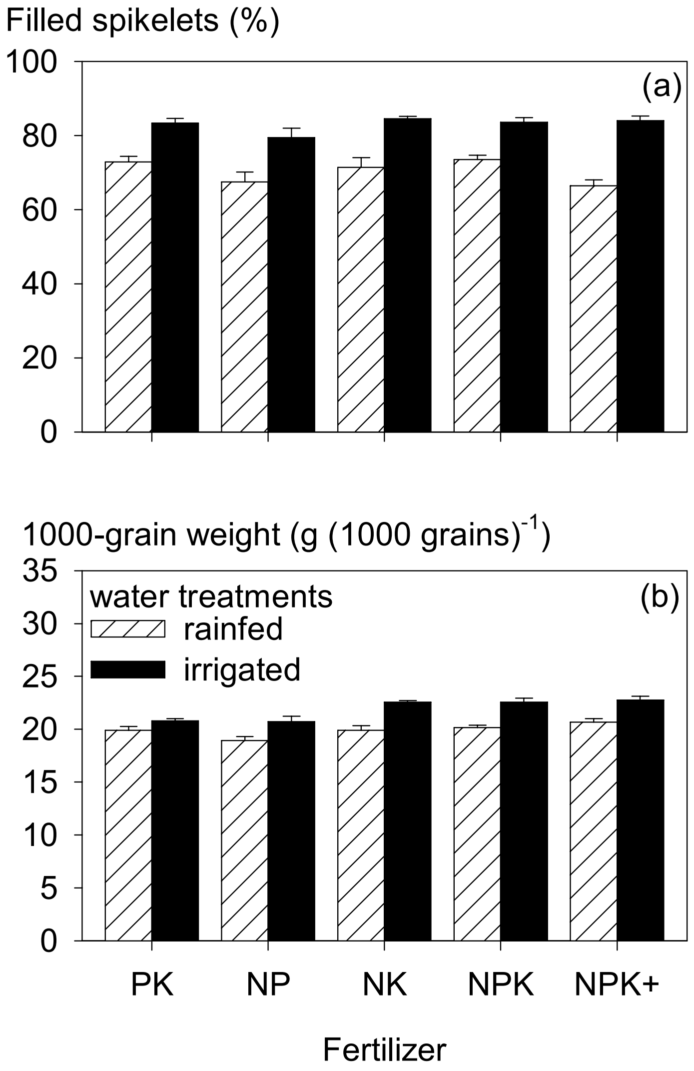

Figure 4. Percent filled spikelets (a) and 1000-grain weight (b) in 1997–1998 early wet season. Fertilizer treatments are explained in Figure 1. Vertical and capped bars represent the standard errors of the mean.

discrepancy may be attributed to the probability level of drought. For the same 1997–1998 early wet season, Wade et al. (1999b) reported a wide-range of rainfed rice yields (608–5,100 kg ha^{-1}) in farmers' fields indicating high spatial variation of rainfed rice yields in these areas.

Water by nutrient interaction did not significantly affect rice yields and biomass production (data not shown). The non-significant effect of water by nutrient interaction confirms earlier findings in many areas under similar agro-ecological conditions (Khunthasuvon et al., 1998), but the situation may be different in other rainfed lowland environments (Mackill et al., 1996).

Nutrient effects on rice yield

Fertilizer treatments significantly influenced yield (Fig. 2). Under well-watered conditions, the average yield reduction due to omission of N was 1945 kg ha^{-1} (42%) compared with the recommended fertilizer input of 120-22-90 kg NPK ha^{-1}. Average yield reduction caused by omission of K was 1570 kg ha^{-1} (33%) and that due to omission of P was 200 kg ha^{-1} (4%). Under rainfed conditions, yield reductions were 1830 kg ha^{-1} (42%), 1580 kg ha^{-1} (36%), and 150 kg ha^{-1} (3%) for N, K, and P omission, respectively. The relatively high yield reduction in the absence of N and K fertilizers indicates the inadequacy of indigenous soil supply to meet the N and K requirements of the rice crop. The application of 120 kg N ha^{-1} and 90 kg K ha^{-1} significantly increased yield under both well-watered and rainfed rice in all seasons, but no further yield increase resulted from higher rates of N or K.

The effect of fertilizer treatments on rice yield could be attributed to the uptake of the different macronutrients. In pest-free conditions, average nutrient uptakes were 52 kg N, 26 kg P, and 41 kg K per ha in nutrient omission plots and 114 kg N, 29 kg P, and 134 kg K per ha in well-fertilized conditions. Average nutrient uptakes in seasons that are affected by pests were significantly lower (42 kg N, 16 kg P, and 20 kg K per ha in nutrient omission plots and 88 kg N, 17 kg P, and 65 kg K per ha in well-fertilized conditions) than in pest-free conditions. The difference in nutrient uptakes is associated with plant biomass.

Under pest-free conditions, internal nutrient use efficiencies in the N- and P-omission plots (18 kg N and 5 kg P Mg^{-1} grain, respectively) indicate a high N and P supply while that in the K-omission plots (12 kg K Mg^{-1} grain) indicates a K deficiency for the rice crop (Dobermann and Fairhurst, 2000). The K deficiency is consistent with earlier findings by Wihardjaka et al. (1999) and Mamaril et al. (1994, 1995) in this rice-growing area. On the other hand, the high N and P supply in Jakenan is not representative of most rainfed lowland areas in Asia (Wade et al., 1999b).

Conclusions

In one (1997–1998 early wet season) out of six seasons (P = 0.99), rainfed rice yields in Jakenan were 20–23% lower than those of well-watered rice. In late wet seasons, yield reduction due to drought of the same exceedance probability could be much higher. In this study, there was no significant yield loss due to drought in normal late wet season (P = 0.44), but yield loss could be much more in higher toposequence position where groundwater table was deeper. These results indicate that drought may easily be the largest yield constraint in many rainfed rice ecosystems.

Nitrogen and potassium significantly influenced rice yields and biomass production in Jakenan. Average yield reduction due to N omission was 42% and to K omission

33–36%. Under the experimental conditions, water by fertilizer interaction did not affect rice yield and biomass production, indicating that supplying adequate nutrient always results in rice yield increase. The current fertilizer recommendation results in a substantial yield increase. However, no further yield increase is gained beyond the recommended levels. Such relationships need to be verified in other rainfed rice ecosystems (Mackill, 1996) where significant water by nutrient interaction may occur. The complexity of the rainfed rice system requires careful characterization of the experiments for accurate interpretation of results and their implications.

Pests are major threats for dry-season rice in Jakenan. In two of the three late wet seasons, estimated yield losses from pests were 56–59%. The maximum yield loss was comparable with that in systematic studies on characterizing the rice pests and quantifying yield losses in India by Savary et al. (1997). This indicates that pest can be a common yield constraint to rainfed lowland rice in Asia. Early planting of the second rice crop may alleviate the problem by reducing the insect densities that tend to congregate on remaining host plants.

The relative importance of drought, nutrient deficiency and pest infestation may vary in different rainfed rice areas. Integrated assessment taking into account all possible yield-determining, -limiting, -reducing factors (Van Ittersum and Rabbinge, 1997) and their interactions is necessary to determine yield constraints in other rainfed lowland areas of south and south-east Asia and to identify management options for increasing productivity and yield stability in this area. The data from field measurements have to be compared with the theoretical values determined from simulation models such as ORYZA2000 (Bouman et al., 2001). Simulation models can be used together with long-term weather data to complement field experiments in exploring wide-range of management strategies for alleviating the effect of drought and nutrient stress in rainfed lowland rice.

CHAPTER 3

Modelling the effect of groundwater depth on yield-increasing interventions in rainfed lowland rice[1]

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Abstract

Because of drought and nutrient stress, the yields of rainfed lowland rice in Central Java, Indonesia, are generally low and unstable. Variation in groundwater depth can contribute to experimental variability in results of yield-increasing interventions. To test this hypothesis, we used the crop growth simulation model ORYZA2000 to explore the impacts of groundwater depth on the effect of sowing date, tillage, fertilizer-N application and supplementary irrigation on the yield of lowland rice at Jakenan, Central Java, Indonesia. ORYZA2000 was first parameterized and evaluated using data from eight seasons of field experiments between 1995 and 2000. The model adequately simulated the soil water balance, crop growth and grain yield. With shallow to medium groundwater depth (less than 0.5 m deep), rainfed rice yields are close to potential yields with timely sowing in the wet season. With groundwater tables fluctuating mostly between 0.5 and 1.5 m, rainfed yields are 0.5−1.0 Mg ha^{-1} lower than potential yields with timely sowing. The decrease in yield with late sowing sets in earlier and proceeds faster with deeper groundwater depths. Deep tillage and supplementary irrigation increase yield more with deep groundwater tables than with shallow groundwater tables, but N fertilization increases yield more with shallow than with deep groundwater tables. Groundwater depth should be taken into account in the selection of yield-increasing interventions.

Keywords: Crop modelling, ORYZA2000, fertilizer application, planting dates, supplementary irrigation, tillage.

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[1] Published as:
Boling, A.A., B.A.M. Bouman, T.P. Tuong, M.V.R. Murty & S.Y. Jatmiko, 2007. Modelling the effect of groundwater depth on yield-increasing interventions in rainfed lowland rice in Central Java, Indonesia. Agricultural Systems 92, 115-139.

Introduction

Rainfed lowland rice covers about 30% of the total rice area in Central Java, Indonesia (Amien and Las, 2000). Farmers grow two rice crops in the wet season: a direct-seeded crop called *Gogorancah* in the early wet season (November to February), with yields varying between 3.5 and 6.8 Mg ha^{-1}, and a transplanted crop called *Walik Jerami* in the late wet season (March–June), with yields between 1.2 and 4.5 Mg ha^{-1} (Mamaril et al., 1994; Setyanto et al., 2000; Wihardjaka et al., 1999). Whereas the differences in yield between the early and late wet-season rice crops are mainly caused by differences in weather (radiation, temperature and rainfall), the overall low and unstable yields are mainly caused by drought stress and nutrient deficiencies (Mamaril et al., 1994; Wade et al., 1999b; Wihardjaka et al., 1999). Various management strategies have been suggested to increase yields in the rainfed rice environment (Fukai et al., 1998). For example, sowing dates can be adapted to make optimal use of the combination of solar radiation, temperature and rainfall (Tuong et al., 2000b). Tillage can be adapted to modify soil hydraulic properties and improve root distribution and growth and soil water extraction (Lilley and Fukai, 1994). The introduction of on-farm water reservoirs offers scope for supplemental irrigation to alleviate drought stress (Syamsiah et al., 1994). The application of fertilizers can be optimized in accordance to weather patterns that determine potential yield levels (Ladha et al., 1998). However, rainfed lowlands are extremely heterogeneous and field experiments often produce divergent results. Most rainfed lowlands are characterized by undulating landscapes with small to medium topographic differences (Tuong et al., 2000a). Groundwater table depths vary along toposequences (Tsubo et al., 2006) with important consequences for water availability and soil fertility. It can be hypothesized that the differences in water availability as induced by variation in groundwater depth contribute to the variation in experimental results on yield-increasing interventions as mentioned above. Since groundwater tables can not be easily controlled in field experiments, simulation modelling is an ideal tool to test this hypothesis and quantify the interactions between groundwater depth and yield under various management practices. The ORYZA2000 model simulates crop growth and development of lowland rice in potential, N-limited and water-limited production situations (Bouman et al., 2001). Our study aimed at applying ORYZA2000 to assess the effect of groundwater table depth on rice yield under various management interventions (namely establishment date, tillage, supplementary irrigation and nitrogen fertilization), and to derive optimal management recommendations for different groundwater depths in the rainfed areas of Central Java. Because a thorough evaluation of ORYZA2000 has only been reported for fully irrigated and N-limited conditions (Bouman and Van Laar, 2006), we first evaluated ORYZA2000 under concurrent water-limited (rainfed) and

N-limited conditions using experimental data collected at a research station at our study site.

Materials and methods

Experiments

The experiments were conducted at Jakenan Experiment Station (6°47′ S, 111°12′ E, 8 m above sea level). The site is representative for a rainfed lowland area that covers about 150,000 ha in Central Java. The 50-year (1953−2002) average annual rainfall in the area is 1550 mm, with 1060 mm falling between November and March. Average daily maximum temperature is 31.7 °C and average minimum is 23.5 °C. Solar radiation is low (13 MJ m^{-2} d^{-1}) from December to February and high (18 MJ m^{-2} d^{-1}) from August to October. The soil at the experiment station is alluvial, with light-textured surface soil (43% sand, 46% silt, 11% clay), low organic carbon content (0.41%), relatively low CEC_c (3.48 $cmol_c$ kg^{-1}) and low exchangeable bases (0.03 K, 2.80 Ca, 0.22 Mg $cmol_c$ kg^{-1}).

Eight field experiments with rice variety IR64 were conducted between 1995 and 2000 (Table 1). In all experiments, the early wet-season crops were direct seeded and the late wet-season crops were transplanted. Pest management was targeted at keeping the rice crops free from insects, diseases and weeds. In 1995 and 1996, late-season crops were included that ran into the early parts of the dry season, with two water treatments (irrigated and rainfed) in main plots and conventional (shallow, down to 10 cm depth) and deep tillage (down to 30 cm depth) treatments in subplots, laid out in a split-plot design with four replicates. Between 1997 and 2000, three early wet-season and three late wet-season experiments included two water treatments (irrigated and rainfed) in main plots and five fertilizer treatments in subplots, laid out in a split-plot design with four replicates. More details of the 1997−2000 experiments are given in Boling et al. (2004).

In 1995 and 1996, the water retention characteristics of soils following the conventional and deep tillage treatments were determined using the wind method, pressure plate assembly and hanging water column (Wopereis et al., 1994). The soil hydraulic conductivity was determined *in situ* using the column method.

In all experiments, 12-hill samples (0.27 m^2) were taken to determine the biomass of leaf blades, leaf sheaths and culms, and panicles at regular (10−14 day) intervals during the growing season. Yield was determined from a 6 m^2 sampling area. The depth of any standing water on the field and of the groundwater below the fields was measured daily. In the absence of standing water, soil water potentials were measured daily using tensiometers installed at 10.0−12.5 cm depth.

Table 1. Details of field experiments used in evaluation of ORYZA2000, Jakenan Experiment Station, 1995–2000.

Season and year	Treatment			
	Water	Tillage[1]	Sowing date	Fertilizer (kg NPK ha^{-1})
Early wet season				
1997–1998	Irrigated, Rainfed	Deep	2 Dec. 1997	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108
1998–1999	Irrigated, Rainfed	Deep	31 Oct. 1998	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108
1999–2000	Irrigated, Rainfed	Deep	25 Oct. 1999	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108
Late wet season				
1995	Irrigated, Rainfed	Shallow, deep, puddled	16 Mar. 1995	120-22-60
1996	Irrigated, Rainfed	Shallow, deep	10 Mar. 1996, 8 April 1996	120-22-90
1998	Irrigated, Rainfed	Deep	30 Mar. 1998	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108
1999	Irrigated, Rainfed	Deep	23 Feb. 1999	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108
2000	Irrigated, Rainfed	Deep	11 Feb. 2000	0-22-90, 120-22-0, 120-0-90, 120-22-90, 144-27-108

[1] Shallow or conventional tillage (i.e. farmer's practice): plots were ploughed and harrowed by animal drawn country plough to depth of approximately 10 cm; Deep tillage: plots were ploughed by tractor to depth of 30–40 cm and harrowed by animal drawn harrow; Puddled: plots were ploughed by animal drawn country plough to depth of approximately 10 cm, submerged for one week and puddled by rotary power cultivator.

Daily weather data were collected from a weather station at the site. Rainfall and solar radiation for the eight crop seasons are summarized in Table 2. Compared with historical records, rainfall was considered below normal [probability of exceedance (P) > 0.80] in the 1997–1998 early wet season and the 1996 late wet season, above normal ($P < 0.20$) in the 1999–2000 early wet season and the 1999 late wet season, and normal in the other seasons.

Table 2. Rainfall and solar radiation for the eight seasons of field experiments, 1995–2000.

Year and crop season	Rainfall[1]		Solar radiation[2]
	Amount (mm)	Exceedance probability (P)	(MJ m^{-2})
Early wet season			
1997–1998	432	0.98	781
1998–1999	692	0.71	705
1999–2000	1061	0.08	730
Late wet season			
1995	328	0.80	700
1996	212	0.98	682
1998	456	0.45	722
1999	658	0.08	681
2000	510	0.37	732

[1] Cumulative value during the crop cycle;

[2] Cumulative value during the crop's reproductive stage.

ORYZA2000: Water dynamics and drought effects

A description of the processes of growth and development under potential conditions, and of the N dynamics and their effects on growth and development in ORYZA2000, has been presented by Bouman and Van Laar (2006). Here, we describe the effects of water dynamics on crop growth and development and give details of the water balance PADDY.

Effects of drought on crop growth

Drought in rice is defined here as the condition where the soil water content in the root zone is below saturation. Such a condition has been reported to affect leaf expansion, leaf rolling, leaf senescence, photosynthesis, assimilate partitioning, root growth and spikelet sterility (Bouman and Tuong, 2001). In the model, drought-stress factors are calculated as a function of the soil water tension in the root zone

$$\text{Stress factor} = (\Psi_s - \Psi_u) / (\Psi_u - \Psi_l) \quad (1)$$

where, Ψ_s is the soil moisture tension in the root zone (kPa); Ψ_u is the upper soil tension limit for the stress factor (kPa); and Ψ_l, lower soil tension limit for the stress factor (kPa).

All drought-stress factors are multiplicative factors, and have values ranging from 0 to 1. The value 1 means that the growth process is not affected (resulting in potential production) and the value 0 means that the process has come to a complete standstill. The value of the factors is calculated by scaling the soil moisture tension in the root zone between a lower limit when the process in question becomes affected and an upper limit when the process is maximally affected. Values for the lower and upper limits are taken from Wopereis et al. (1996). The soil moisture tension is simulated by the PADDY soil water balance model (see below). The drought-stress factors in the model affects leaf area development, photosynthesis, transpiration, assimilate partitioning and spikelet sterility.

Leaf expansion rates of plants stressed in the vegetative phase decrease rapidly after an initial period of normal growth. In the model, the relative leaf growth rate in the exponential phase of growth is multiplied by the drought factor 'leaf expansion reduction'. Leaves roll under drought, which reduces solar radiation interception. The leaf area index (LAI) calculated under non-water-stressed conditions in the model is multiplied by a 'leaf-rolling factor' before it enters the photosynthesis and transpiration routines. Drought after flowering also accelerates the senescence and death rates of the leaves. In the model, the leaf loss rate due to normal senescence is multiplied by a 'dead leaf' factor.

Crops under drought close their stomata to reduce the rate of transpiration per unit leaf area. This increases the resistance to the gas exchange of CO_2, reducing the rate of photosynthesis. In the model, the assumption is adopted that the ratio of transpiration to gross photosynthesis under non-stressed conditions is constant (Van Laar et al., 1997). The maximum leaf photosynthesis rate is reduced by a 'relative transpiration' factor. Under drought stress, carbohydrate partitioning between shoot and root is modified in favour of the root biomass (O'Toole and Chang, 1979). In the model, the relative transpiration rate is used as a reduction factor in the fraction of total carbohydrates allocated to the shoots, following Van Laar et al. (1997).

Drought stress around flowering enhances spikelet sterility. Turner et al. (1986) found a relationship between temperature increase due to drought and increased spikelet sterility, and related the increase in temperature to the leaf rolling score. We used their relationships to model the effect of drought on spikelet sterility by adding the drought-induced temperature increase, calculated from the 'leaf-rolling factor', to the daily ambient temperature.

Soil water balance

Soil water dynamics are computed with the soil water balance model PADDY, which is fully integrated as a subroutine in ORYZA2000 and linked to the above-ground module via soil water content and soil water potential. PADDY is a universal multiple-layer model that can be used for both puddled and nonpuddled rice soils (Bouman et al., 2001). The number and thickness of soil layers are user-defined. The vertical flows of water in and out of each layer are simulated on a daily basis. Extraction of water from the top soil layer is by transpiration and evaporation. Potential transpiration and evaporation rates are calculated based on equations by Penman-Monteith, Priestley-Taylor, or Makkink (Van Kraalingen and Stol, 1997), depending on users' preference and data availability. Actual transpiration is calculated from potential values by multiplication with the relative transpiration rate. With ponded water (see below) or with a saturated topsoil, actual evaporation rates are equal to the potential rates. With water contents below saturation, the evaporation rate drops from potential values proportional to the square root of time (Penning de Vries et al., 1989).

Inflow into the first layer is from rainfall and irrigation. With impeded drainage, a standing water layer may develop on the surface and the maximum depth of ponding is determined by bund height (model input parameter). When there is ponded water on the surface, vertical water flow through the profile is either a fixed, user-defined percolation rate or a user-defined percolation rate depending on groundwater table depth. In the presence of a puddled topsoil, percolation rates can also be calculated dynamically from hydraulic conductivity characteristics from the plough sole (the bottom layer of the puddled topsoil) and the nonpuddled subsoil. The conductivity characteristics are expressed by either Van Genuchten parameters (Van Genuchten, 1980) or by parameters of a power function.

When there is no ponded water on the surface, incoming water (rainfall plus irrigation) is redistributed by calculating for all layers gain and loss terms, starting with the top layer. All water in excess of field capacity is drained from the layer, with a maximum rate equal to the saturated hydraulic conductivity of the layer. If, in a specific soil layer, the rate of inflow of water exceeds the saturated hydraulic conductivity, the water content of that layer may increase and may reach saturation. Any additional excess water flowing in is redistributed upward and a perched water table develops. Water contents can drop below field capacity when water extraction by transpiration and evaporation exceeds the net inflow rate. The water retention characteristics of each soil layer, needed to calculate upward and downward flows, are model input data and can be supplied either as measured data or as Van Genuchten parameters. These soil parameters depend on physical soil properties which can be modified by tillage.

Groundwater is assumed to remove all water draining out of the profile and can either be below the soil profile (deep drainage) or within the profile itself. The depth of the groundwater table is a model input parameter and can vary in time. Capillary rise of water from the groundwater table is calculated on the basis of soil moisture tensions in each soil layer using modified procedures of Van Diepen et al. (1988). Soil moisture tensions are calculated from computed soil water contents by either linear interpolation between the (user-supplied) retention data or by using the Van Genuchten parameters.

Model parameterization and evaluation

Parameterization

We used the standard crop parameters for rice variety IR72 (Bouman et al., 2001), with parameter values for specific leaf area and assimilate partitioning derived from field experiments with IR64 in the early 1990s in the Philippines (M. Dingkuhn, unpublished data). The partitioning factors for assimilates were re-parameterized using the biomass data of leaf blade, leaf sheath and culm, and panicles from our field experiments in 1995–1996. For each experiment in the period 1995–2000, crop development rates were calculated from observed phenological stages. Since we had no measurements of leaf area index, we retained the standard values for specific leaf area.

For each experiment, the soil percolation rate was first estimated from daily observations on field water depths, and then fine-tuned by model fitting (refining the parameter value until simulated field-water depths best agreed with measured field-water depths). Similarly, soil N supply was first estimated from crop N uptake in zero-N treatments, and subsequently fine-tuned by model fitting. Fine-tuning was usually accomplished within a ±20% range of first-estimated values. Measured groundwater depth data were entered as boundary conditions in PADDY. The soil water retention characteristics were directly measured in 1995 and 1996 and the parameters of the Van Genuchten equations were derived through curve fitting on the measured soil water retention and conductivity data. Since these parameters may vary with tillage, this was done for soils with different tillage treatments separately.

For each year, recorded values of daily maximum and minimum temperature, radiation, wind speed and relative humidity were used. We used the Penman-Monteith method to calculate potential evaporation and transpiration rates

Evaluation

To evaluate the performance of ORYZA2000, we used the experimental data from all experimental treatments between 1995 and 2000 (irrigated, rainfed, all fertilizer-N levels) that received ample P and K fertilizer. The model was run for each treatment and each experiment using the constructed IR64 crop data file, derived soil properties and actual daily weather data and groundwater table depths. Except for the calculated experiment-specific development rates, all crop parameters were identical in all simulation runs. Since fallow management practices and land preparation at the start of each experiment affected soil properties such as topsoil percolation rate and indigenous N supply, we used the experiment-specific parameterized values of these properties in the simulations.

Following Bouman and Van Laar (2006), we used a combination of graphical presentations and statistical measures to evaluate the performance of the model in simulating our experimental data. We graphically compared the simulated and measured soil water tension, field water depth, above-ground biomass and grain yields. For the same variables, we computed the slope (α), intercept (β) and coefficient of determination (R^2) of the linear regression between simulated (Y) and measured (X) values. We also calculated the Student's *t*-test of means assuming unequal variance. Furthermore, the absolute (RMSE_a) and normalized (RMSE_n) root mean square errors between simulated and measured values were computed:

$$\text{RMSE}_a = (1/n \sum(Y_i - X_i)^2)^{0.5} \quad (2)$$

$$\text{RMSE}_n = 100 \times [1/n \sum (Y_i - X_i)^2]^{0.5} / \sum X_i/n \quad (3)$$

where, *n* is the number of observations

Model scenarios

First, we calculated potential yields under fully irrigated and well-fertilized conditions with a 15-day interval sowing date throughout the year to serve as reference. Next, we used the measured groundwater depths in the field experiments to construct three groundwater scenarios. Measured daily groundwater table depths were first averaged over all years and aggregated into weekly values. We then defined a 'shallow depth' scenario as the mean depth minus the standard error, a 'medium depth' scenario as the mean depth and a 'deep depth' scenario as the mean depth plus the standard error. The yearly variation in groundwater table depths in the three groundwater scenarios is given in Fig. 1. The differences in groundwater depth between the shallow and the deep scenario varied between 0.10 and 1.70 m. In the shallow scenario, groundwater actually reaches the soil surface and leads to ponded water on the field for most of the wet season.

We then explored the effect of the following management interventions on crop yield under the three groundwater scenarios

1. *Sowing date*. Rainfed rice yields were simulated on a 15-d sowing interval throughout the year.
2. *Tillage*. We constructed a conventional (shallow) and a deep tillage scenario, using the Van Genuchten parameters of the 1995–1996 experiment for the conventional and deep tillage treatments, respectively.

3. *Fertilizer N*. We constructed four scenarios: 0, 60, 120 (locally recommended) and 144 kg N ha^{-1} fertilizer N.
4. *Supplementary irrigation*. The effect of supplementary irrigation that could be provided by small on-farm ponds was studied in three scenarios. In the first, (I_1), 7.5 mm of irrigation water was applied each time the moisture content of the topsoil fell below field capacity. In the second, (I_2), rainfed conditions were assumed from establishment to panicle initiation (PI), followed by daily irrigations of 7.5 mm from PI to maturity. The third scenario (I_3) was similar to the second, but used irrigations of 3.3 mm instead of 7.5 mm to simulate a more limited water supply under extreme drought conditions.

As default, we calculated yields under rainfed conditions (except for the supplementary irrigation scenario), with soil properties from the conventional tillage treatment in the 1995−1996 experiment (except for the tillage scenario), and potential N supply (except for the fertilizer scenario). The early wet-season crop (November-February) was direct seeded and the late wet-season crop (March−June) was transplanted, using 21-day-old seedlings at the rate of 2.5 plants hill^{-1} and 44 hills m^{-2}. Sowing date for the late wet-season crop refers to sowing in the seed bed. All model explorations used 24 years of measured weather data from 1977 to 2000, collected at the Jakenan Experiment Station.

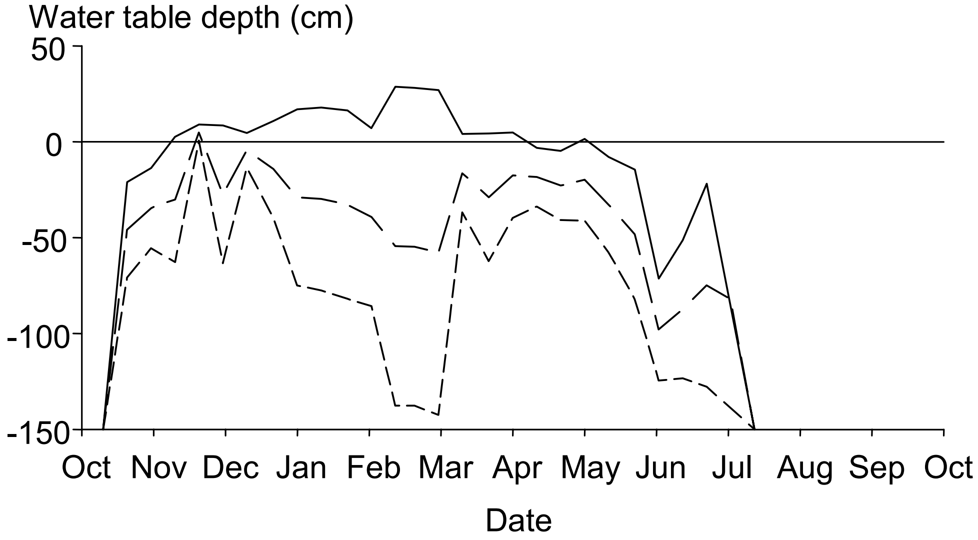

Figure 1. Groundwater depth in time for the shallow (solid line), medium (long-dashed line) and deep (short-dashed line) groundwater scenarios.

Results and discussion

Soil parameters

Soil water retention and conductivity characteristics and Van Genuchten parameters for conventional and deep tillage treatments are given in Table 3. Soil layer 2 of the conventional tillage treatments has higher water contents at saturation and wilting point, but lower saturated hydraulic conductivity than that of deep tillage. Parameterized soil percolation rates ranged from 0.1 to 6.0 mm d^{-1} in different seasons and years and were well within the range measured at other rainfed lowland sites (Fukai et al., 2000; Sharma et al., 1995). Except for 1997–1998, the mean percolation rates were similar. Percolation rates were higher in 1997–1998 when groundwater levels were deep and rainfall was below normal. Indigenous soil N supply rates ranged from 0.2 to 1.8 kg N ha^{-1} d^{-1}. The wide range in soil N supply rates suggests a large variability in soil nitrogen dynamics (Cassman et al., 1996) that may be the result of differences in weather (temperature, rainfall in fallow period) and duration of fallow periods.

Model evaluation

Soil water balance

The dynamics of measured and simulated field water depth under rainfed conditions are compared in Fig. 2 for two seasons with extreme rainfall conditions: below-normal rainfall ($P = 0.98$) in the early wet seasons of 1997–1998 and above normal ($P = 0.08$) in the early wet seasons of 1999–2000 (Table 2). The fluctuation in simulated field water depth generally agrees with the dynamics of measured values. Similar trends between measured and simulated field water depths were observed in the other seasons and years (data not shown). For all crop seasons, $RMSE_a$ between measured and simulated values was 56 mm (Table 4) over a range of 0 to 233 mm.

Simulated soil water tension in the surface layer matched with the dynamics of measured values in the 1996 late wet season and the 1997–1998 early wet season when rainfall was below normal (Fig. 3). Similar dynamics in measured and simulated soil water tension were observed at deeper soil depths (data not shown). Student's *t*-test also showed that simulated and measured soil water tension was similar at the 95% confidence level. $RMSE_a$ between measured and simulated values was 24 kPa (Table 4) over a range of 0−80 kPa.

For both field water depth and soil water tension, $RMSE_n$ was larger than 50%, slope α of the regression line between simulated and measured values was not close to 1 and the intercept β was not close to 0. Though the temporal trends were simulated

Table 3. Soil water retention characteristics, saturated hydraulic conductivity, and Van Genuchten parameters of four soil layers under shallow and deep tillage treatments in Jakenan, 1995–1996.

Soil layer	Thickness	Water content			Saturated hydraulic	Van Genuchten parameters[1]			
		Saturation	Field capacity	Wilting point	conductivity	VGA	VGL	VGN	VGR (cm^3 cm^{-3})
	(m)		(cm^3 cm^{-3})		(cm d^{-1})	(cm^{-1})	-	-	
Shallow tillage									
1	0.10	0.413	0.281	0.129	1.30	0.0095	0.50	1.2695	0.01
2	0.20	0.429	0.300	0.147	0.11	0.0163	0.50	1.2142	0.01
3	0.20	0.451	0.375	0.277	0.56	0.0276	0.50	1.0837	0.01
4	0.20	0.445	0.367	0.287	0.20	0.0310	0.50	1.0823	0.01
Deep tillage									
1	0.10	0.413	0.281	0.129	1.30	0.0095	0.50	1.2695	0.01
2	0.20	0.410	0.319	0.138	0.86	0.0103	0.50	1.2336	0.01
3	0.20	0.451	0.375	0.277	0.56	0.0276	0.50	1.0837	0.01
4	0.20	0.445	0.367	0.287	0.20	0.0310	0.50	1.0823	0.01

[1] Source: Van Genuchten (1980)

$$S = (\theta - \mathrm{VGR})/(\theta s - \mathrm{VGR}) = [1 + |\mathrm{VGA}|^{\mathrm{VGN}}]^{-m}$$

$$K(S) = K_\mathrm{s}\, S^{\mathrm{VGL}}[1 - (1 - S^{1/m})^{m}]^{2}$$

where:

S	=	degree of saturation	-
θs	=	saturated values of volumetric water content θ	cm^3 cm^{-3}
m	=	1 – 1/VGN	-
K_s	=	saturated hydraulic conductivity	cm d^{-1}
VGA	=	Van Genuchten *alpha* parameter	cm^{-1}
VGL	=	Van Genuchten *lambda* parameter	-
VGN	=	Van Genuchten *n* parameter	-
VGR	=	Van Genuchten residual water content	cm^3 cm^{-3}

quite well (Figs 1 and 2), the dynamics of simulated and measured values often differed by 1 day. It should be realized, though, that the time step of integration in the model is 1 day, and it is unknown whether the rainfall events occurred during the night (i.e., after integration of state variables) or during the day (i.e., before integration). Similarly, it is mostly unknown whether irrigations were applied before or after

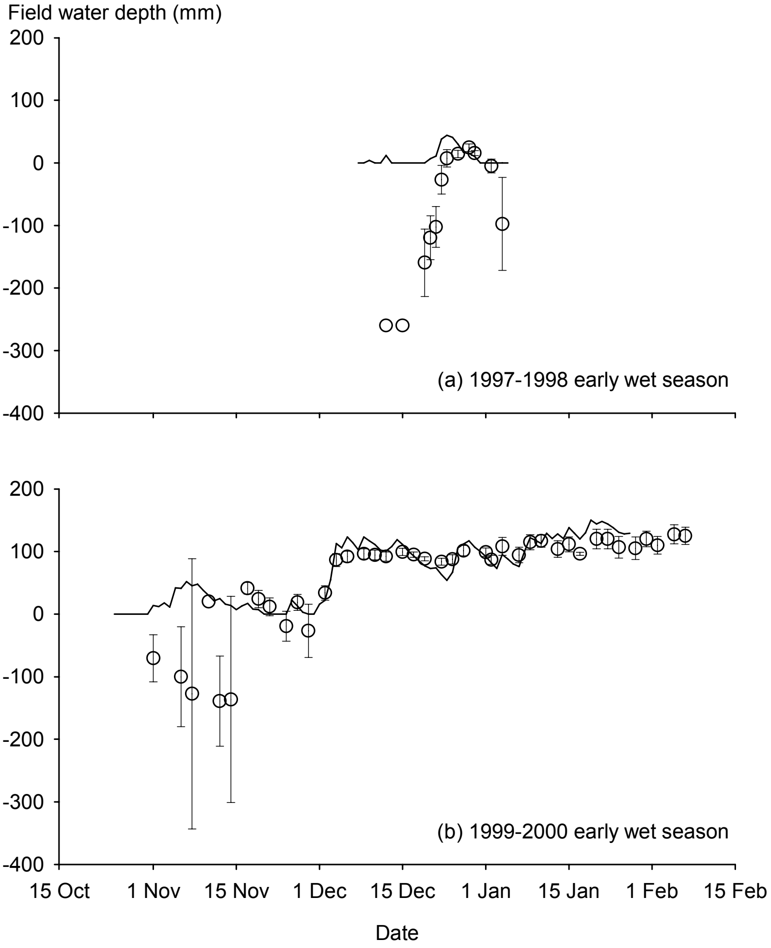

Figure 2. Simulated (lines) and measured (○) field water depth in time under rainfed conditions in the 1997–1998 (a) and 1999–2000 (b) early wet seasons. Vertical bars are the standard errors of the mean.

recording field water depth. Based on these considerations, and on the relatively low values of $RMSE_a$, non-significant *t*-test (for soil water tension only) and agreement in temporal trends of field water depth and soil water tension, we judged the model sufficiently adequate to simulate the soil water balance for the purposes of this study.

Crop growth and grain yield

The dynamics of simulated and measured above-ground biomass for irrigated and rainfed situations in five late wet seasons are presented in Fig. 4. Similar levels and trends were observed under irrigated and rainfed conditions in the three early wet seasons (data not shown). In all seasons, the simulated biomass in irrigated and rainfed treatments fell mostly within the standard deviation of the measured values. Above-ground biomass in rainfed treatments was lower than in irrigated treatments only in the 1996 late wet season (Fig. 4b) and in the 1997−1998 early wet season (data

Table 4. Evaluation results for ORYZA2000 simulations of field water depth, soil water tension at 0–5 and 5–10 cm depth, biomass, and yield over the entire growing season, 1995–2000.

Parameter	N	X_{mean} (SD)	Y_{sim} (SD)	CV_{mean} (%)	$P(t)$	α	β	R^2	RMSE_a	RMSE_n (%)
Field water depth (mm)	500	82 (70)	65 (60)	NA	0.00**	0.59	16.34	0.47	56	68
Soil water tension (kPa)	416	19 (14)	19 (29)	NA	0.43ns	1.23	–4.15	0.34	24	123
Above-ground total biomass (Mg ha^{-1})	284	4.41 (3.48)	4.49 (3.38)	17	0.39ns	0.92	0.43	0.89	1.14	26
Culm and leaf sheath biomass (Mg ha^{-1})	285	2.17 (1.63)	2.28 (1.56)	19	0.21ns	0.84	0.45	0.78	0.79	36
Panicle biomass (Mg ha^{-1})	142	2.51 (1.82)	2.25 (1.50)	24	0.10ns	0.73	0.42	0.78	0.90	36
Grain yield (Mg ha^{-1})	31	3.94 (1.35)	3.71 (1.30)	19	0.24ns	0.86	0.30	0.80	0.65	16

Note:

N = number of data pairs; X_{mean} = mean of measured values; CV_{mean} = mean of coefficient of variation of measured values; Y_{sim} = mean of simulated values; SD = standard deviation; $P(t)$ = significance of paired t-test; $P(t) > 0.05$ means simulated and measured values are the same at 95% confidence level; α = slope of linear relation between simulated and measured values; β = intercept of linear relation between simulated and measured values; R^2 = coefficient of determination of $Y = \alpha X + \beta$; RMSE_a = absolute root mean square error; RMSE_n = normalized root mean square error; NA = not applicable.

** = simulated and measured values are significantly different at 1% level. ns = simulated and measured values are similar at 95% level.

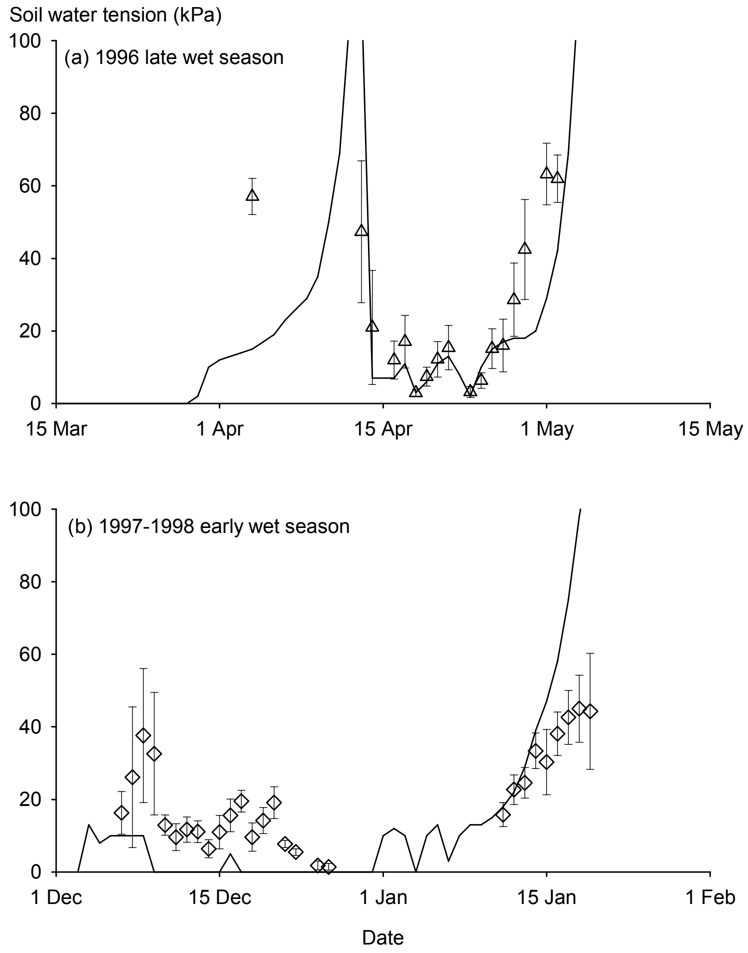

Figure 3. Simulated (lines) and measured soil water tension at 10 cm (◊) and 12.5 cm (Δ) depths in time, in the 1996 late wet season (a) and the 1997–1998 early wet season (b). Vertical bars are the standard errors of the mean.

not shown), caused by below-normal rainfall ($P > 0.80$, Table 2), resulting in the absence of standing water (Fig. 2a) and in relatively high soil water tensions (Fig. 3). In other seasons, biomass production in rainfed treatments was similar to that in the irrigated treatments because rainfall was adequate to keep the soil at saturated conditions.

Measured and simulated above-ground biomass for 0, 120 and 144 kg N ha^{-1} treatments in irrigated conditions for five late wet seasons are presented in Fig. 5. The differences in growth among the N levels were simulated quite well. Similar levels and trends were observed for the three N levels in the irrigated treatments of the three late wet seasons and in all rainfed treatments (data not shown).

The statistical parameters (Table 4) and scatter diagrams (Fig. 6) show a relatively close association between simulated and measured total above-ground biomass and grain yield. The slope α was close to 1, the intercept β close to 0 and R^2 close to 1.

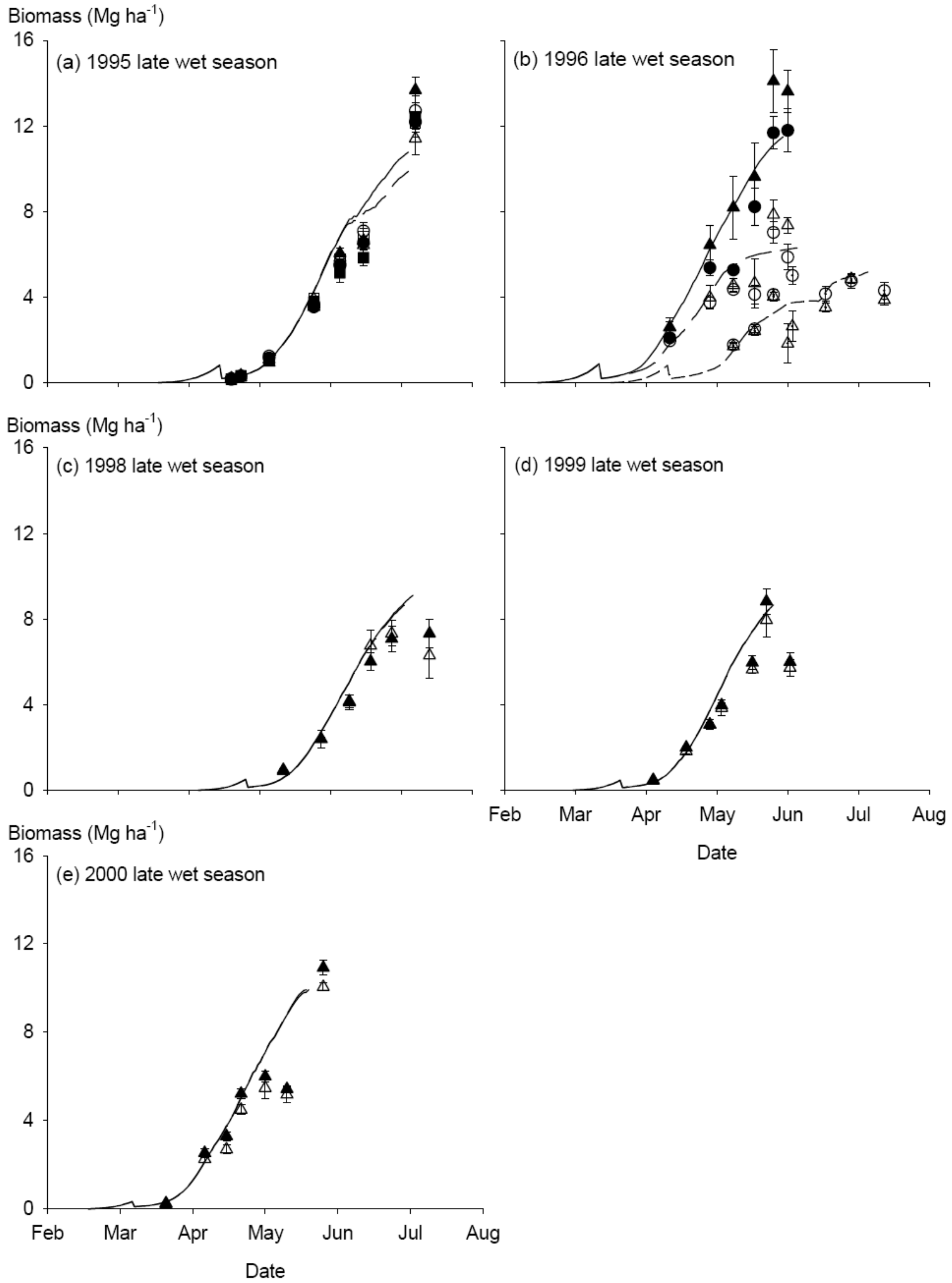

Figure 4. Simulated (solid lines are irrigated, dashed lines are rainfed) and measured (symbols) above-ground biomass in time. The symbol ● is for shallow tillage, ▲ deep tillage and ■ puddled irrigated treatments; and o is for shallow tillage, Δ deep tillage and □ puddled rainfed treatments. Vertical bars are the standard errors of the mean.

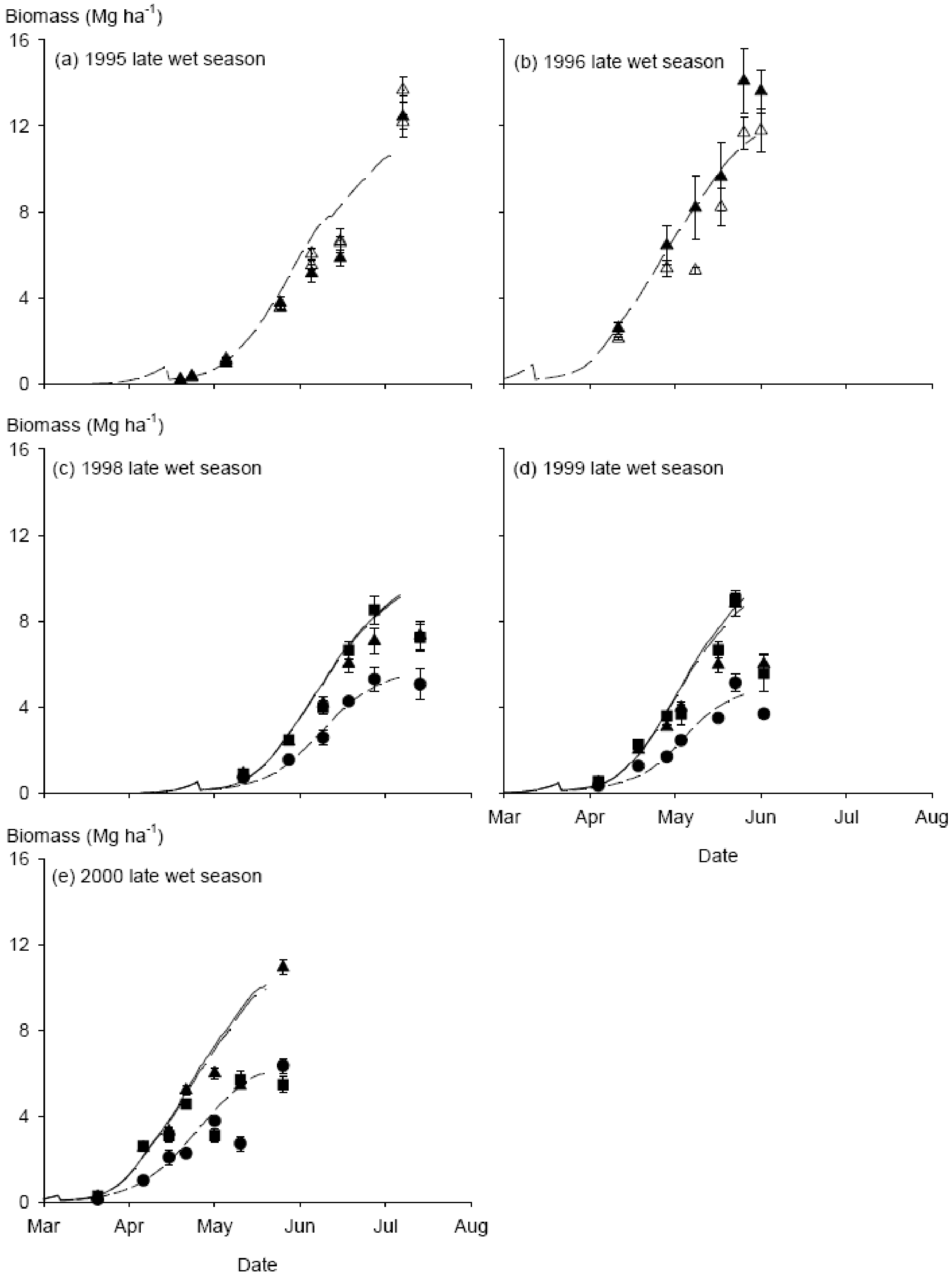

Figure 5. Simulated (lines) and measured (symbols) above-ground biomass in time. The short-dashed lines are for 0 kg N ha^{-1}, the long-dashed lines for 120 kg N ha^{-1} and the solid lines for 144 kg N ha^{-1}. The symbol ● is for 0 kg N ha^{-1}, ▲ for 120 kg N ha^{-1} and ■ for 144 kg N ha^{-1} under irrigated conditions; and o is for 0 kg N ha^{-1}, Δ for 120 kg N ha^{-1} and □ for 144 kg N ha^{-1} under rainfed conditions. Vertical bars are the standard errors of the mean.

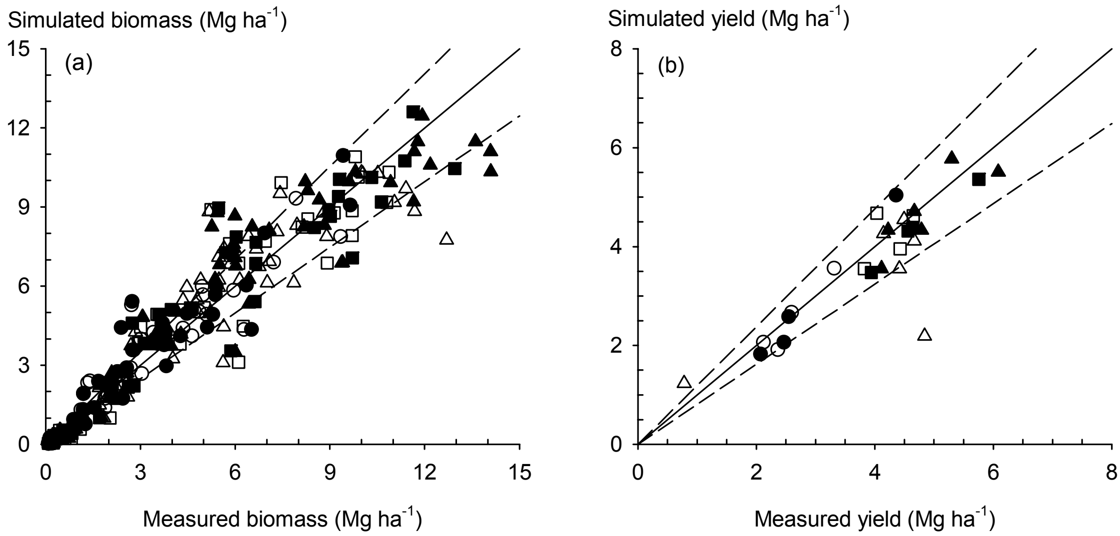

Figure 6. Simulated versus measured above-ground biomass (a) and grain yield (b) in all treatments, 1995–2000. The symbol ● is for 0 kg N ha^{-1}, ▲ for 120 kg N ha^{-1} and ■ for 144 kg N ha^{-1} under irrigated conditions; and o is for 0 kg N ha^{-1}, Δ for 120 kg N ha^{-1} and □ for 144 kg N ha^{-1} under rainfed conditions. Solid lines are the 1:1 relationship; dotted lines are plus and minus coefficient of variation (CV) of measured values around the 1:1 line.

Student's *t*-test also showed that simulated and measured above-ground biomass and grain yield were similar at the 95% confidence level. RMSE$_a$ between measured and simulated above-ground biomass values was 1.14 Mg ha^{-1} over a range of 0.08 to 14.09 Mg ha^{-1}. Close agreement was also observed between simulated and measured leaf sheath and culm and panicle biomass. RMSE$_n$ values of biomass were about 1.5−1.8 times higher than the CV$_{mean}$ of measured values. RMSE$_a$ of grain yield was 0.65 Mg ha^{-1} over a range of 0.78–6.11 Mg ha^{-1}. RMSE$_n$ was 16% and was of the same order of magnitude as the CV$_{mean}$ of grain yield measurements.

The graphical comparison and all of the statistical parameters indicate the adequacy of the model to simulate crop growth and development and grain yield under irrigated, N-limited and water-limited production situations in the study area.

Scenario analyses

Yield potential

Depending on date of sowing, mean simulated potential yields ranged from 3.74 to 5.53 Mg ha^{-1} (Fig. 7), which compares well with our own experimental results as well as with those reported in the area by Setyanto et al. (2000) and Wade et al. (1999b). The standard errors of the potential yields are low, indicating little variation in

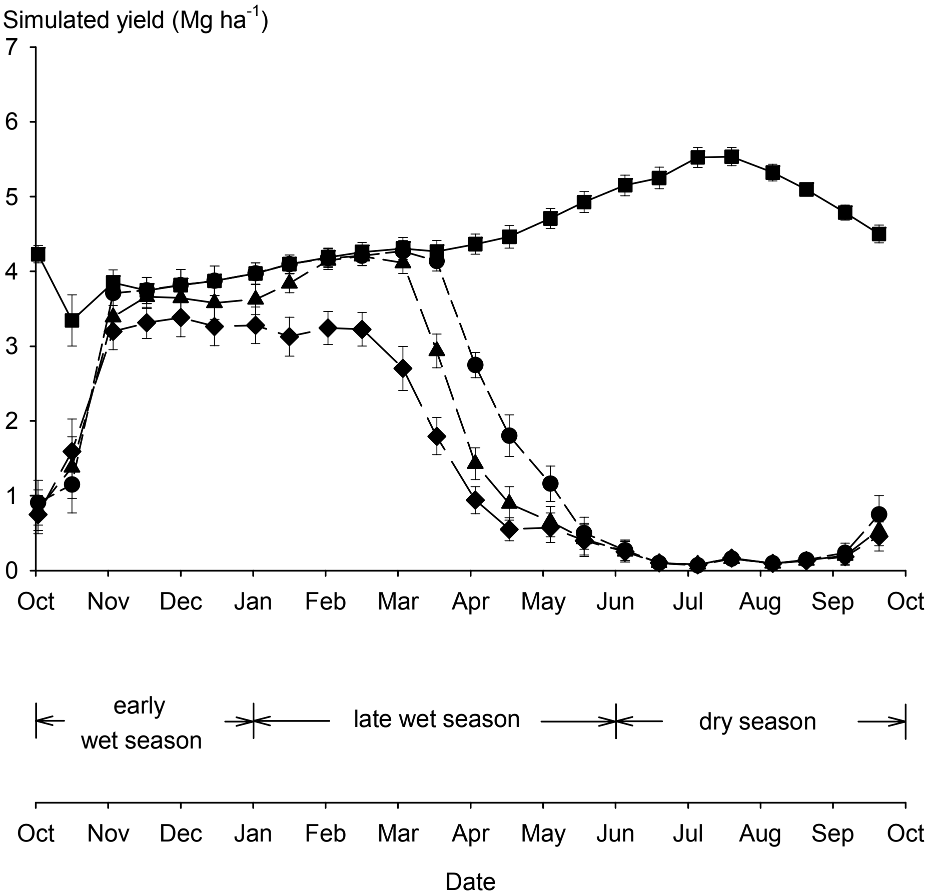

Figure 7. Mean simulated potential yield (■) and rainfed yield under shallow (●), medium (▲) and deep (♦) groundwater scenarios, versus day of sowing. Vertical bars are the standard errors of the mean.

potential yield across years. Rice sown in the early wet season had a lower potential yield, on average 3.81 Mg ha^{-1}, than rice planted in the late wet season, on average 4.36 Mg ha^{-1}. This lower yield potential is mainly the consequence of relatively low radiation levels during grain filling: 13.60 MJ m^{-2} in the early wet-season compared with 15.28 MJ m^{-2} in the late wet-season.

Sowing date

Because of the rainfall distribution, the rainfed yields were relatively high in the early wet season, 3–4 Mg ha^{-1}, but declined sharply with later sowing in the late wet season (Fig. 7). Yields completely collapsed with sowing after May because of lack of rainfall.

Throughout the early wet season, and with timely sowing in the late wet season before April, rainfed yields under shallow and medium groundwater depths were close to or the same as potential yields. With a deep groundwater table, however, rainfed

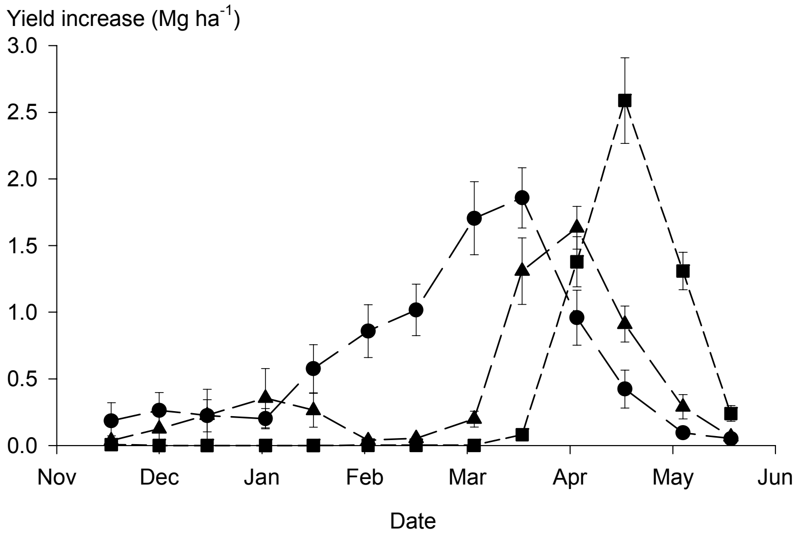

Figure 8. Mean simulated yield increase (compared with conventional tillage) versus day of sowing of rainfed rice with deep tillage, under shallow (■), medium (▲) and deep (●) groundwater scenarios. Vertical bars are the standard errors of the mean.

yields were 0.5 Mg ha^{-1} lower than potential yields in the early wet season, and about 1 Mg ha^{-1} lower than potential yields with early sowing in the late wet season in February. The largest differences among groundwater scenarios occurred in the late wet season: yield declined earlier and declined faster with deeper groundwater tables. With sowing in the beginning of March, yields with a shallow groundwater table were still at the same level as potential yields, about 4.2 Mg ha^{-1}, whereas rainfed yields with a deep groundwater table were only 2.5 Mg ha^{-1}. With sowing in late April, yields with a shallow groundwater table were close to 1.8 Mg ha^{-1}, whereas yields with medium and deep groundwater tables dropped below 0.5 Mg ha^{-1}.

Tillage

Groundwater depth had a clear impact on the effect of tillage on rainfed yields with sowing towards the end of the wet season (Fig. 8). With a shallow groundwater depth, yields were still at potential level with sowing until late March (Fig. 7) and deep tillage had no impact on yield. However, in the late wet season, deep tillage increased yields over conventional tillage with a maximum of 2.5 Mg ha^{-1} with sowing in late April. Again, with sowing from June onward, yields dropped to zero because of drought. The overall pattern of yield increase caused by deep tillage with a medium groundwater depth was similar to that with a shallow groundwater depth, except that the benefits were noticeable already with sowing in late March, which peaked at about a 1.6 Mg ha^{-1} yield increase with sowing in early April and declined already in early May. The

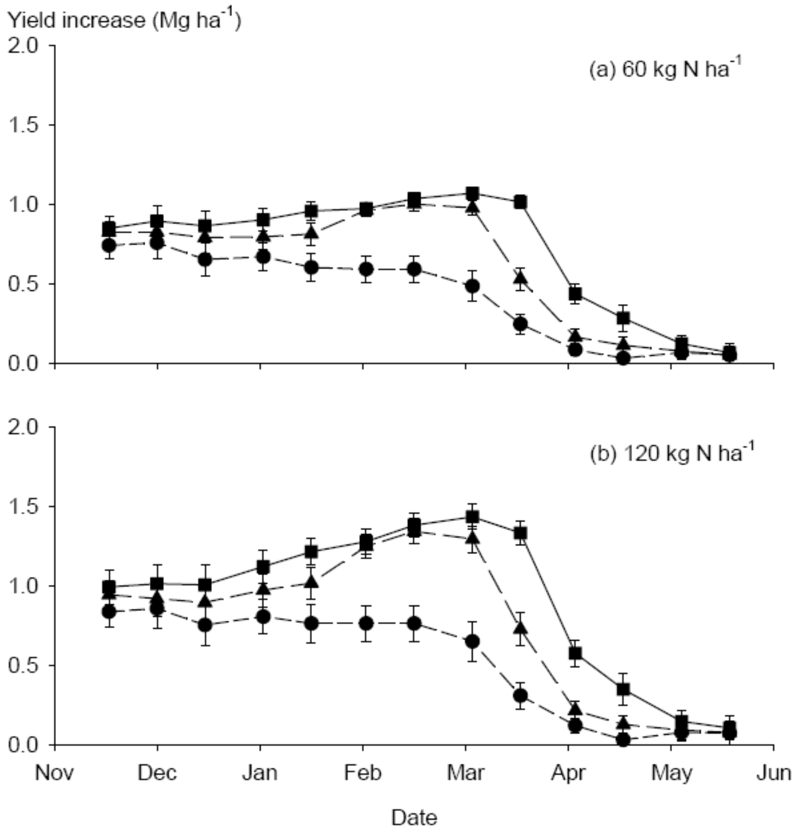

Figure 9. Mean simulated yield increase (compared with zero-N application) versus day of sowing of rainfed rice with 60 (a) and 120 (b) kg N ha^{-1} fertilizer, under shallow (■), medium (▲) and deep (●) groundwater scenarios. Vertical bars are the standard errors of the mean.

effects of deep tillage, however, were most pronounced with a deep groundwater table. The average yield increase was 0.6 Mg ha^{-1} with sowing in late January, peaked at 1.9 Mg ha^{-1} with sowing in late March and declined to zero with sowing in mid-May.

The higher yields with deep tillage were attributed to increased transpiration resulting from increased soil water content by capillary rise (data not shown) due to higher saturated conductivity (Table 3). Under below-normal rainfall conditions, the capillary rise with deep tillage was higher than with conventional tillage, resulting in improved soil water availability under a wide range of groundwater depths. However, the largest yield increases occurred with relatively shallow water tables that provided significant capillary inflow into the root zone.

Fertilizer application

Groundwater depth had an impact on the effect of fertilizer application on rainfed yields with sowing throughout the wet season (Fig. 9). With shallow and medium groundwater depths, the application of 60 kg N ha^{-1} resulted in a yield increase over

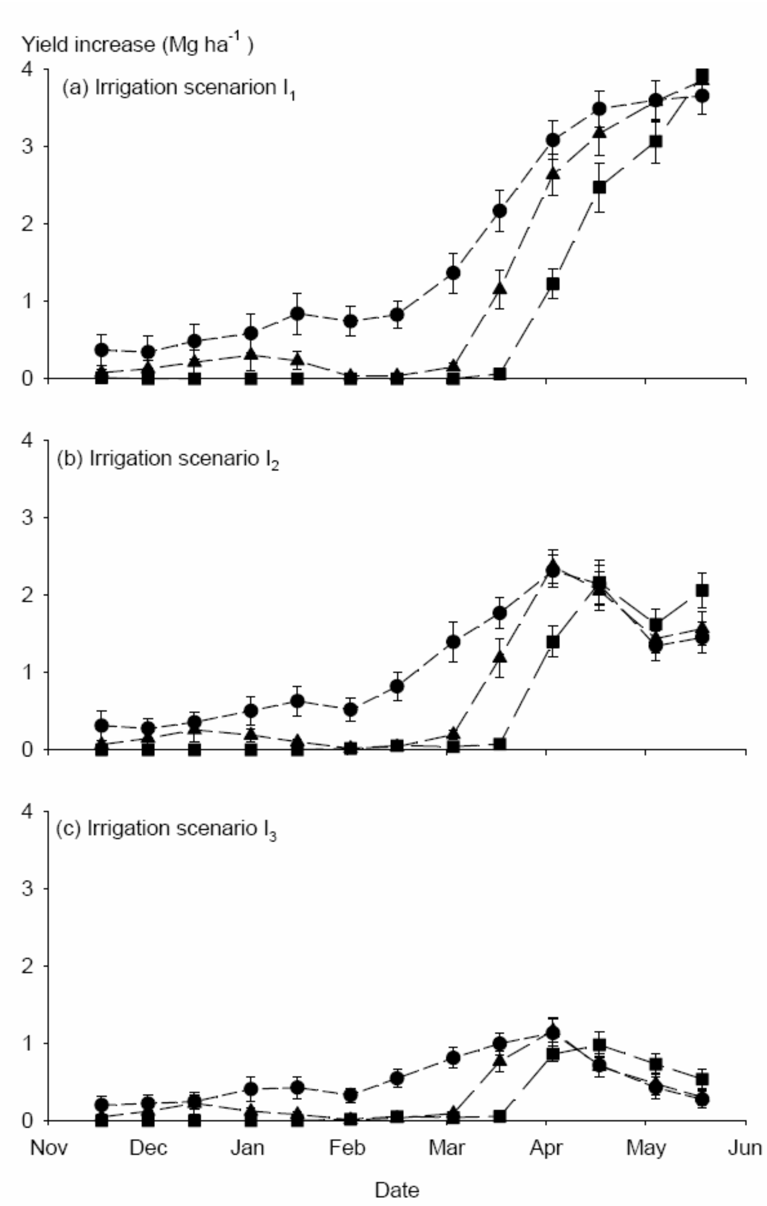

Figure 10. Mean simulated yield increase (compared with rainfed) versus day of sowing with supplementary irrigation I_1 (a), I_2 (b) and I_3 (c), under shallow (■), medium (▲) and deep (●) groundwater scenarios. Vertical bars are the standard errors of the mean.

zero fertilizer-N application of from 0.8 to 1.0 Mg ha^{-1} with sowing between November and March. The effect of fertilizer-N gradually decreased with later sowing to a minimum of 0.1–0.3 Mg ha^{-1} yield increase with sowing in late April. With a deep groundwater table, however, the application of 60 kg N ha^{-1} resulted in only about a 0.8 Mg ha^{-1} yield increase with early sowing in November and December. This beneficial effect gradually decreased to zero yield increase with late sowing from mid-April onward. The lower benefits of fertilizer-N with deep groundwater table (compared with medium and shallow groundwater table) were caused by water limitations that reduced the beneficial effects of extra N availability.

The seasonal effect of fertilizer-N application became more pronounced with higher fertilizer doses. With 120 kg N ha^{-1}, yield increases with shallow and medium groundwater tables were about 1 Mg ha^{-1} with sowing between November and January, but went up to 1.4 Mg ha^{-1} with sowing later in the wet season around early March. The larger benefits from fertilizer-N application with later sowing derived from higher yield potentials because of higher radiation levels (compare with Fig. 7). With a deep groundwater table, the lack of water limited yield and the benefits of 120 kg N ha^{-1} were only slightly higher than those of 60 kg N ha^{-1}.

The application of 144 kg N ha^{-1} did not increase yields more than the application of 120 kg N ha^{-1} with any of the groundwater depths (data not shown). The yield potential in the whole wet season is relatively low (Fig. 9) and no more than 120 kg N ha^{-1} is needed to reach this potential.

Supplementary irrigation

Groundwater depth had an impact on the effect of supplementary irrigation on yields in the late wet season (Fig. 10). This impact of groundwater depth was quite similar for all three irrigation scenarios. With a shallow groundwater table, supplementary irrigation started to increase yields with sowing from late March onward and had a high impact on yield increase with late sowing from April onward. In this latter period, yield increases were some 1.2−3.1 Mg ha^{-1} in scenario I_1, 1.4−2.4 Mg ha^{-1} in I_2 and 0.9−1.2 Mg ha^{-1} in I_3. With a medium groundwater depth, the magnitudes of yield increases were the same as with shallow groundwater, though the benefits appeared earlier in the season with sowing from early March onward. With a deep groundwater table, yield increases were already on the order of 0.7 Mg ha^{-1} in I_1 and 0.3−0.5 Mg ha^{-1} in I_2 and I_3 with early sowing in February. Yield increases went up with later sowing and reached roughly the same levels as with medium and shallow groundwater tables with sowing in April to late May.

On average, the benefits of I_1 were slightly higher than those of I_2 and I_3, and only with late sowing between late April and late May did I_1 consistently result in 1.7−2.5 Mg ha^{-1} higher yield increases than I_2 and I_3. Irrigation applications for crops sown towards the end of the late wet season in I_1 varied from 45 mm for sowing in early March to 349 mm for sowing in mid-April. Irrigation applications for crops sown from mid-February to mid-April in I_2 and I_3 were fixed at 275 and 120 mm, respectively.

Conclusions

ORYZA2000 adequately simulates the soil water balance and crop growth and development of rice under various levels of fertilizer-N application and under rainfed and irrigated conditions in the study area. Despite the inherent heterogeneities that occur in rainfed environments, the $RMSE_a$ values of predicted biomass and grain yield in our experimental data set are of the same order of magnitude as those reported for fully irrigated conditions in the Philippines.

Differences in groundwater depth of 0.10−1.70 m have large effects on rainfed rice yields and on the efficacy of yield-increasing interventions. With shallow groundwater reaching to the surface, rainfed yields with an ample supply of nutrients are equivalent to the yield potential in the early wet season. However, with deep groundwater, predominately fluctuating between 0.15 and 0.80 m depth, rainfed yields in the early wet season are about 20% lower. In the late wet season, with diminishing rainfall and falling groundwater tables, yields drop from their early wet-season levels to around 0 Mg ha^{-1} with delayed sowing from around March to May. This yield decrease is affected strongly by groundwater depth: the deeper the groundwater table, the earlier the yield decrease sets in. In the late wet season, yields with deep groundwater are some 50% lower than with shallow groundwater. Farmers with a deep groundwater table run higher risks of yield loss from delayed sowing than farmers with a shallow groundwater table.

Deep tillage and supplementary irrigation increase yield more with deep groundwater tables than with shallow groundwater tables. The effect of these yield-increasing measures is most prominent in the late wet-season rice crop for which yield increases with supplementary irrigation can go up to 3.8 Mg ha^{-1}, and yield increases with deep tillage up to more than 2.6 Mg ha^{-1}. With deeper groundwater tables, the beneficial effects of these measures occur earlier in the late wet season than with shallower groundwater tables. Both measures increase yields by making more water available to the crop. The full benefits of these measures, however, are only realized with sufficient fertilizer-N application.

Contrary to the effects of deep tillage and supplementary irrigation, the application of fertilizer N increases yield more with shallow groundwater tables than with deep groundwater tables. With shallow and medium groundwater tables, an amount of 120 kg N ha^{-1} is sufficient to reach yield levels of potential production. The application of 120 kg N ha^{-1} increases yield more in the late wet season (roughly by 1.2 and 1.4 Mg ha^{-1}) than in the early wet season (roughly around 1.1 Mg ha^{-1}) because of higher yield potentials caused by more radiation in the late wet season. With deep groundwater tables, any application of fertilizer N above 60 kg N ha^{-1} does not significantly increase yield because the lack of water limits crop growth more than the lack of N. Extra N application needs to be combined with either deep tillage or supplementary irrigation to further increase yields.

In practice, variation in groundwater depth can occur among seasons in the same field (such as observed in our field experiments) or among fields in the same season because of topographic differences. Our shallow depth scenario may be applicable to the bottom of a toposequence and the deep scenario to the top of a toposequence.

Groundwater depths should be considered in identifying appropriate yield-increasing interventions in rainfed lowland rice areas. In areas with deep groundwater table, it is equally essential to have timely crop establishment, deep tillage and supplementary irrigation. Where the groundwater is shallow, increasing fertilizer N input is more effective than deep tillage and supplementary irrigation.

Likewise, it is equally important that the groundwater depth should be specified in reports on the effects of yield increasing interventions of rainfed lowland rice; and the extrapolation domains of the interventions should only include areas with similar groundwater conditions.

CHAPTER 4

The effect of toposequence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia[1]

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Abstract

A large proportion of rainfed lowland rice in Southeast Asia is grown in gently sloping areas along toposequences with differences in elevation of a few meters. These small elevation differences can lead to differentiation in soil properties and hydrological conditions, which in their turn may affect crop performance and yield. It may be appropriate to replace blanket crop management recommendations in rainfed areas with toposequence-specific management recommendations. However, thorough statistical analyses of the relationships between toposequence position and field and crop conditions are lacking. In this chapter, we statistically analyse the effect of toposequence position on soil properties, hydrological conditions, yield and yield increase by weed control and/or fertilizer management in rainfed areas in four villages in Indonesia and Thailand each in 2000–2002.

There were substantial differences in field hydrology (average depth of ponded surface water and of groundwater, number of days without ponded surface water), exchangeable K, organic C, and clay content depending on toposequence position. There were also differences in some other soil properties including N, P, CEC, pH, sand, silt, bulk density, in yield, and the magnitude of yield increase due to intensive weed control and/or application of recommended fertilizer doses, but these effects were not consistent across countries, seasons, and years. The hypothesis that the toposequence position would be a useful recommendation domain for weed control and fertilizer recommendations was not supported by our statistical results. The reasons why toposequence position has inconsistent statistical effect could be (1) that the variability in the field conditions is larger among villages than among toposequence positions, and/or (2)

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[1] Submitted to Field Crops Research

that farmers already respond to differences in field conditions in their prevalent management practices, thus masking the effects of toposequence-specific variation on yield. Our findings suggest that despite the large toposequence effects on soil nutrient and water availability, weed and fertilizer management recommendations should be field-specific and time-specific rather than toposequence-specific.

Keywords: Fertilizer application, field hydrology, rainfed rice, weed control, yield improvement.

Introduction

Rainfed rice in Asia is grown on approximately 59 Mha which is 44% of the total rice area (Maclean et al., 2002). Average rice yield is low at 2.1 Mg ha^{-1}, and productivity is generally hampered by uncertain water supply, low soil fertility, and weed competition (Wade et al., 1999a). Most rainfed lowlands are characterized by an undulating topography and by high spatial variability of environmental conditions (Tuong et al., 2000a). Farmers grow their crop in bunded fields on gently sloping land with differences in elevation often of a few meters only. Even small elevation differences, however, may lead to differentiation in soil properties and hydrological conditions (Hseu and Chen, 2001; Tsubo et al., 2006). Topography directly affects soil forming processes through erosion and deposition, and toposequence-specific gradients in soil texture have been observed by Eshett et al. (1989), Posner and Crawford (1992), and Yamauchi (1992). Variation has been observed in soil nitrogen (N), phosphorus (P), and potassium (K) content (Moormann et al., 1977; Eshett et al., 1989; Posner and Crawford, 1992; Yamauchi, 1992) between upper and lower fields. Soil nutrient status directly affects crop growth and yield formation (Yamauchi, 1992; Dingkuhn and Asch, 1999; Homma et al., 2004). After heavy rainfalls, there are large amounts of run-off from upper rice fields which can get intercepted by the lower fields. Consequently, the groundwater table may be deeper, and the soil drier, in the upper fields than in the lower fields. These differences in field hydrology result in differential water availability for crop growth and directly affect yield formation. Field water status can also affect nutrient availability and influence weed growth (Oyediran et al., 1999; Johnson and Kent 2002), which may further differentiate crop performance. Due to these effects of toposequence position on the yield of rice, it has been suggested that toposequence-specific management recommendations may be more appropriate than ‘blanket recommendations’ in rainfed areas (Banik et al., 2006). Many of the toposequence studies to date, however, are descriptive in nature and thorough statistical bases for toposequence-based management recommendations are rarely available. In this chapter, we therefore statistically analysed the effect of toposequence position on soil properties, hydrological conditions, crop yield and biomass in rainfed areas in Indonesia and Thailand. Explicitly, we statistically analysed the variation in the effects of nutrient and/or weed management on yield across toposequence positions. The ultimate aim is to find out if the toposequence position is a suitable unit to serve as recommendation domain for nutrient and weed management options.

Materials and methods

Experiments

We used data from experiments conducted in farmers' fields near Jakenan Experiment Station in Java, Indonesia (6°47′ S, 111°12′ E, 8 m above sea level), and near Ubon Rice Research Center in Northeast Thailand (15°19′ N, 104°40′ E, 127 m above sea level). At both sites, average annual rainfall is about 1550 mm, of which 70% falls in November–March in Indonesia and 62% in July–November in Thailand. In Indonesia, the average minimum temperature is 23.6 ± 1.6 °C and the average maximum temperature 31.7 ± 2.5 °C. In Thailand, minimum temperature ranges from 17.0 (January) to 24.6 °C (May) and maximum temperature from 30.0 (December) to 35.8 °C (April).

Indonesia

The experiments were conducted in four villages (Table 1) in the wet seasons from October 2000 to June 2002. In each year, there was an early and a late wet-season crop, to give four crops grown in the study. In each village, four fields across a toposequence were selected (top, upper middle, lower middle, bottom) that were cultivated by the same farmer. Each field was divided into six plots with the following nutrient and weed control treatments:

- Farmers' practice (FP)
- FP without weeding (FP−W)
- FP with intensive weeding (FP+W)
- FP without fertilizer (FP−N)
- FP with recommended nutrient management (FP+N)
- FP with intensive weeding and recommended nutrient management (FP+W+N)

The experiment layout was a split-plot with toposequence position as main plot and combinations of nutrient and weed management as subplot, and with villages as replications. The size of the subplot was at least 5 m × 6 m. Bunds were constructed around plots with nutrient treatments (FP−N, FP+N, FP+W+N) to minimize lateral nutrient movement to and from other treatments without bunds (FP, FP−W, FP+W). Treatments were grouped as plots with or without bunds.

Table 1. Location, altitude, and length and slope of the toposequences in Indonesia and Thailand.

Village	District	Latitude	Longitude	Altitude (m asl[3])	Toposequence length[1] (m)	Toposequence slope[2] (%)
Indonesia						
Megulung	Rembang	6° 46′ S	111° 16′ E	17	466	4.3
Jadi	Rembang	6° 47′ S	111° 17′ E	30	875	1.5
Sidomukti	Pati	6° 47′ S	111° 12′ E	14	749	2.1
Pelemgede	Pati	6° 50′ S	111° 10′ E	29	354	4.8
Thailand						
Kha Khom	Muang	15° 20′ N	104° 41′ E	132	198	2.0
Kham	Kuangnai	15° 19′ N	104° 39′ E	148	65	10.3
Khu Khat 1	Kuangnai	15° 25′ N	104° 34′ E	152	214	1.5
Khu Khat 2	Kuangnai	15° 26′ N	104° 35′ E	144	205	0.7

[1] Horizontal distance between the top and the bottom toposequence positions;

[2] Slope calculated from the top to bottom positions of the toposequence;

[3] Meters above sea level at the middle position of the toposequence.

To determine the contribution of current and additional levels of weed management and fertilizer doses the study comprised a range of treatments. Treatment FP was used to quantify the effect of farmers' current management practices on rainfed rice yields. In the first year in these fields, farmers chose their own rice variety, plant density, method of land preparation and seeding, fertilizer application, and weed management. In the second year, however, all farmers planted variety IR64 at 15 × 15-cm hill spacing. Treatments FP−N and FP−W were 'control' treatments to ascertain the lowest production levels: FP−N (non-fertilized) to quantify the yield change caused by the farmers' practice of fertilization, and FP−W (non-weeded) to quantify the yield change caused by the farmers' practice of weed control. Treatments FP+W and FP+N quantified the yield change caused by intensive weeding and by recommended fertilization, respectively. Treatment FP+W+N quantified the yield change caused by the combined effect of intensive weeding and recommended fertilization.

In FP+N and FP+W+N, the following fertilizer doses were applied: 30 N, 22 P, 45 K, 20 S, and 5 kg Zn ha^{-1} basal; 60 N and 45 kg K ha^{-1} at maximum tillering; 30 kg N ha^{-1} at panicle initiation. In FP plots, ranges of fertilizer applied were 76–166 N, 0–45 P, 0–51 kg K ha^{-1}. In FP+W and FP+W+N, hand weeding was done at least once a week to minimize weed competition.

Thailand

Experiments were conducted in four villages (Table 1) in three wet seasons (single crop) from June 2000 to November 2002. The same split-plot design was applied as used in Indonesia. In each village, three fields managed by the same farmer across a toposequence (top, middle, bottom) were chosen. Each field was divided into three plots with different fertilizer treatments (there were no weed control treatments): FP, FP−N, FP+N.

The recommended fertilizer application rates were 40 N, 25 P, 12.5 kg K ha^{-1}. In FP plots, ranges in amounts applied were 1–78 N, 1–21 P, 1–11 kg K ha^{-1}. In all seasons, variety KDML 105 was transplanted at 20 × 20-cm hill spacing. Land preparation started at the onset of the rainy season. Hand weeding and pesticide spraying were used to minimize pest damage.

Measurements

Soil samples from 0–20 cm depth were taken before the basal fertilizer application at 10 random locations in each field in the 2000–01 early wet season in Indonesia and in the 2002 wet season in Thailand. The samples were mixed, after which sub-samples of about 500 g per field were ground to < 2 mm for analysis of particle size (clay, silt, sand), bulk density, available water content (calculated as the difference in moisture content at pF=1 and at pF=4 (permanent wilting point)), total N, Olsen P, exchangeable K, CEC, pH (1:1 soil, water). In Indonesia, additional soil samples were taken in 2001–02 early wet and 2002 late wet seasons for soil N, P, K, CEC, and pH analyses.

At each field, the depth of standing water (ponded water on the surface) was measured daily in 40-cm-long, 5-cm-diameter PVC tubes, installed in the soil to a depth of 25 cm. The bottom 22 cm of the tubes was perforated with 3-mm-diameter holes at 2-cm intervals. Soil inside the PVC tube was removed to allow measurement of belowground water depth. The depth of the groundwater was measured daily in 5-cm-diameter, 150-cm-long PVC tubes, perforated in the bottom 75-cm length and installed to a depth of 100 cm below the soil surface. From the hydrological measurements, we computed the average depth of standing water and of groundwater, and the total number of days without ponded water on the soil surface during the season.

At each plot, 0.50-m^2 samples were taken at physiological maturity to determine total canopy biomass. Grain yield was determined from a 5-m^2 sampling area at harvest and is expressed as rough (unhulled) rice at 14% moisture content.

Data analysis

The yield increase caused by intensive weeding (ΔY_{W}) or by recommended nutrient management (ΔY_{N}) was estimated by:

$$\Delta Y_{\mathrm{W}} = Y_{\mathrm{FP+W}} - Y_{\mathrm{FP-W}} \tag{1}$$

$$\Delta Y_{\mathrm{N}} = Y_{\mathrm{FP+N}} - Y_{\mathrm{FP-N}} \tag{2}$$

where, $Y_{\mathrm{FP+W}}$ is the yield in the FP+W treatment, $Y_{\mathrm{FP+N}}$ is the yield in the FP+N treatment, $Y_{\mathrm{FP-W}}$ is the yield in non-weeded plots, and $Y_{\mathrm{FP-N}}$ is the yield in non-fertilized plots.

The yield increase caused by farmers' practice (ΔY_{FP}) or by the combined effect of nutrient and weed management ($\Delta Y_{\mathrm{N\times W}}$) was estimated by:

$$\Delta Y_{\mathrm{FP1}} = Y_{\mathrm{FP}} - Y_{\mathrm{FP-W}} \tag{3}$$

$$\Delta Y_{\mathrm{FP2}} = Y_{\mathrm{FP}} - Y_{\mathrm{FP-N}} \tag{4}$$

$$\Delta Y_{\mathrm{N\times W1}} = Y_{\mathrm{FP+W+N}} - Y_{\mathrm{FP-W}} \tag{5}$$

$$\Delta Y_{\mathrm{N\times W2}} = Y_{\mathrm{FP+W+N}} - Y_{\mathrm{FP-N}} \tag{6}$$

where, Y_{FP} is the yield in the FP treatment; and $Y_{\mathrm{FP+W+N}}$ is the yield in the FP+W+N treatment.

Combined analysis of variance was used to compare the main effects and interactions among toposequence position, village, and season, on the soil and hydrological characteristics, crop biomass, crop yield, and yield increase caused by weed and/or nutrient management. Since toposequence positions at villages were not randomly chosen and crop, soil, and hydrological measurements were repeated over different seasons, the data were analysed using the MIXED procedure in SAS (Littell et al., 1996). In the analysis of variance, villages were used as blocking factor. When the analysis of variance showed significant factorial effect, the least significant difference (LSD) test was used for pair-wise comparison. We statistically analysed the trends in crop, soil, and water parameters, yield and yield increase due to weed/nutrient management across toposequence positions. Trends were determined where differences in measurements between the top and bottom toposequence positions were significant and where measurements at the middle toposequence positions followed the same trend.

Cluster analysis was used to identify homogeneous subgroups or a set of groups which both minimize within-group variation and maximize between-group variation of the combination of soil chemical and physical properties, water status, and crop data of the control (FP–N) treatment in a village, toposequence position, and season (referred to as case). Dendrograms (tree-like structures) were constructed from standardized data over four seasons in Indonesia and over three seasons in Thailand using Ward's agglomerative clustering method (Everrit, 1980). In Ward's method, union of every possible pair of cases is considered and the cases whose fusion results in the minimum loss of information (minimum error sum of squares) were combined into groups (clusters). Groups were determined when there is 10% decrease in the proportion of overall variation accounted for by joining two or more clusters (semi-partial R^2 = 0.10).

Results

Soil properties

Soil properties were not influenced by the interaction of season × toposequence position (Table 2). In both countries, the clay content differed among toposequence positions within villages, as did, CEC, pH, sand and silt content in Indonesia; and N, P, K, organic C, and available water in Thailand (Table 2). The clay content at the top of the toposequence was lower than at the bottom in 6 out of the 8 villages in the two countries, but the difference in magnitude varied (Fig. 1). In Indonesia, exchangeable

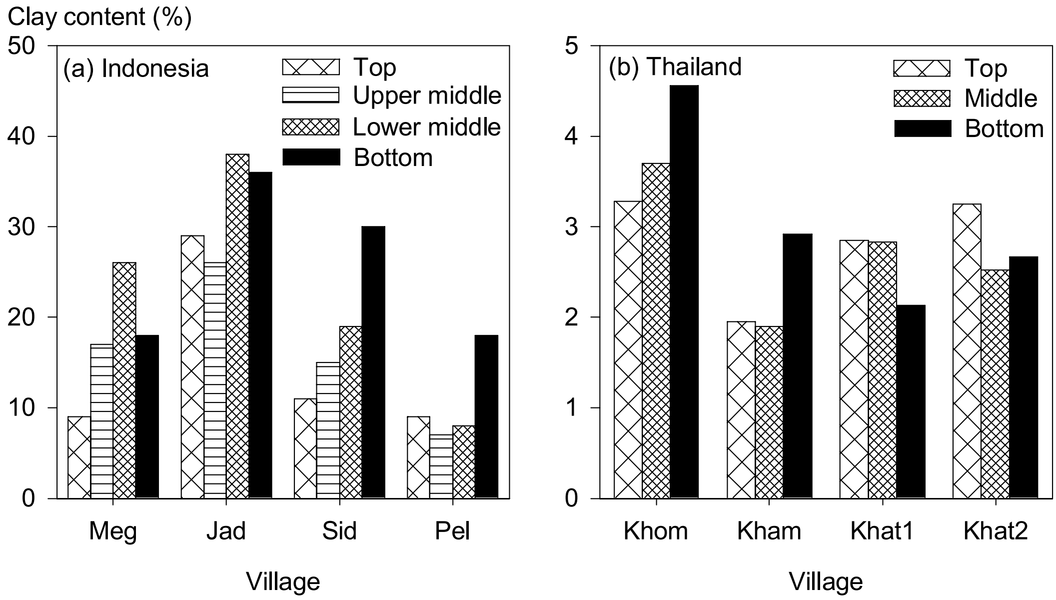


Figure 1. Clay content of surface soil at different toposequence positions at different villages in Indonesia (a) and in Thailand (b). Village codes are Meg=Megulung, Jad=Jadi, Sid=Sidomukti, Pel=Pelemgede, Khom=Kha Khom, Kham=Kham, Khat1=Khu Khat 1, and Khat2=Khu Khat 2.

Table 2. Analysis of covariance of soil chemical and physical properties at different toposequence positions in Indonesia and in Thailand.

Country	Parameter	Source of variation[1]				
		Covariance	Village	Toposequence position	Season	Season × Toposequence
Soil chemical properties						
Indonesia	Total N	ns	ns	ns	**	ns
	P Olsen	ns	+	ns	+	ns
	Exchangeable K	ns	**	**	+	ns
	CEC	**	*	*	ns	ns
	Organic C	ns	*	+	**	ns
	pH (water)	+	**	**	**	ns
Thailand	Total N	**	NA	ns	NA	NA
	P Olsen	*	NA	ns	NA	NA
	Exchangeable K	*	NA	ns	NA	NA
	CEC	ns	NA	ns	NA	NA
	Organic C	*	NA	ns	NA	NA
	pH (water)	ns	NA	ns	NA	NA
Soil physical properties						
Indonesia	Sand	**	NA	ns	NA	NA
	Silt	**	NA	ns	NA	NA
	Clay	**	NA	+	NA	NA
	Bulk density	ns	NA	*	NA	NA
	Available water	ns	NA	ns	NA	NA
Thailand	Sand	ns	NA	ns	NA	NA
	Silt	ns	NA	ns	NA	NA
	Clay	**	NA	ns	NA	NA
	Bulk density	ns	NA	ns	NA	NA
	Available water	**	NA	ns	NA	NA

[1] **, *, + are significant at 1, 5 and 10% levels, respectively; ns=not significant; NA=source of variation not applicable for the data set.

Table 3. Chemical properties[1] of the 0–20 cm surface soil at different toposequence positions in Indonesia and in Thailand.

Country	Toposequence position	Total N	P Olsen	Exchangeable K	Cation exchange capacity	Organic C	pH (water)
		%	(mg kg^{-1})	(cmol$_c$ kg^{-1})	(cmol$_c$ kg^{-1})	(%)	(-)
Indonesia	Top	0.05 a	23.41 a	0.06 b	6.88 b	0.49 b	5.2 c
	Upper Middle	0.05 a	21.38 a	0.07 b	8.37 b	0.51 ab	5.5 bc
	Lower Middle	0.06 a	21.14 a	0.10 a	14.99 a	0.56 ab	6.3 a
	Bottom	0.06 a	26.90 a	0.12 a	16.76 a	0.62 a	5.8 ab
Thailand	Top	0.01 a	5.15 a	0.02 a	1.03 a	0.26 a	4.3 a
	Middle	0.02 a	5.62 a	0.01 a	1.09 a	0.30 a	4.6 a
	Bottom	0.02 a	9.08 a	0.02 a	1.38 a	0.36 a	4.5 a

[1] In a column within a country, average (4-village) values followed by same letter are not significantly different at 5% level by LSD.

Table 4. Soil physical properties[1] of the 0–20 cm surface soil at different toposequence positions in Indonesia and in Thailand.

Country	Toposequence position	Particle distribution			Bulk density	Available water
		Sand	Silt	Clay		
		(%)	(%)	(%)	(g cm^{-3})	(cm^3 cm^{-3})
Indonesia	Top	37 a	48 a	14 b	1.50 a	27.90 a
	Upper middle	40 a	44 a	16 ab	1.45 ab	28.80 a
	Lower middle	33 a	44 a	23 ab	1.33 c	28.88 a
	Bottom	29 a	46 a	26 a	1.35 bc	28.12 a
Thailand	Top	74 a	23 a	3 a	1.58 a	18.22 a
	Middle	73 a	22 a	3 a	1.62 a	19.27 a
	Bottom	67 a	30 a	3 a	1.72 a	16.78 a

[1] In a column within a country, average (4-village) values followed by same letter are not significantly different at 5% level by LSD.

K, CEC, organic C, pH, clay content, and bulk density differed significantly among toposequence positions, with often the top and upper middle positions having similar values and the lower middle and bottom having similar values (Tables 3 and 4). Exchangeable K, CEC, and organic C content generally increased from top to bottom, while bulk density decreased from top to bottom. Soil pH was lower at the top than at the lower middle and bottom positions. Other soil properties were not statistically different at different toposequence positions.

In Thailand, soil N, P, K, and organic C content at the top were lower and available water was higher than at the bottom toposequence positions, but the difference in magnitude varied within three out of the four villages. However, the measurement variation in these soil properties among villages was high, resulting in not statistically different properties across toposequence positions.

Field hydrology

During the crop growth periods, 22 of the 24 hydrological cases in Indonesia and Thailand (Table 5) have statistically different groundwater depths among toposequence positions. Out of the 22, 18 cases have deeper and two cases have shallower, groundwater levels at the top than at the bottom toposequence positions and in two cases groundwater depths at the top are not statistically different from those at the bottom toposequence position, but groundwater depths at the middle positions are different from those at the top and at the bottom. Similarly (data not shown), 21 out of 24 cases have different field water depths, of which 17 cases have shallower and one case has deeper field water depths at the top toposequence positions than at the bottom toposequence positions, while in three cases field water depths at the top are not statistically different from those at the bottom toposequence position, but field water depths at the middle position are different from those at the top and at the bottom Moreover, the top toposequence positions have more days without ponded surface water than the bottom toposequence positions in four out of the seven seasons (Table 6). In general, seasons with more days without ponded surface water also have more cases with shallower field water and deeper groundwater depths at the top than at the bottom toposequence positions. There were, however, along short ($\leq$ 225 m) toposequences with low ($\leq$ 1.5%) slopes some cases with deeper field water and shallower groundwater at the top than at the bottom toposequence positions.

Rice biomass and yield

Canopy biomass and yield of control plots (non-fertilized treatment in Thailand; and non-weeded treatment in Indonesia) were not influenced by the interaction of season × toposequence position (Table 7). However, the biomass and yield in non-fertilized

Table 5. Average groundwater depths[1] (cm) in plots at top, middle, and bottom toposequence positions at four villages in different seasons in Indonesia and in Thailand.

Country	Village	Toposequence position	2000	2001		2002	
			Early wet	Late wet	Early wet	Late wet	Early wet
Indonesia	Megulung	Top	–16.1 bc	–15.9 a	–68.9 b	–42.8 b	NA
		Upper middle	–20.2 c	–30.8 b	–94.2 c	–59.4 b	NA
		Lower middle	–8.9 ba	–14.5 a	–43.1 a	–46.1 b	NA
		Bottom	–4.1 a	–13.0 a	–24.2 a	–16.7 a	NA
	Jadi	Top	–16.5 b	–29.6 b	–28.0 b	–51.4 b	NA
		Upper middle	–19.6 b	–42.5 b	–50.2 c	–54.7 b	NA
		Lower middle	–1.9 a	–10.6 a	–12.7 a	–23.0 a	NA
		Bottom	6.2 a	–4.8 a	–1.5 a	–32.0 a	NA
	Sidomukti	Top	–41.5 b	–59.2 b	–57.1 ba	–47.9 a	NA
		Upper middle	–36.4 b	–24.9 a	–69.8 b	–42.0 a	NA
		Lower middle	–25.3 ba	–26.0 a	–68.6 b	–44.9 a	NA
		Bottom	–15.9 a	–11.8 a	–44.9 a	–47.9 a	NA
	Pelemgede	Top	NA	NA	–27.8 a	–55.6 b	NA
		Upper middle	NA	NA	–26.0 a	–54.5 b	NA
		Lower middle	NA	NA	–26.9 a	–47.0 b	NA
		Bottom	NA	NA	–16.2 a	–31.9 a	NA
Thailand	Kham	Top	–8.7 c	NA	–21.6 c	NA	–24.0 c
		Middle	2.4 b	NA	4.9 b	NA	6.9 b
		Bottom	52.7 a	NA	42.3 a	NA	29.9 a
	Kha Khom	Top	–7.8 c	NA	–14.6 c	NA	–16.4 b
		Middle	5.2 b	NA	16.3 b	NA	–1.7 ab
		Bottom	26.4 a	NA	28.7 a	NA	6.1 a
	Don Chi/ Khu Khat 1	Top	31.5 a	NA	38.4 a	NA	–35.9 b
		Middle	10.4 b	NA	34.1 b	NA	–45.3 b
		Bottom	–6.4 c	NA	24.6 c	NA	–4.2 a
	Khu Khat 2	Top	NA	NA	NA	NA	–28.5 c
		Middle	NA	NA	NA	NA	–20.4 b
		Bottom	NA	NA	NA	NA	1.0 a

[1] A negative sign indicates that the water level was below the soil surface. In a column within a village, average daily values followed by same letter are not significantly different at 5% level by LSD. NA is not applicable.

Table 6. Accumulated number of days without ponded surface water at the top, middle, and bottom toposequence positions in different seasons and years in Indonesia and in Thailand.

Country	Toposequence position	2000	2001		2002	
		Early wet	Late wet	Early wet	Late wet	Early wet
Indonesia	Top	102 a	77 a	99 a	86 a	NA
	Upper middle	111 a	76 a	100 a	86 a	NA
	Lower middle	78 b	52 b	98 a	82 a	NA
	Bottom	41 c	35 b	92 a	62 b	NA
Thailand	Top	108 a	NA	22 a	NA	108 a
	Middle	99 a	NA	19 a	NA	81 ab
	Bottom	81 a	NA	8 a	NA	66 b

[1] In a column within a country, average (4-village) values followed by same letter are not significantly different at 5% level by LSD. NA is not applicable.

Table 7. Analysis of covariance of canopy biomass and grain yield in non-weeded (FP-W) and non-fertilized (FP-N) plots at different toposequence positions in Indonesia and in Thailand.

Parameter	Country	Source of variation[1]				
		Covariance	Village	Toposequence position	Season	Season × Toposequence
Treatment FP–W						
Canopy biomass	Indonesia	ns	ns	**	*	ns
Grain yield	Indonesia	ns	ns	**	**	ns
Treatment FP–N						
Canopy biomass	Indonesia	ns	*	*	+	ns
Canopy biomass	Thailand	*	ns	ns	ns	ns
Grain yield	Indonesia	ns	*	*	**	ns
Grain yield	Thailand	**	ns	*	*	ns

[1] **, *, + are significant at 1, 5 and 10% levels, respectively; ns=not significant;
NA=source of variation not applicable for the data set.

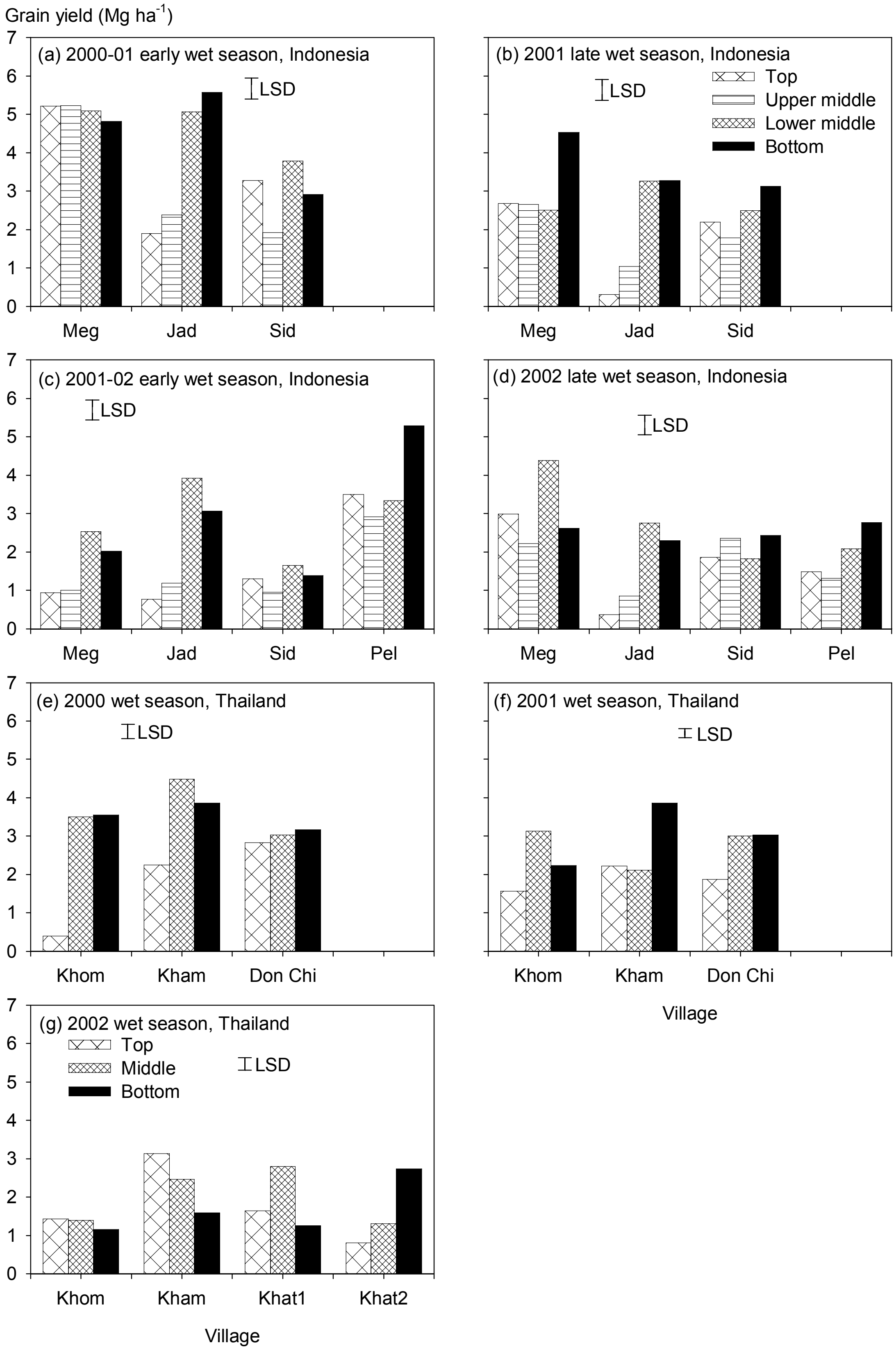


Figure 2. Grain yield in non-fertilized (FP–N) plots at different toposequence positions of different villages during four crop seasons in Indonesia (a–d) and three crop seasons in Thailand (e–g). Village codes are explained in Figure 1.

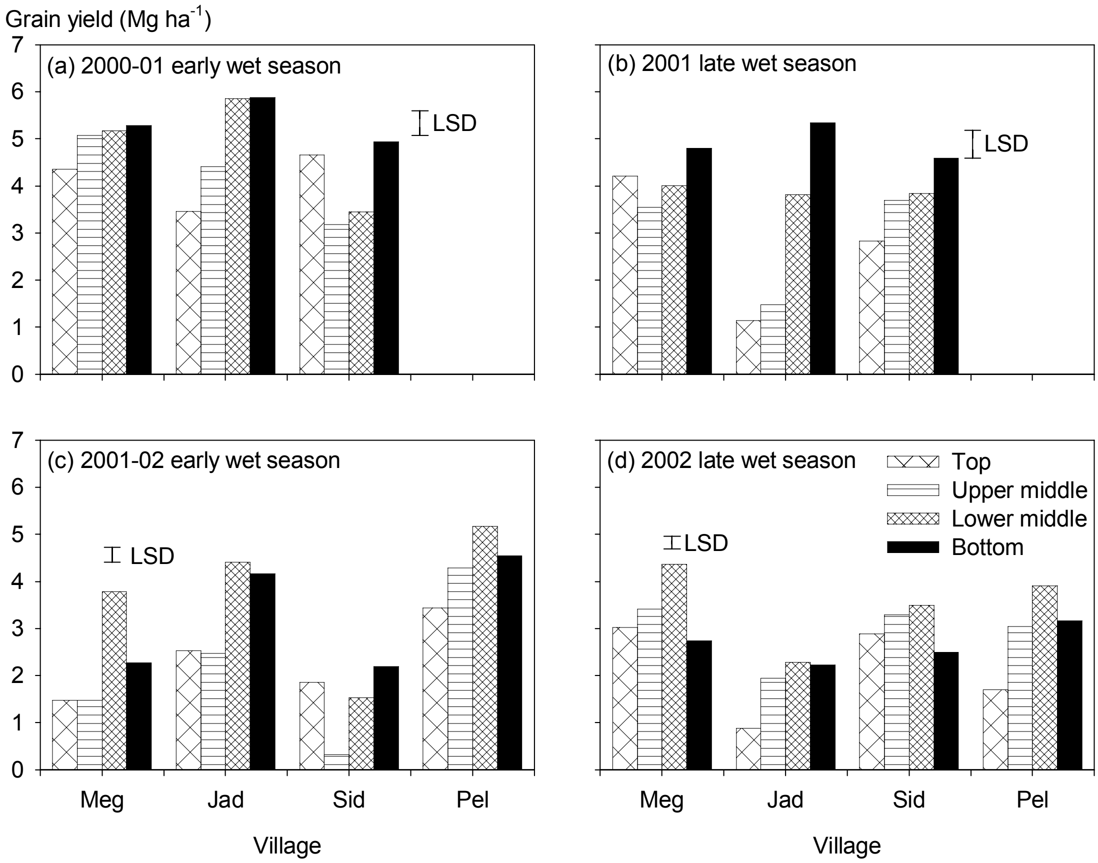


Figure 3. Grain yield in non-weeded (FP–W) plots at four toposequence positions of four villages during four crop seasons in Indonesia. Village codes are explained in Figure 1.

plots varied among toposequence positions within villages in Thailand (Table 7). Yield did not differ among toposequence positions in six out of 11 season × control treatment combinations (Figs 2 and 3). Yield differences in non-fertilized plots were observed among toposequence positions in two (2001–02 early wet, 2002 late wet) out of the four seasons in Indonesia and in two (2001–02 wet seasons) out of the three seasons in Thailand (Fig. 2). Similarly, yield differences among toposequence positions were observed in non-weeded plots in one (2001–02 early wet) of the four seasons in Indonesia (Fig. 3). The higher toposequence positions usually had lower yields than the lower positions.

Effect of intensive weed management

In Indonesia, variation in crop biomass and grain yield in non-weeded (FP–W) plots was influenced by season and toposequence position (Table 7). Average crop biomass in the non-weeded plots across toposequence positions and seasons was 6.27 Mg ha^{-1} (data not shown) and average grain yield was 2.89 Mg ha^{-1} (Fig. 3). Intensive weeding

Table 8. Yield increase (Mg ha^{-1}) in plots under intensive weeding (ΔY_{W}) and under farmers' practice (ΔY_{FP1}) (over yield in non-weeded plots but with otherwise farmers' practice), at different toposequence positions in different seasons and years in Indonesia.

Management	Toposequence position	2000	2001		2002
		Early wet	Late wet	Early wet	Late wet
Intensive weeding	Top	1.62 a	0.05 a	0.85 a	0.40 a
	Upper middle	1.25 ab	0.00 a	0.69 a	0.90 a
	Lower middle	0.47 b	0.28 a	1.38 a	0.66 a
	Bottom	0.41 ab	0.30 a	0.82 a	0.36 a
Farmers' practice	Top	1.65 a	0.26 a	1.37 ab	0.30 b
	Upper middle	1.06 a	0.00 b	0.82 ab	0.81 a
	Lower middle	1.15 a	0.17 ab	1.53 a	0.46 ab
	Bottom	0.71 a	0.12 ab	0.77 b	0.27 b

[1] In a column within a treatment, average (4-village) values followed by same letter are not significantly different at 5% level by LSD.

increased yields of non-weeded plots on average by 0.94 Mg ha^{-1} in early wet seasons and by 0.36 Mg ha^{-1} in late wet seasons (Table 8). In three out of the four seasons, the yield increases were not statistically different in all toposequence positions.

Effect of recommended fertilizer application

In non-fertilized plots (FP–N), average crop biomass across toposequence positions and seasons was 5.24 Mg ha^{-1} in Indonesia and 4.36 Mg ha^{-1} in Thailand (data not shown). Average yield across toposequence positions and seasons was 2.64 Mg ha^{-1} in Indonesia and 2.46 Mg ha^{-1} in Thailand (Fig. 2). As in non-weeded plots, the variation in biomass and yield in non-fertilized plots was influenced by single effects of toposequence and season, and not by the interaction of season × toposequence position (Table 7). However, crop biomass and yield in non-fertilized plots varied among toposequence positions within villages in Thailand.

Application of the recommended fertilizer doses increased yields over non-fertilized plots on average by 1.25 Mg ha^{-1} in both early and late wet seasons in Indonesia (Table 9). In Indonesia, there was no significant effect of toposequence position on the yield increase in three out of the four seasons, whereas in the remaining season, statistically different yields were distinguished at two positions. In the one season with available data in Thailand, the effect of applying recommended fertilizer doses was very small and not statistically different at the different toposequence positions.

Effect of combined weed control and fertilizer application

Farmers' practice

In Indonesia, farmers' practices of weed control and fertilizer application (FP) increased yields over those in non-weeded plots (FP–W) on average by 1.13 Mg ha^{-1} in the early wet seasons and by 0.26 Mg ha^{-1} in the late wet seasons (Table 8). In three of the four seasons, the yield increases were statistically different but differed in magnitude across toposequence positions. In the remaining season, the effects of weed control were not statistically different. Farmers' practices of weed control and fertilizer application increased yields over those in non-fertilized plots on average by 0.78 Mg ha^{-1} in both, the early and the late wet season in Indonesia (Table 9). In three of the four seasons, there was no significant effect of toposequence position on yield increase, and in the remaining season only two levels of yield increase could be distinguished.

In Thailand, average yield increase of farmers' practice over non-fertilized plots was only 0.26 Mg ha^{-1}, and no significant differences were observed among toposequence positions in the three seasons.

Table 9. Yield increase (Mg ha^{-1}) in plots under recommended fertilizer application (ΔY_{N}), under farmers' practice (ΔY_{FP2}), and under combined recommended fertilizer application and intensive weeding ($\Delta Y_{\mathrm{N\times W2}}$) (over yield in unfertilized plots but with otherwise farmers' practice), at different toposequence positions in different seasons and years in Indonesia and Thailand.

Management	Country	Toposequence position	2000	2001		2002	
			Early wet	Late wet	Early wet	Late wet	Early wet
Recommended fertilizer	Indonesia	Top	1.54 a	1.54 a	1.21 a	0.92 b	NA
		Upper middle	1.89 a	1.75 a	1.09 a	1.65 a	NA
		Lower middle	0.49 a	1.54 a	0.90 a	1.16 ab	NA
		Bottom	1.05 a	1.60 a	0.83 a	0.78 ab	NA
Recommended fertilizer	Thailand	Top	NA	NA	NA	NA	0.18 a
		Middle	NA	NA	NA	NA	0.27 a
		Bottom	NA	NA	NA	NA	0.00 a
Farmers' practice	Indonesia	Top	0.70 a	1.00 a	0.69 a	0.45 ab	NA
		Upper middle	1.04 a	1.08 a	0.62 a	1.23 a	NA
		Lower middle	0.18 a	1.13 a	0.86 a	0.75 ab	NA
		Bottom	0.93 a	1.27 a	0.35 a	0.13 b	NA
Farmers' practice	Thailand	Top	0.48 a	NA	0.23 a	NA	0.83 a
		Middle	0.00 a	NA	0.50 a	NA	0.00 b
		Bottom	0.01 a	NA	0.31 a	NA	0.20 ab
Intensive weeding and recommended fertilizer	Indonesia	Top	1.70 a	1.85 a	1.57 a	1.18 b	NA
		Upper middle	2.00 a	2.30 a	1.59 a	1.90 a	NA
		Lower middle	0.85 a	2.05 a	0.82 a	1.12 b	NA
		Bottom	1.37 a	1.73 a	1.01 a	0.86 b	NA

[1] In a column within a treatment in a country, average (4-village) values followed by same letter are not significantly different at 5% level by LSD.

Intensive weed control and recommended fertilizer application

In Indonesia, the combined use of intensive weeding and the recommended fertilizer doses increased yields over those in non-fertilized plots on average across both seasons by 1.50 Mg ha^{-1} (Table 9). There was no significant effect of toposequence position on the yield increase in three of the four seasons, and in the remaining season only two levels of yield increase could be distinguished.

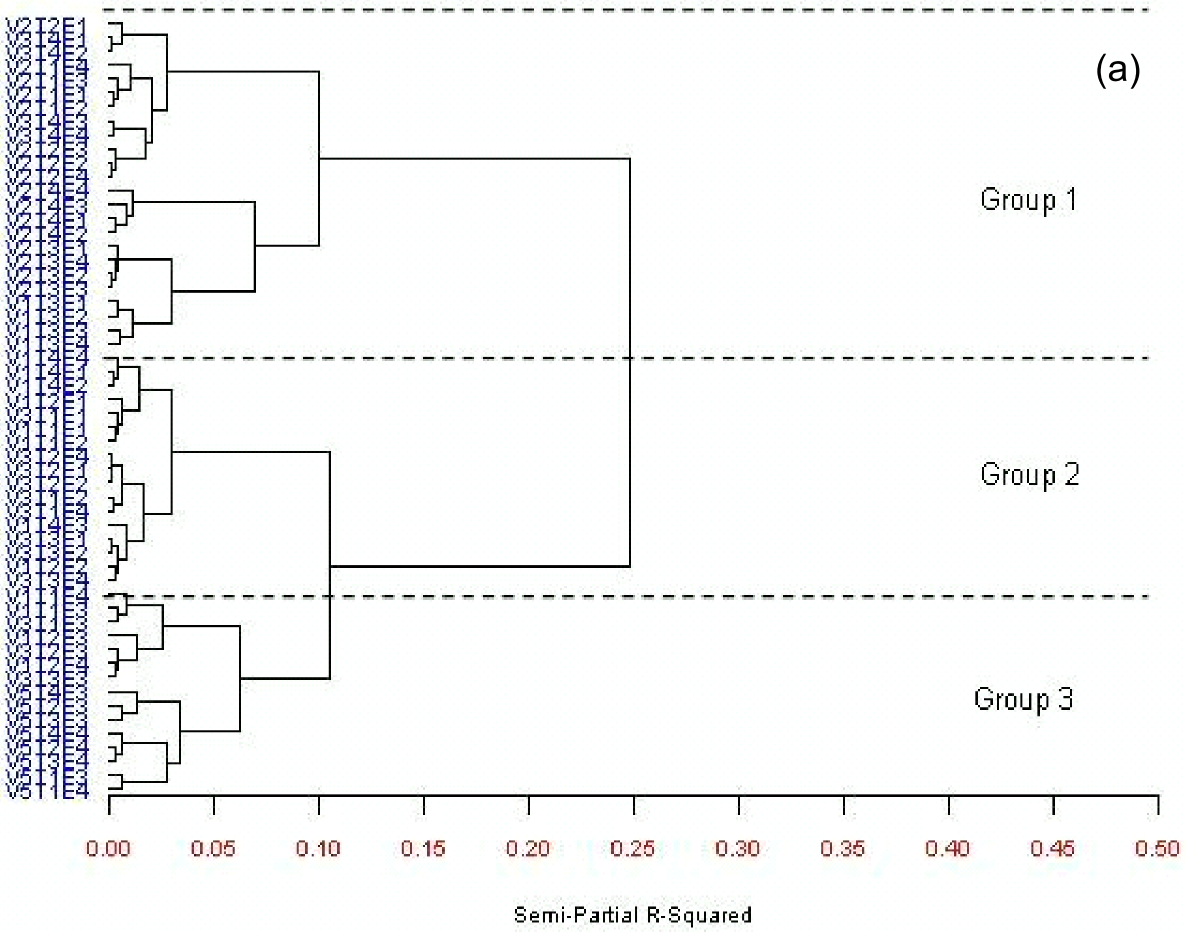
Cluster groups

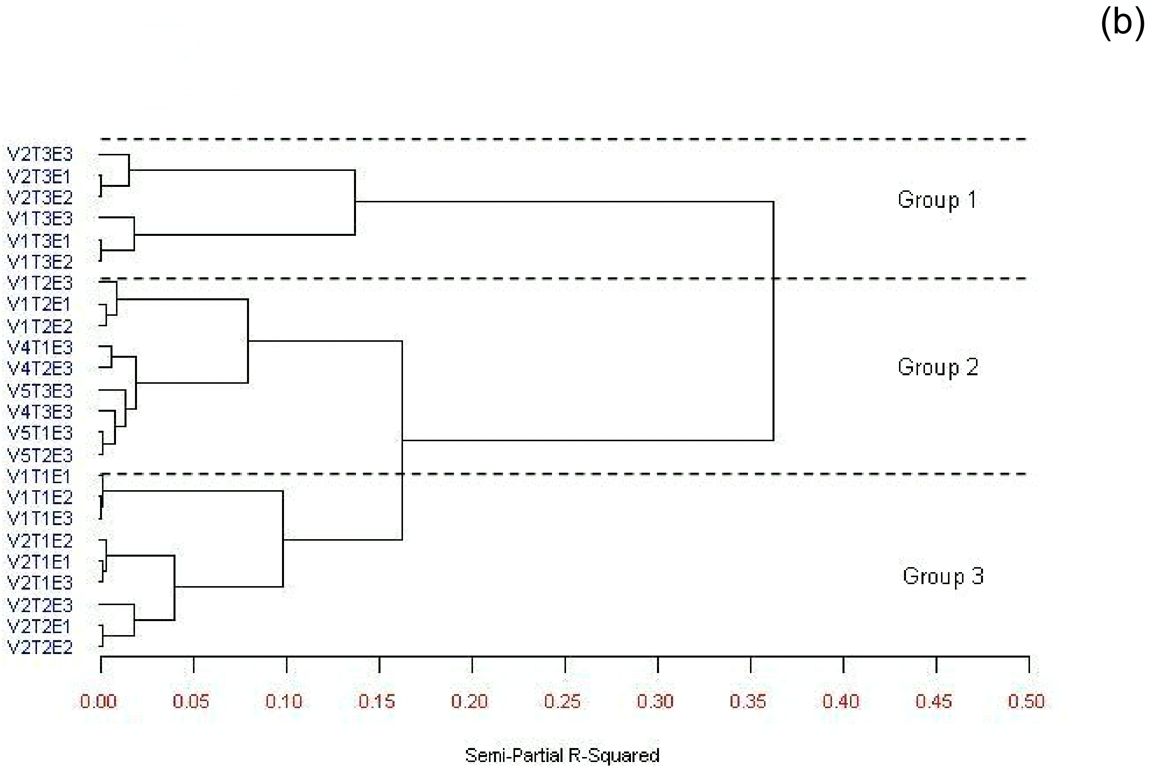
In non-fertilized (FP–N) plots, the combination of soil properties, water status, and plant data in different villages, toposequence positions, and seasons (referred to as cases) in each country were grouped into three clusters (Fig. 4). The clustering was largely associated with toposequence position. In Indonesia, 16 out of 24 cases in group 1 belong to the lower middle and bottom toposequence positions, while 10 of the 15 cases in group 3 belong to the upper middle and top toposequence positions (Fig. 4A). In Thailand, all cases in group 1 belong to bottom positions, five out of nine cases in group 2 belong to middle toposequence positions, and six out of nine cases in group 3 belong to top toposequence positions (Fig. 4B).

Discussion and conclusions

There were substantial differences in clay content, exchangeable K and organic C depending on the toposequence position in Indonesia and Thailand. Clay content, exchangeable K, and organic C at the top toposequence positions were lower than the bottom. Strong singular or covariate relationships between toposequence position and many other soil chemical (N, P, CEC, pH) and physical (sand, silt, bulk density) properties in one country were not observed in the other country. The increasing trend in exchangeable K, organic C, and clay content from top to bottom along the toposequence is consistent with reports for the Philippines (Van Breemen et al., 1980), Nigeria (Eshett et al., 1989), and Senegal (Posner and Crawford, 1992). However, Yamauchi (1992) noted an opposite trend for K in Nigeria.

There were also substantial differences in field hydrology: the plots at the top of the toposequence were consistently drier than those at the bottom. Average depth of standing water at the surface was shallower, groundwater was deeper, and the number of cumulative days without ponded surface water smaller at the top than at the bottom. These observations are consistent with observations reported by Hseu and Chen (2001) and Tsubo et al. (2006). The relative dryness and lower clay content of the plots at the top were probably caused by downward and lateral water movements along the toposequence.


(a)
Group 1
Group 2
Group 3
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Semi-Partial R-Squared


(b)
V2T3E3
V2T3E1
V2T3E2
V1T3E3
V1T3E1
V1T3E2
V1T2E3
V1T2E1
V1T2E2
V4T1E3
V4T2E3
V5T3E3
V4T3E3
V5T1E3
V5T2E3
V1T1E1
V1T1E2
V1T1E3
V2T1E2
V2T1E1
V2T1E3
V2T2E3
V2T2E1
V2T2E2
Group 1
Group 2
Group 3
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Semi-Partial R-Squared

Yields in the control treatment were mostly similar across toposequence positions. The absence of a strong toposequence effect on yield in Indonesia and Thailand agrees with a similar finding in Laos reported by Tsubo et al. (2006). Similarly to yield, the effect of weed control or fertilizer application on yield was generally not statistically different across toposequence positions. Yield increases associated with application of recommended fertilizer doses in Indonesia were within the range reported for fertilizer experiments at Jakenan Experiment Station by Mamaril et al. (1995), Wihardjaka et al. (1999), and Boling et al. (2004).

The overall conclusion is that there were substantial differences in field hydrology, exchangeable K, organic C, and clay content and there were substantial but inconsistent differences in some other soil properties (N, P, sand and silt content, CEC, pH, bulk density), in yield, and in magnitude of yield increase associated with adoption of intensive weed control and/or recommended fertilizer doses among toposequence positions. Consequently, the hypothesis that the toposequence position would be a useful recommendation domain for weed control and/or fertilizer application is not supported by the results of our statistical analyses. There may be two reasons why toposequence has no statistically significant effect on yield or yield increase associated with change (weed control and fertilizer) in management practices. First, variation in soil and hydrological properties of fields at the same toposequence position among villages could be larger than variation in these properties among toposequence positions. If this is true, then improvements in yield over blanket management recommendations across a wide range in rainfed environments can only be realized through field-specific management practices such as offered by site-specific nutrient management (Dobermann et al., 2002). The second reason may be that farmers' practices are already fine-tuned to their field-specific conditions (Rashid et al., 1997; Wijnhoud et al., 2003), so that differences in soil or hydrological properties are already accounted for to some extent. This would be especially true in the first year of our study in Indonesia, where each farmer may have managed each of

Figure 4. Dendrogram for the combination of plant, soil, and water data of non-fertilized (FP–N) plots in different environment cases in Indonesia (a) and Thailand (b). Environment cases are identified by village (V), toposequence position (T), and experiment season (E). In Indonesia, V1=Megulung, V2=Jadi, V3=Sidomukti, V5=Pelemgede, T1=top, T2=upper middle, T3=lower middle, T4=bottom, E1=2000–01 early wet season, E2=2001 late wet season, E3=2001–02 early wet season, E4=2002 late wet season; In Thailand, V1=Kha khom, V2=Kham, V3=Don Chi, V4=Khu Khat 1, V5=Khu Khat 2, T1=top, T2=middle, T3=bottom, E1=2000, E2=2001, E3=2002.

his plots across the toposequence differently. In the second and third year, rice variety and plant density were standardized, but differences in other management practices, such as establishment method and fertilizer schedule, could still have masked the effect of toposequence-specific field conditions. The fact that our intensive weed control and recommended fertilizer dose produced not statistically different yield increases across toposequence positions would then still leave open the possibility that management recommendations adjusted to toposequence position could further increase (or differentiate) yields. A more detailed analysis of the specific conditions of the fields along our toposequences would be needed to further investigate this hypothesis.

CHAPTER 5

Yield constraint analysis of rainfed lowland rice in Central Java, Indonesia: 2. Farmers' fields[1]

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Abstract

Yield constraint analysis for rainfed rice at a research station gives insight into the relative role of yield-limiting factors, which may form the basis for designing alternative management strategies that may increase yield and yield stability in farmers' fields. However, soil nutrient status and water conditions along toposequences in rainfed farmers' fields may differ from those of the research station. Therefore, there is a need to also analyse yield constraints in farmers' fields.

We analysed yield-determining and yield-limiting factors on rice yields along toposequences in farmers' fields using data from toposequence experiments conducted in 2000–02 in Indonesia. Farmers' fields showed large spatial and temporal variation in hydrology (354–1235 mm seasonal rainfall, –150 to 50 cm field water depth) and farmers' fertilizer doses (76–166 N, 0–45 P, and 0–51 kg K ha^{-1}). Farmers' yields ranged from 0.32 to 5.88 Mg ha^{-1}. The average yield gap due to water was 28%, to N 55%, to P 20%, and to K 53%, but with large temporal and spatial variability. Average grain production per unit rainfall recorded (rainfall use efficiency) was 4.37 kg ha^{-1} mm^{-1}, and varied among toposequence positions. The yield gaps due to water and N at the top and upper middle positions were higher, whereas rainfall use efficiency was lower than at the lower middle and bottom toposequence positions.

The relative limitations of water, N, and K in farmers' fields were similar to those observed in nearby Jakenan Experiment Station. However, their relative importance varied strongly among toposequence positions and villages in rainfed rice areas. Yield constraint analysis is necessary for identifying appropriate management strategies to increase productivity and yield stability in farmers' fields in other rainfed lowland areas.

Keywords: Field water, groundwater, plant nutrient uptake, resource use efficiency, toposequence, yield loss.

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[1] To be submitted to Nutrient Cycling in Agroecosystems

Introduction

Climate in rainfed environments is variable, and farmers' fields in rainfed lowland rice systems are characterized by a high degree of heterogeneity in topography and soil conditions along toposequences and across sites (Boling et al., 2007b), so that rice crop performance varies from year to year and from location to location. A quantitative approach has been used to identify the role of water deficits, nitrogen (N) limitation, potassium (K) limitation, and pest infestation in yield formation of rainfed lowland rice at research stations (Boling et al., 2004). Such yield constraint analysis may lead to the identification of management strategies that could increase yield and yield stability in rainfed rice. However, yield constraints within a research station do not necessarily reflect the constraints under different soil nutrient (Eshett et al., 1989; Posner and Crawford, 1992; Yamauchi, 1992) and water conditions (Hseu and Chen, 2001; Tsubo et al., 2006; Boling et al., 2007b) that occur along toposequences in rainfed farmers' fields. The variation in yield due to water and nutrient limitations along toposequences is not well understood. Thus, there is a need to analyse yield constraints in farmers' fields (Cassman and Pingali, 1995; Francis et al., 1995; Mittler, 2006) to identify efficient management strategies for rainfed lowland rice areas.

We hypothesize that the variation in rice yields and the differential yield response to nutrient additions along the toposequence may be partly explained by the spatial and temporal variability in hydrology and plant nutrient availability. We performed a yield-gap analysis on an existing database on toposequence experiments in farmers' fields conducted in 2000–2002 in Indonesia, with the objective to identify the effects of yield-determining and yield-limiting factors on rice yields along toposequences.

Materials and methods

Experiments

We analysed the data gathered in a series of field experiments conducted in 2000–02 in bunded fields surrounding the Jakenan Experiment Station (6°47′ S, 111°12′ E) in Java, Indonesia. The experiments were conducted in four crop seasons (two early wet seasons, October–February; and two late wet seasons, March–July). Experimental treatments were laid out using split-plot designs with four villages as replications. Toposequence positions (top, upper middle, lower middle, bottom) were used in the main plot and six combinations of nutrient and weed management were used in the subplot. More details of the experiments are given in Boling et al. (2007b).

All four seasons were used for analysing the spatial and temporal variations in rainfall, field-water and groundwater depths, and farmers' rice yields along toposequences. Two of the four seasons (2001–02 early wet and 2002 late wet) and the three nutrient treatments in four villages (Megulung, Jadi, Sidomukti, and Pelemgede) were used for yield gap analysis. The nutrient treatments were the farmers' practice (FP), non-fertilized (FP–N), and fertilized according to recommendations (FP+N). In these seasons, rice cultivar IR64 was planted at 15 × 15-cm hill spacing in all plots.

Farmers' management practices

Farmers' choice of crop establishment was season-specific: in the 2001–02 early wet season, all of the farmers dry-seeded rice and in the 2002 late wet season, they transplanted rice, irrespective of village or position in the toposequence.

Farmers applied different N and P fertilizer doses at different toposequence positions and villages (Table 1). Supplemental K was applied at all toposequence positions in one village (Pelemgede) and at the upper middle position in another village (Megulung). As for crop establishment method, farmers' fertilizer use did not follow any specific pattern in relation to toposequence position.

Observations

Daily rainfall was recorded at the middle toposequence position in the four villages. Field-water depths and groundwater depths were recorded daily in each main plot. For each experimental plot, dates of emergence, panicle initiation (PI), flowering, and physiological maturity were recorded. Rice yield was determined from 5-m^2 sampling areas at harvest. At physiological maturity, 22 hills (0.50-m^2 area) were sampled for straw and panicle dry weights, nutrient (N, P, K) concentrations, and panicle damage. Plant N, P, and K concentrations were measured. Plant N was determined using Kjeldahl digestion (Varley, 1966). P was determined colorimetrically as reduced phosphomolybdate at 625 μ (Jackson, 1958; Chapman and Pratt, 1961; Jones and Case, 1990). K was determined by soaking with 1N HCl and subsequent analysis of the filtrate (Yoshida et al., 1976) using atomic absorption spectrophotometry. More details on these measurements are given in Boling et al. (2007b).

Data analysis

Yield gap due to water limitation

Simulations were carried out using the ORYZA2000 model (Bouman et al., 2001). The model can adequately simulate field-water depth, soil-water tension, leaf, stem, and panicle biomass; and grain yield of rice at various levels of fertilizer N under well-watered (Bouman and Van Laar, 2006; Jing et al., 2007; Belder et al., 2007) and rainfed conditions (Boling et al., 2007a).

In this study, the model was used to simulate potential and water-limited yields of

Table 1. Farmers' fertilizer inputs (kg ha^{-1}) in different toposequence positions in four villages in Indonesia.

Village	Toposequence position	Fertilizer rate[1] Nitrogen	Phosphorus	Potassium
Megulung	Top	129	22	0
	Upper middle	141	31	43
	Lower middle	144	45	0
	Bottom	131	21	0
Jadi	Top	166	36	0
	Upper middle	147	29	0
	Lower middle	98	17	0
	Bottom	138	24	0
Sidomukti	Top	152	12	0
	Upper middle	76	0	0
	Lower middle	76	20	0
	Bottom	83	32	0
Pelemgede	Top	156	31	51
	Upper middle	156	31	51
	Lower middle	83	18	18
	Bottom	92	0	40

[1] Fertilizer rate from inorganic sources.

rice cultivar IR64 using data from the field experiments carried out in farmers' fields. Crop phenological development rates were calculated from observed phenological stages for each experimental treatment at different toposequence positions per village. Groundwater depth measurements in the main plot, rainfall measurements in the village, and solar radiation, maximum and minimum temperatures, relative humidity, and wind speed recorded at the Jakenan Experiment Station were used as model inputs.

Yield gap due to water deficit (ΔY_{W}) was estimated using the simulated potential ($Y_{\mathrm{pot,\,sim}}$) and water-limited ($Y_{\mathrm{rf,\,sim}}$) yields in plots with recommended fertilizer levels:

$$\Delta Y_{\mathrm{W}} = Y_{\mathrm{pot,\,sim}} - Y_{\mathrm{rf,\,sim}} \quad (1)$$

Yield gap due to nutrient limitation

Nutrient-limited yields were estimated using measured crop nutrient uptake for the macro-elements nitrogen (N), phosphorus (P), and potassium (K), and the theoretical physiological efficiencies (Dobermann and Fairhurst, 2000), i.e., initial slopes of the nutrient uptake-yield curves (Van Keulen, 1982; 1986). Yield gaps due to N (ΔY_N), P (ΔY_P), and K (ΔY_K) were estimated by:

$$\Delta Y_N = Y_{pot,\ sim} - 70\ N_{upt,\ mea} \tag{2}$$

$$\Delta Y_P = Y_{pot,\ sim} - 525\ P_{upt,\ mea} \tag{3}$$

$$\Delta Y_K = Y_{pot,\ sim} - 70\ K_{upt,\ mea} \tag{4}$$

where, $N_{upt,\ mea}$, $P_{upt,\ mea}$, and $K_{upt,\ mea}$ represent measured crop N, P, and K uptake, respectively, in non-fertilized plots.

Total yield gaps (ΔY_{tot}) were estimated from simulated potential yields and measured yields in non-fertilized plots ($Y_{FP–N,\ mea}$) at different toposequence positions and villages:

$$\Delta Y_{tot} = Y_{pot,\ sim} - Y_{FP–N,\ mea} \tag{5}$$

Resource use efficiencies

Two indicators for water use efficiency (rainfall use efficiency, water productivity) and two for nutrient use efficiency (internal nutrient use efficiency, nutrient removal rate) were calculated from non-fertilized plots. Rainfall use efficiency (Hein and De Ridder, 2006) was calculated as measured grain yield per mm of rainfall recorded in the village during the crop season. Water productivity (Bouman, 2007) was calculated as measured grain yield per mm of simulated transpiration.

Internal nutrient use efficiency was calculated as measured grain yield per unit measured nutrient uptake by the crop. Nutrient removal rate was calculated as nutrient requirement per Mg of grain.

Results and discussion

Hydrology

Rainfall in the 2001–02 early wet season in Megulung and in the 2002 late wet season in Sidomukti was below normal ($P > 0.80$, Table 2) and normal ($0.20 < P < 0.80$) in the other situations.

The below-normal rainfall (drought) in Megulung resulted in field-water levels below the soil surface, deep groundwater levels, and more days with no standing water than in seasons having normal rainfall (Boling et al., 2007b). The below-normal rainfall in Sidomukti resulted in groundwater depths that dropped to 100 cm below the soil surface from flowering to maturity (reproductive stage) (Fig. 1.2).

The effect of rainfall varied at different toposequence positions in different villages.

Table 2. Seasonal rainfall and exceedance probability during the experimental period.

Village	2000–01 early wet season	2001–02 early wet season	2001 late wet season	2002 late wet season
	Seasonal rainfall[1] (mm)			
Megulung	1007	808	584	451
Jadi	1041	889	521	530
Sidomukti	1053	938	500	354
Pelemgede	1051	1235	609	521
	Exceedance probability[2] associated with seasonal rainfall			
Megulung [a]	0.58	0.83	0.31	0.69
Jadi [a]	0.58	0.75	0.46	0.39
Sidomukti [b]	0.31	0.53	0.61	0.88
Pelemgede [c]	0.65	0.25	0.38	0.67

[1] Five-month rainfall total accumulated during the crop growing season: early wet season is October-February and late wet season is March–July.

[2] Exceedance probabilities were calculated using long-term data of nearest rainfall station: [a]1990–2003 in Sumber; [b]1953–2002 at Jakenan Experiment Station; [c]1981–2004 in Puckawangi.

For example, high rainfall intensity (> 75 mm d^{-1}, February 2002) increased field-water and groundwater depths to 50 cm above the soil surface at the lower toposequence positions in Megulung (Fig. 1.1d) and Jadi (Figs 2c, 2d), compared with less than 20 cm at other sites (Figs 1.2, 1.3). Field-water and groundwater depths varied at different toposequence positions throughout the experimental period. For example, water depths at the top toposequence position in Jadi (Fig. 2a) fluctuated below the soil surface from November 2000 to April 2001 and was below the soil surface for 72–76 days from November 2001 to January 2002 (crop establishment until panicle development stage) and for 36–40 days from mid-April to May 2002 (reproductive stage). Water depths in the upper middle positions also fluctuated below the surface from November 2001 to January 2002, but at greater depths than in the top position. In contrast, water levels in the lower middle and bottom toposequence positions generally fluctuated above the surface and dropped below the surface for shorter periods (50–65 days) from November 2001 to January 2002 and in May 2002 (Figs 2c, 2d). The wide range in rainfall conditions and the fluctuations in field-water and groundwater depths during the experimental period illustrate the strong spatial and temporal variation in hydrology in rainfed rice areas, even within 15-km distance.

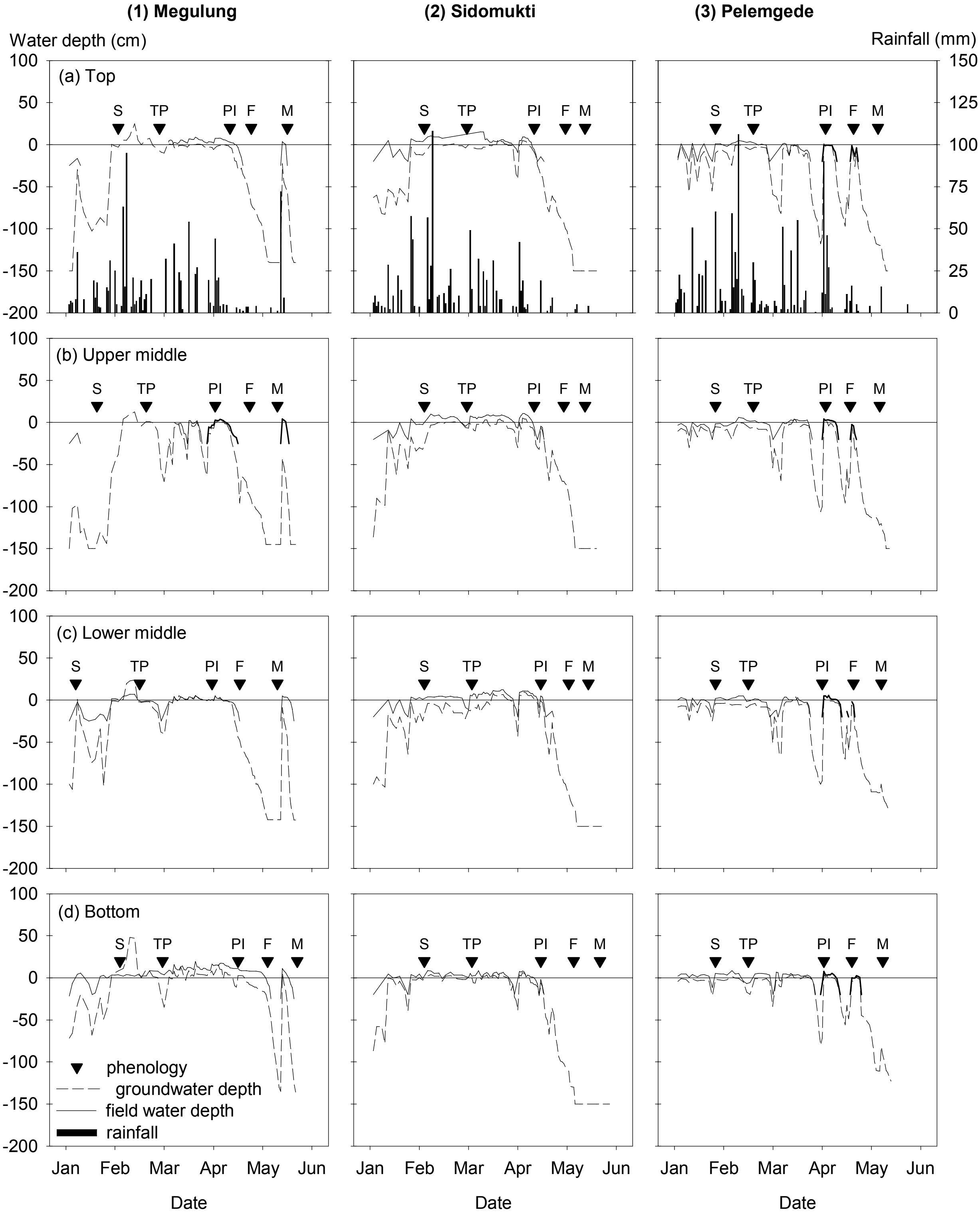

Figure 1. Rainfall, field-water depth, and groundwater depth in (a) top, (b) upper middle, (c) lower middle, and (d) bottom toposequence positions of three villages (1–3) in a representative season (2002 late wet season). The symbol ▼ indicates the dates of field activities and crop phenological stages. S = seeding; TP = transplanting; PI = panicle initiation; F = flowering; M = maturity.

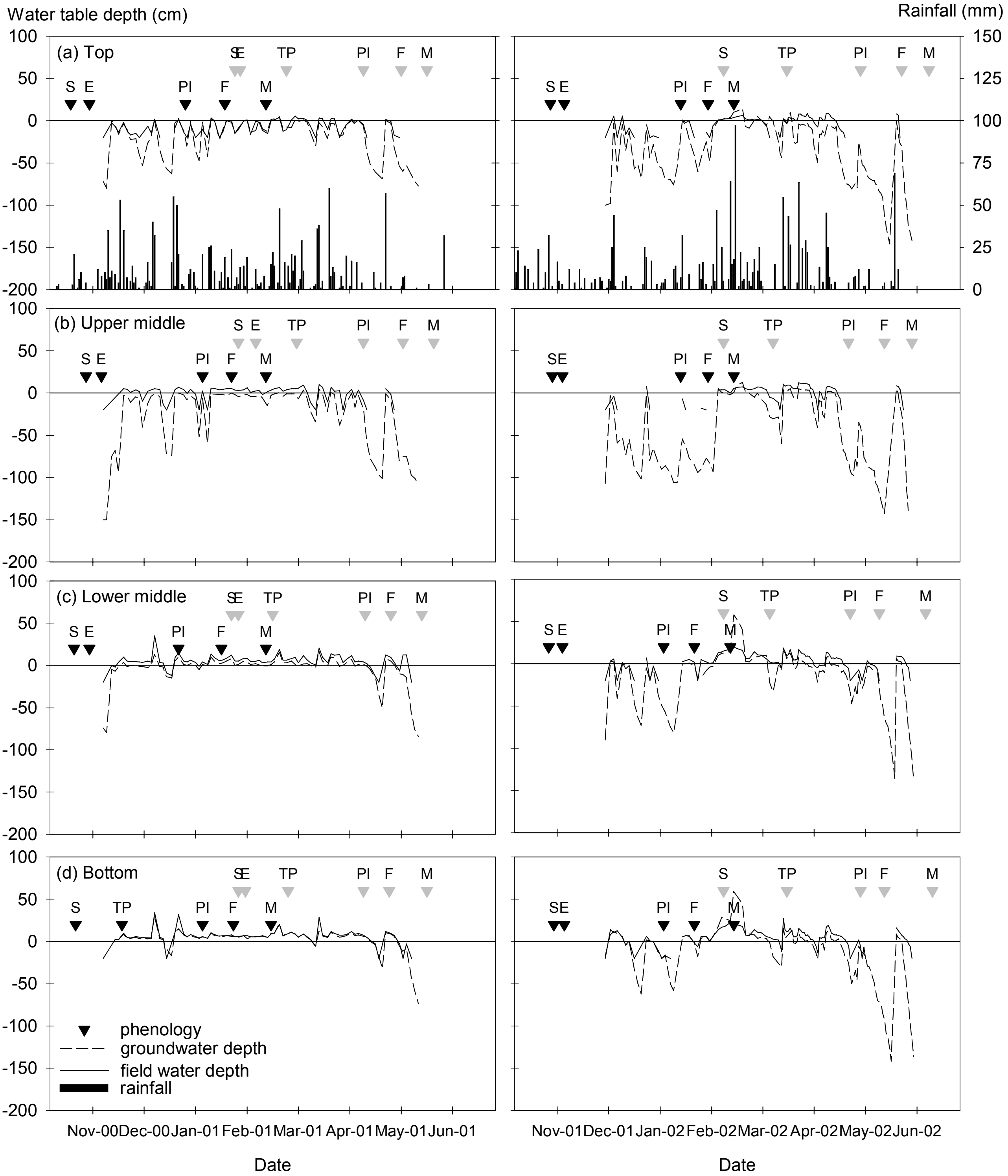

Figure 2. Rainfall, field-water depth, and groundwater depth in (a) top, (b) upper middle, (c) lower middle, and (d) bottom toposequence positions of a representative village (Jadi) during the two years of field experiments. Colour indicates field activities and crop phenological stages for early wet season (black) and late wet season (gray) crops. S = seeding; E=emergence; TP = transplanting; PI = panicle initiation; F = flowering; M = maturity.

Grain yield under farmers' management practices

Under farmers' management practices, rainfed rice yield (Fig. 3) ranged from 0.32 (upper middle position, Sidomukti, 2001–02 early wet season) to 5.88 Mg ha^{-1} (lower middle and bottom positions, Jadi, 2000–01 early wet season). Grain yield generally increased from the top to the bottom toposequence position in all four crop seasons. The difference in yield between adjacent toposequence positions varied among the villages. The variation in farmers' yields at different toposequence positions was associated with field-water depths. For example, lower yields were observed at the top position in Jadi where groundwater depths were deep, whereas higher yields were observed at the bottom position where groundwater depths were shallow.

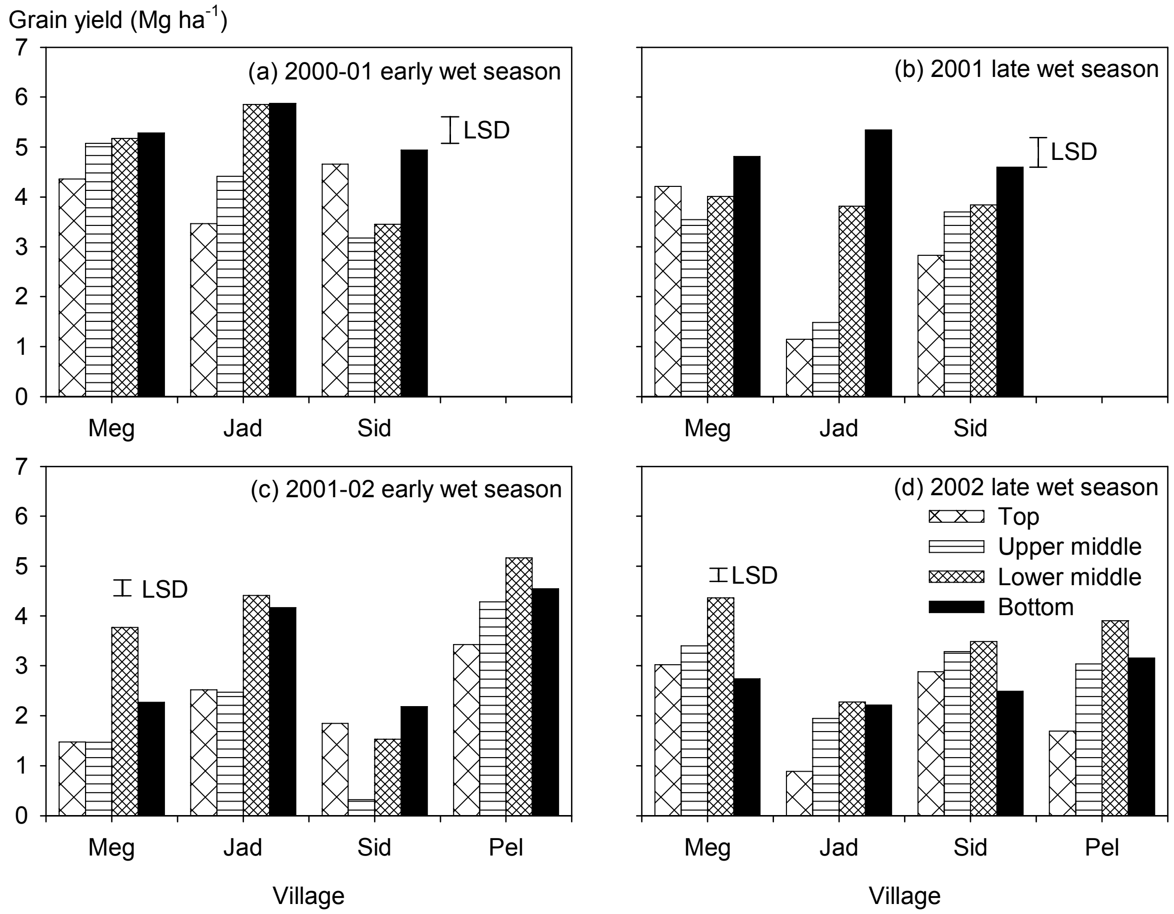

Figure 3. Grain yield under farmers' management practices at 4 toposequence positions of different villages during four crop seasons. Village codes are Meg=Megulung, Jad=Jadi, Sid=Sidomukti, and Pel=Pelemgede.

Yield gap due to water limitation

In plots with recommended fertilizer levels, the average yield gap due to water deficit was 3% in the 2001–02 early wet season, with some days without standing water during the crop's vegetative stage (Fig. 2), and ranged from 1% to 76%, with an average of 28% in the 2002 late wet season when standing water was absent during the crop's reproductive stage (Figs 1 and 2). In the latter season, the yield gap was wider at the top and upper middle toposequence positions than at the lower middle and bottom toposequence positions in the three villages (Fig. 4) where rainfall was normal (Table 2). However, the reverse was true in Sidomukti, where rainfall was below normal (Table 2), but, in response to that situation, planting date varied at different toposequence positions (Fig. 1.2). In this village, the average yield gap due to water (52%) was wider than in the other villages (11–25%).

In general, the wider yield gaps in the upper paddies were associated with the absence of standing water and deeper groundwater depths (Boling et al., 2007b). In Sidomukti, however, where younger seedlings were transplanted earlier in the top and upper middle toposequences, water deficits (indicated by deep groundwater depths) started later in the reproductive stage of the rice crops. The estimated yield gap in Sidomukti was within the range measured in farmers' fields by Wade et al. (1999a), but was wider than that measured at Jakenan Experiment Station (Setyanto et al., 2000; Boling et al., 2004). Flexible management practices, such as adapted planting dates, can be important to avoid drought stress.

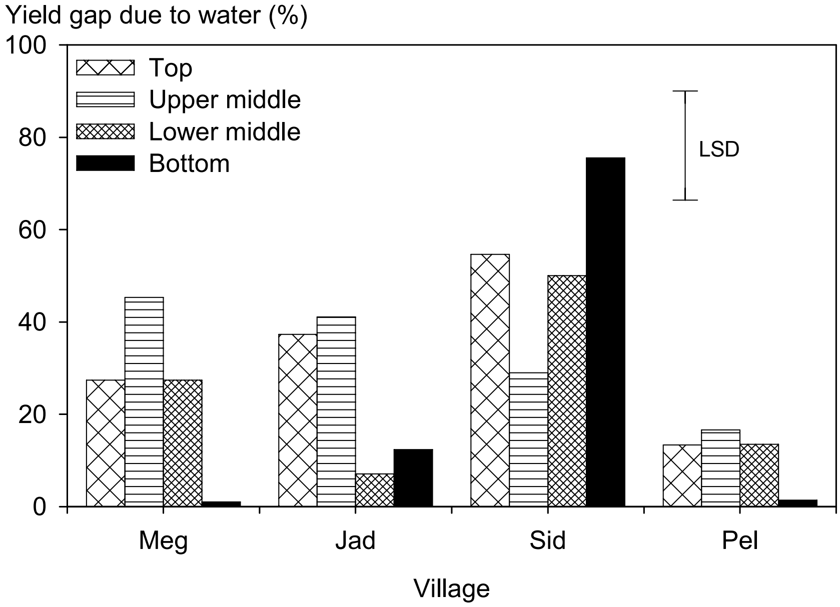

Figure 4. Yield gaps due to water deficit in plots with recommended fertilizer doses at different toposequence positions during the 2002 late wet season. Village codes are explained in Figure 3.

Yield gap due to nutrient limitation

In the 2001–02 early wet season (when the yield gap due to water deficit was narrow), the overall yield gap due to nutrient deficiency was 57% in non-fertilized plots, a value within the 41–64% range, measured by Wihardjaka et al. (1999) at Jakenan Experiment Station. Average yield gaps due to N, P, and K were 55%, 20%, and 53%, respectively. Yield gaps due to N in the top and upper middle positions were wider than in the lower middle and bottom toposequence positions in three of the four villages (Fig. 5a). Yield gaps due to K were similar among toposequence positions, but were narrower in Jadi (28%), where high exchangeable K (0.15 $cmol_c$ kg^{-1}) was recorded, than in the other villages (56–66%, Fig. 5b). In farmers' fields, the yield gap estimates due to N were 13%, to P 16%, and to K 17% higher than the upper limits measured at the Experiment Station by Mamaril et al. (1995), Wihardjaka et al. (1999), and Boling et al. (2004).

In non-fertilized plots, average crop N uptake across seasons (Figs 6a and 6c, quadrant *ii*) in the top and upper middle positions (26 kg ha^{-1}) was lower than in the lower middle and bottom positions (41 kg ha^{-1}). In the 2002 late wet season, average crop K uptake increased from 30 kg ha^{-1} in the top to 39 kg ha^{-1} in the bottom position (Fig. 6d, quadrant *ii*), but this difference was not observed in the 2001–02 early wet season (Fig. 6b, quadrant *ii*). The differential N uptake in both seasons and K uptake in one season among toposequences was attributed to the field-water conditions (Boling et al., 2007b), whereas for N also the higher organic carbon contents in the lower toposequence positions may have played a role.

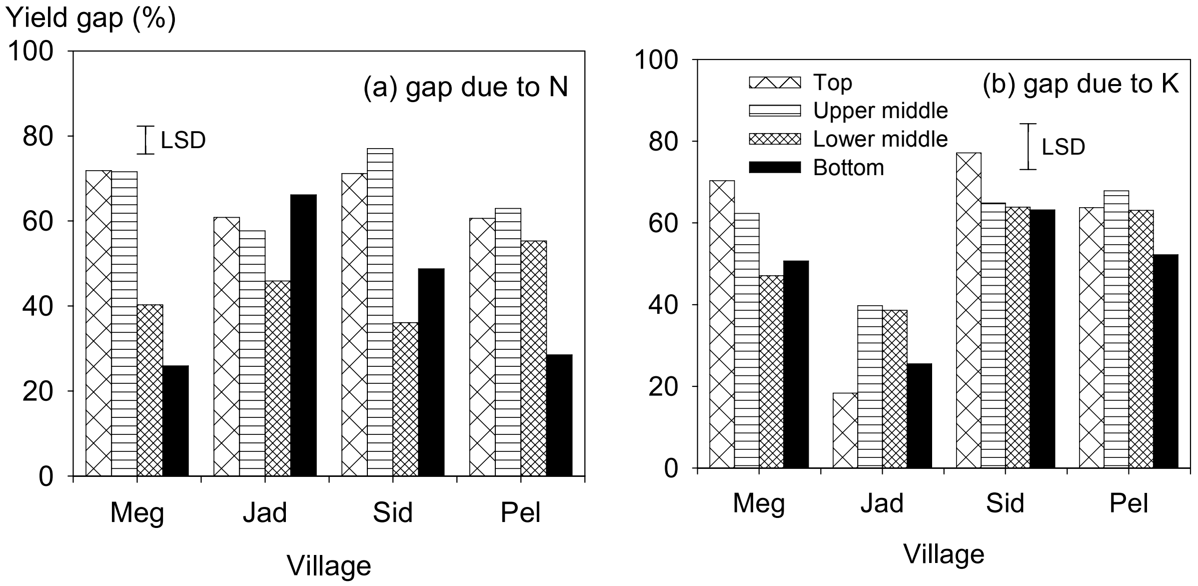

Figure 5. Yield gaps due to N (a) and K (b) deficiency in non-fertilized plots in different toposequence positions during the 2001–02 early wet season. Village codes are explained in Figure 3.

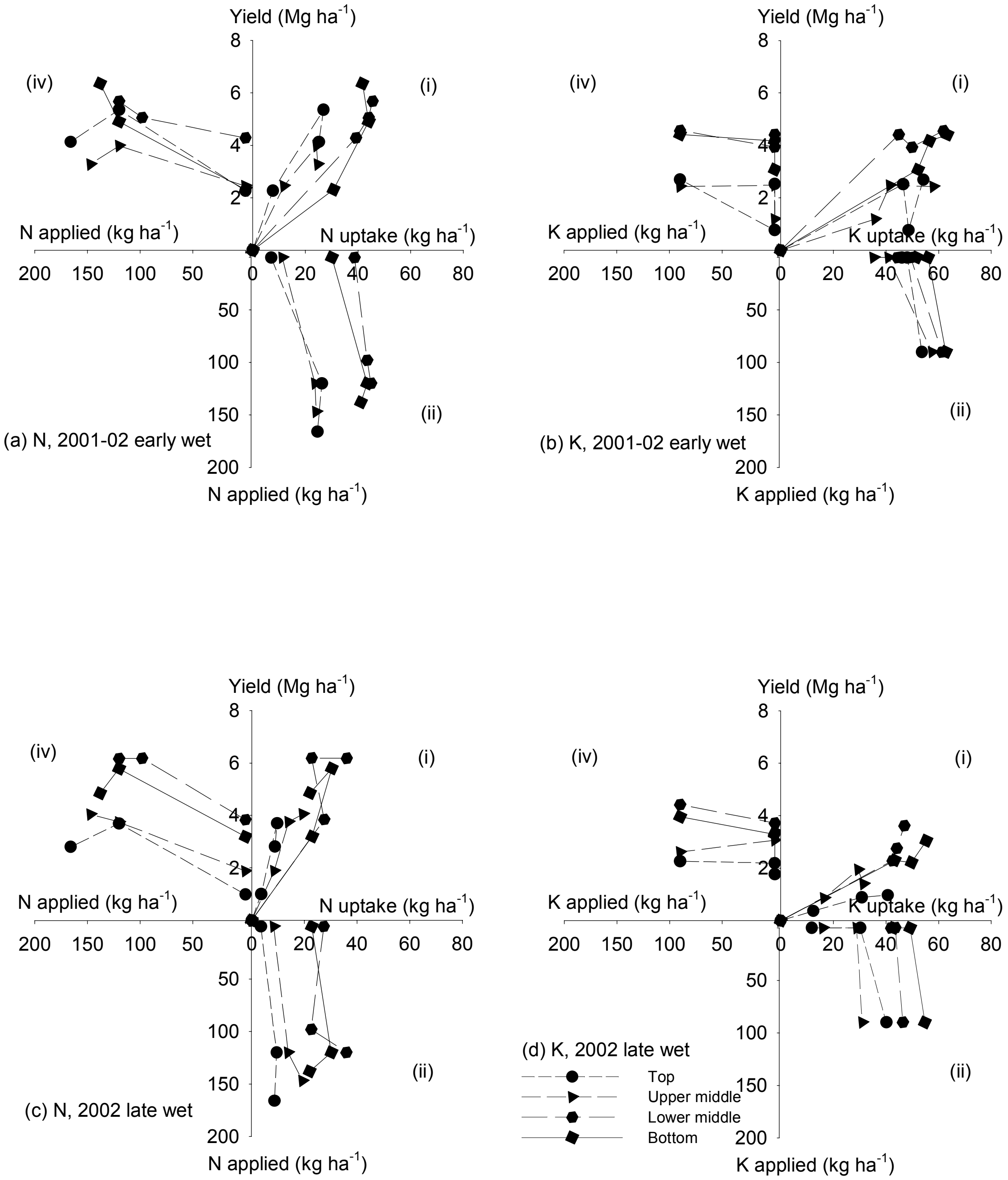

Figure 6. Yield (Mg ha^{-1}), plant N (a, c) and K (b, d) uptake (kg ha^{-1}), and fertilizer applied (kg ha^{-1}) in a representative village (Jadi) and 2001–02 early wet (a, b) and 2002 late wet (c, d) seasons.

The generally high indigenous soil N, P, and K supplies in farmers' fields are consistent with earlier findings in experimental fields in Indonesia (Boling et al., 2004), but are not representative for most rainfed lowland areas in Asia (Wade et al., 1999a; Naklang et al., 2006).

Recoveries for chemical N- and K-fertilizers varied slightly among seasons and villages (Fig. 6, quadrant *ii*), but were low (0.15–0.25 for N; 0.13–0.29 for K) in all situations, although comparable to the lower quartile values reported from irrigated systems (Dobermann and Fairhurst, 2000). In the 2001–02 early wet season, the low recovery of N fertilizer (Figs 6a and 6b, quadrant *ii*) could be associated with the relatively dry soil conditions until panicle development (Fig. 2). In the 2002 late wet season, slightly higher proportions of the N and K fertilizers were taken up (Figs 6c and 6d, quadrant *ii*), but that did not lead to increased production (Figs 6c and 6d, quadrant *iv*), presumably due to water limitations during the reproductive stage of the crop (Figs 1 and 2). The low recoveries of N and K were associated with concentrations of 0.75% N, 0.09% P, and 1.74% K in the straw, well above the minimum values associated with deficiency of the elements (Van Keulen, 1977). These relatively high values could also be associated with water deficits during the grain-filling phase, negatively affecting the translocation of nutrients from straw to grain. The average P:N ratio in straw was 0.11, which is close to the optimum (Van Keulen, 1986; Van Duivenbooden et al., 1996), whereas the K:N ratio was 2.37, which is relatively high. These values do suggest a fairly balanced supply of the three macro-nutrients, with a tendency for a relatively abundant K supply.

Resource use efficiencies

In non-fertilized plots, average grain production per unit rainfall recorded (rainfall use efficiency) was 4.37 kg ha^{-1} mm^{-1}. In both seasons, rainfall use efficiency in the top and upper middle positions was lower than in the lower middle and bottom toposequence positions (Fig. 7). Rainfall use efficiency represents a very crude measure of water use efficiency, as it expresses both the partitioning of rain between use by the crop (transpiration) and other processes, such as runoff/run-on, percolation, and soil surface evaporation (Van Keulen and Van Heemst, 1982), and the efficiency with which water is 'converted' into dry matter and the partitioning between vegetative (straw) and reproductive (grain) organs. Average grain production per unit of transpiration (water productivity), calculated in ORYZA, was similar among the toposequence positions (data not shown) at 7.56 kg ha^{-1} mm^{-1}. The difference in toposequence response between rainfall use efficiency and water productivity illustrates the difference in partitioning between transpiration and the other hydrological processes among toposequence positions.

Average grain production per kg crop nutrient uptake (internal or physiological nutrient use efficiency), similar among toposequence positions, was 65 for N, 288 for P, and 75 for K. The values for N and K are similar to those reported for irrigated rice crops, whereas the values for P are distinctly lower (Dobermann and Fairhurst, 2000).

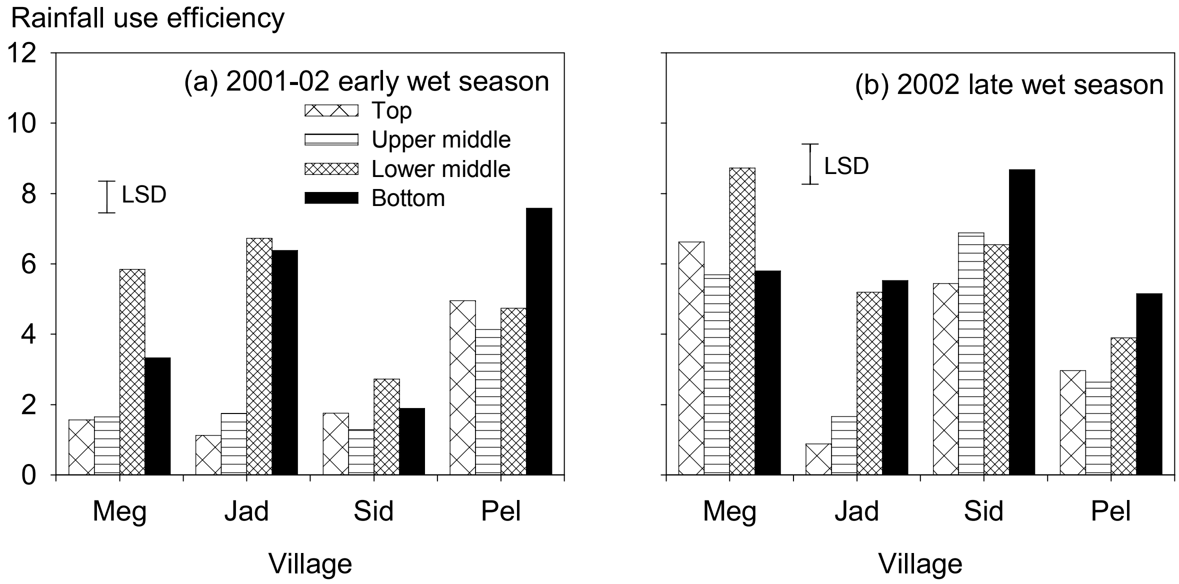

Figure 7. Rainfall use efficiency (kg ha^{-1} grain mm^{-1} rainfall) at four toposequence positions during (a) 2001–02 early wet and (b) 2002 late wet seasons in non-fertilized plots. Village codes are explained in Figure 3.

Average nutrient requirements per Mg of grain (nutrient removal) in non-fertilized plots, again similar for the different toposequence positions, were 16 kg N, 3.6 kg P, and 14 kg K, values comparable with those for optimum to high nutrient availability levels in irrigated rice (Dobermann and Fairhurst, 2000).

Conclusions

Farmers' fields of rainfed rice along toposequences in Indonesia showed high spatial and temporal variation in hydrology (354 to 1235 mm seasonal rainfall, –150 to 50 cm water depth) and farmers' fertilizer doses (76–166 N, 0–45 P, and 0–51 kg K ha^{-1}). The wide range in hydrological conditions and the associated differences in management during the experimental period illustrate the complexity of rainfed rice systems, requiring careful characterization for accurate interpretation of results and their implications.

In one (2002 late wet) season, simulated rainfed (or water-limited) rice yields were 28% lower than the simulated yield potentials. The simulated yield gap due to water limitation was 52% in one village (Sidomukti), where rainfall was below normal (P = 0.88). In three out of the four villages, the yield gap due to water was wider in the upper toposequence positions than in the lower positions. Especially in upper toposequence positions of many rainfed rice ecosystems, water shortage is probably the strongest yield constraint.

In the 2001–02 early wet season, the calculated yield gap due to N, P, and K deficiency in non-fertilized plots was 55%, 20%, and 53%, respectively. The yield gap due to N was similar among villages, but wider in upper toposequence positions. On the other hand, the yield gap due to K was substantial in three villages, whereas, in Jadi (where exchangeable K was relatively high) it was rather narrow, and relatively higher in upper toposequence positions. N and K limitations are among the major yield constraints in rainfed lowland rice in farmers' fields in Indonesia.

The relative limitations of water, N, and K in farmers' fields are similar to those observed at the Jakenan Experiment Station, located in the vicinity of the villages. However, their relative importance may vary strongly among rainfed rice areas and, as shown here, among toposequence positions and among seasons. Integrated assessment, taking into account all possible yield-determining, -limiting, and -reducing factors (Van Ittersum and Rabbinge, 1997) and their interactions, is necessary to identify yield constraints in other rainfed lowland areas of South and South-east Asia as a basis for the identification of management options for increasing productivity and yield stability. Such management options are time- and location-specific and 'response farming' (Stewart, 1986) could therefore be a promising option for these environments.

CHAPTER 6

General discussion

Objectives of the study

This study aimed at improving understanding of spatial and temporal variations in water status and nutrient availability, and their effects on crop growth and yield along toposequences in rainfed lowland rice ecosystems in Southeast Asia, as a basis for the design of improved crop management strategies. We used a combination of statistical and systems analyses, based on a combination of field experiments in research stations (on-station experiments) and in farmers' fields (on-farm experiments) and simulation modelling.

Methodological strengths and weaknesses

Reference (potential, water-limited, or nutrient-limited) yield levels can be determined using field experiments (Chapter 2), simulation modelling (Chapter 3), and physiological nutrient use efficiencies (Chapter 5). These methods are complementary and the results can be integrated to derive comprehensive information on yield gaps of rainfed lowland rice. The strengths and weaknesses of these yield estimation methods are as follows.

Field experiments and statistics

In Jakenan Experiment Station, high temporal variation in rainfall (see Table 2 in Chapter 3), soil nutrient supply, and pest conditions was observed during the experimental period of 1995–2000, i.e. for rainfall from below-normal ($P \geq 0.80$) in the 1997–98 early wet and the 1995–96 late wet seasons to above-normal ($P < 0.20$) in the 1999–2000 early wet and 1998–99 late wet seasons. The on-station experiments also showed temporal variation in environmental conditions at a given location. However, these experiments could not be used to explore the effects of spatial variability in rainfed lowland rice environments.

Experiments in farmers' fields in Indonesia and Thailand, during 2000–02, not only showed temporal, but also spatial variability in rainfall (Fig. 1), field water depths, soil chemical and physical properties, crop biomass, and yield (Chapter 4). As in the research station, rainfall varied from below-normal (2001–02 early wet season in Megulung village and 2002 late wet season in Sidomukti village, Indonesia) to above-normal (2001–02 wet seasons in Thailand). In the 2002 late wet season, when rainfall in Sidomukti village was below-normal, rainfed rice yields in non-fertilized plots

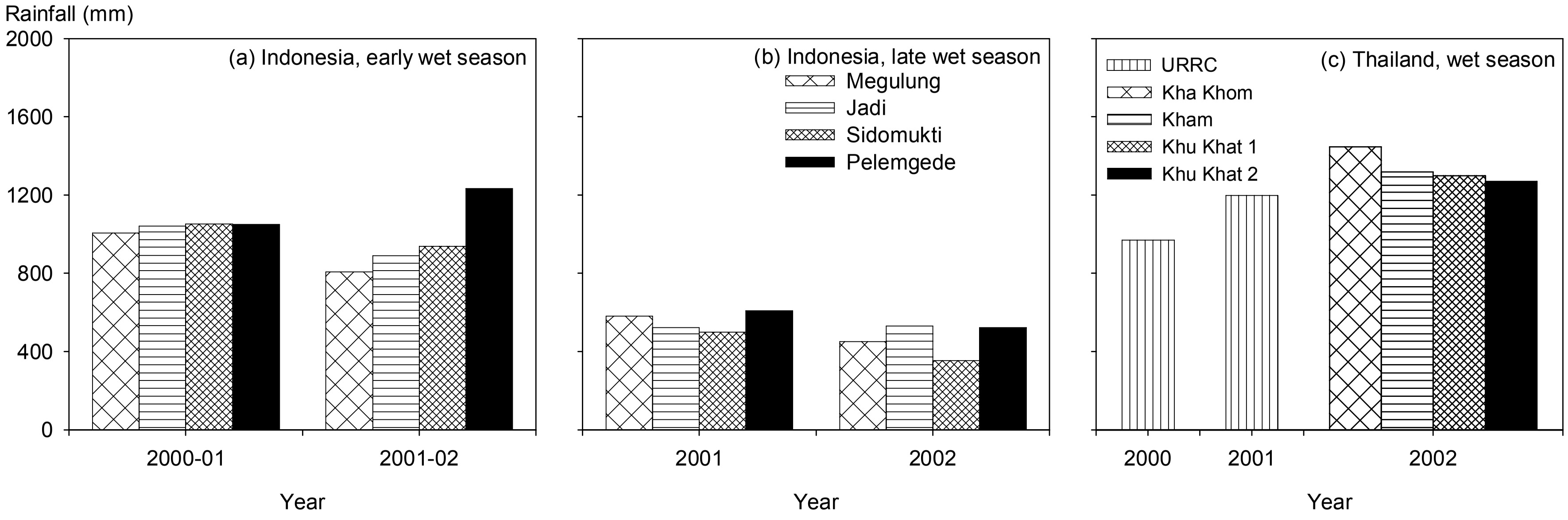

Figure 1. Seasonal rainfall in Indonesia (a, b) and Thailand (c), 2000–02. [In Thailand, rainfall data for 2000–01 were recorded only at the Ubon Rice Research Center (URRC)].

ranged from 0.90 to 1.20 Mg ha^{-1}. Yields from N, P, K omission plots or from irrigated plots that might have been used for comparative purposes, were not available.

Statistical analyses of measured crop, soil, and hydrological characteristics from multi-location, multi-season experiments reveal temporal and spatial variations in field hydrology, soil properties, yield, and yield increase due to weed and fertilizer management (Chapter 4). However, the experimental approach is expensive and time-consuming, and is subject to the vagaries of the weather. Furthermore, the absence of measured reference yield levels makes analysis of yield gaps due to yield-limiting and yield-reducing factors difficult in farmers' fields. Therefore, there is a need for indirect methods for calculating reference yields.

Simulation modelling

The ORYZA2000 model adequately simulated rice yields in Jakenan Experiment Station over a wide range of N levels under irrigated and rainfed conditions (Chapter 3). Simulation modelling allows establishment of site-specific reference yield levels that cannot easily be measured in field experiments. For example, simulated potential yields in Jakenan ranged from 3.74 (for crops sown in October) to 5.53 Mg ha^{-1} (for crops sown in July). Simulation modelling can be used to generate information that complements the limited field measurements, and can be used in spatial and temporal analyses of yield constraints in rainfed rice ecosystems. The use of this approach, however, may be limited by the availability of crop, soil, weather, and management input data required in the model.

Physiological nutrient use efficiencies

The potential yields (y) that were estimated using physiological efficiencies (β) and nutrient uptake (x) in well-watered nutrient omission plots were linearly related ($y = \alpha + \beta x$, $R^2 > 0.50$) and highly correlated ($r > 0.70$) with the measured values (Table 1). However, the root mean square errors (RMSE) for these estimated yield potentials are 56, 244 and 40%, respectively for the N-, P- and K-limited production situations. These RMSE values are well above the coefficient of variation of measured yields (19%).

In general, the goodness-of-fit parameters (Table 1) and the scatter diagrams for PK (N omission) and NP (K omission) plots (Fig. 2) showed a relatively close association between estimated (using physiological efficiency) and measured yields. These results indicate reasonable adequacy of using physiological efficiency to estimate reference yield under N- and K-limited production situations. The results are consistent with the findings of Van Keulen (1982, 1986), Van Duivenbooden et al. (1996), and Dobermann and Fairhurst (2000) who used this method to formulate fertilizer recommendations for rice and other crops. The very high RMSE (244%) of estimated yield for the P omission

Table 1. Evaluation results for estimated yield potentials based on physiological nutrient use efficiencies and crop nutrient uptake in nutrient omission plots under well-watered conditions in Jakenan Experiment Station, 1997–2000.

Description			Unit	Production situation		
				N omission	P omission	K omission
Sample size	*n*		number	24	24	24
Range	minimum		Mg ha^{-1}	2052	5884	964
	maximum		Mg ha^{-1}	5643	19720	5127
Regression	α	$\alpha+\beta x$	Mg ha^{-1}	1887	6277	646
	β	$\alpha+\beta x$	-	0.66	1.57	0.70
	R^2	$\alpha+\beta x$	-	0.66	0.50	0.60
Correlation	*r*		-	0.81	0.71	0.77
Deviation	RMSE		Mg ha^{-1}	1288	8741	992
	RMSE		%	56.18	243.60	39.58

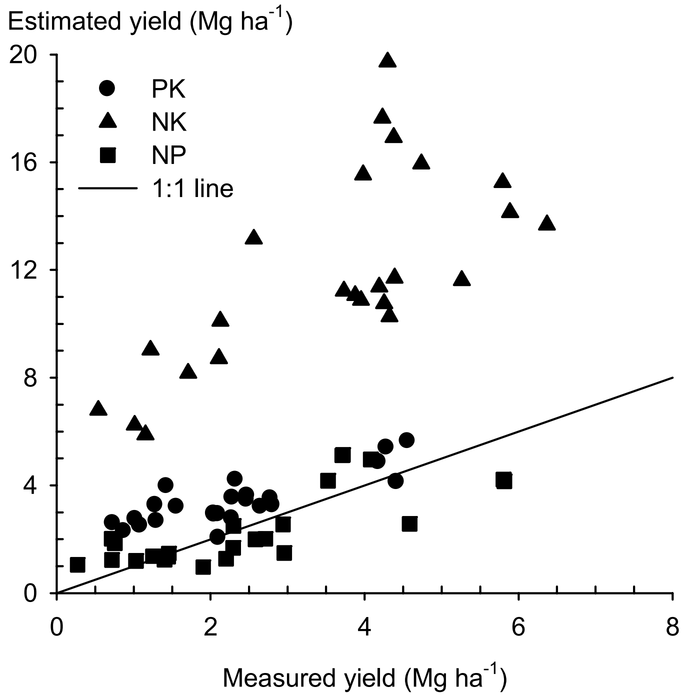

Figure 2. Scatter diagram of estimated yield based on theoretical physiological nutrient use efficiencies and measured grain yield for PK (0-22-90 kg NPK ha^{-1}), NK (120-0-90 kg NPK ha^{-1}), and NP (120-22-0 kg NPK ha^{-1}) plots under irrigated conditions in Jakenan Experiment Station, 1997–2000.

plots indicates very strong variation in indigenous soil phosphorus supply. For locations with a (very) high indigenous phosphorus supply, physiological use efficiency was very low, e.g. 260 kg grain kg^{-1} P, compared to values of 525 kg grain kg^{-1} P in phosphorus-limited situations. Hence, indigenous nutrient supply needs to be carefully checked prior to the use of physiological efficiency to estimate yields.

The method, thus, has potential to combine the findings of on-station experiments with those from farmers' fields to analyse yield gaps and constraints to yield, allowing the analysis to be extended to many more field locations than is possible with experimentation in farmers' fields.

Results of applying these methodologies to rainfed lowland rice

Yield constraint analysis

There was a wide gap between measured yields in rainfed farmers' fields and simulated potential yields (48%), suggesting considerable scope for increasing yields through alleviating biophysical, socio-economic, and technical constraints.

Spatial and temporal variability

Toposequence position had strong and consistent effects on field hydrology, soil clay content, exchangeable K, and organic C (Chapter 4). However, grain yield and the effect of yield-increasing interventions were not only dependent on toposequence position. The effects of yield-increasing measures (for limiting factors) and yield-protecting measures (for reducing factors) varied in time (day, season, year) and space (toposequence position, village, country). Resource use efficiencies in dependence of sowing date, supplementary irrigation, tillage management, fertilizer application, and pest control also varied in time and space.

Yield-limiting factors

In Indonesia, the yield-limiting factors (water, N and K availability) identified at Jakenan Experimental Station (Chapter 2) were also found to be yield-limiting in the surrounding farmers' fields (Chapter 5), despite the differences in methodology and measurement period.

When rainfall was below-normal ($P > 0.80$), the yield gap due to water limitation in plots with recommended fertilizer doses was 23% in the 1997−98 early wet season at the research station and 28% in the 2002 late wet season in farmers' fields in Sidomukti village. Under severe drought ($P = 0.98$) in the 1996 late wet season, the yield gap due to water limitation reached 85% at the research station. These results confirm that water is a major yield-limiting factor in rainfed lowland rice areas.

The average yield gap due N limitation was 42% at the research station and 55% in farmers' fields. Similarly, the average yield gap due to K limitation was 33−36% at the research station and 53% in farmers' fields. The effects of nutrient limitations in normal-to-above normal rainfall conditions were weaker than the effects of water limitation in severe drought situations. In farmers' fields, the effects of nutrient limitations at the top toposequence positions were relatively stronger than at the bottom positions. Thus availability of water and indigenous supply of N and K limited rice yields in the rainfed lowland areas included in our study.

Average yield gap due to P was 3−4% in the research station and 20% in farmers' fields. The relatively high indigenous soil P supply resulted in low physiological efficiencies in both, non-fertilized plots in farmers' fields (315 kg grain kg^{-1} P) and in P-omission plots in the research station (260 kg grain kg^{-1} P) (Dobermann and Fairhurst, 2000). Hence, the estimated yield gaps due to P limitation in farmers' fields are artefacts, associated with the use of physiological nutrient use efficiencies that are applicable only in P-limited situations.

Yield-reducing factors

In two out of the three late wet seasons included in the experiments, 20% of the panicles were damaged by insect pests, causing yield losses estimated at 56−59% in irrigated and well-fertilized treatments at the research station (Chapter 2). Insect pests occurred only when rice crops in the experimental station were established later than in the surrounding farmers' fields and may thus be considered an artefact associated with the later planting of the experimental trials, and not representative of the farmers' fields.

In farmers' fields, the yield gap due to weed infestation averaged 0.65 Mg ha^{-1} (12%), and was statistically the same across toposequence positions and seasons. In non-weeded plots, average yield gaps due to the combined effect of weed infestation, water and nutrient limitation amounted to 2.88 Mg ha^{-1} (60%). Thus, weed infestation also appears a major yield-constraining factor in the rainfed lowland rice areas included in our study.

Suggested management interventions

The wide and consistent yield gaps due to water and nutrient limitations, and pest infestations in both, the research station and in farmers' fields suggest specific management interventions that could lead to higher rice yields under rainfed conditions. The relative importance of water, N and K limitations varied strongly among toposequence positions, villages, and seasons, thus, crop management in rainfed rice areas cannot be toposequence-position-specific, but must be site-, growth stage-, and season-specific (Buresh, 2007). The degree of adoption of such management interventions and thus the realization of the associated yield, however, depends on investments in infrastructure, on policies and on institutional arrangements (Rosegrant et al., 2002; Von Braun, 2006), that include irrigation or water harvesting facilities, fertilizer subsidies, rice trade and pricing policies, and strong partnerships among the agents of change (researchers, extension workers, farmers, community leaders, policymakers, NGOs).

Yield-increasing measures

In Indonesia, the critical planting date of the late wet season crop in situations with shallow water table depths was early April, with medium water table depths mid-March, and with deep water table depths early March, suggesting that higher yields can be attained by timely planting in situations with deeper water tables.

Supplementary irrigation when the moisture content of the top soil fell below field capacity (application of 7.5 mm water each time) increased rainfed rice yields of late wet season crops, by around 0.7 Mg ha^{-1} for crops sown in February in areas with deep water tables and 1.2–3.1 Mg ha^{-1} for crops sown in April under shallow groundwater depths. The results also suggest that supplementary irrigation would increase fertilizer use efficiency in farmers' fields for late-sown crops and for earlier sown crops in deep water table situations.

Deep tillage increased the yields of rainfed rice sown towards the end of the wet season. The yield increase due to deep tillage of crops sown in late April peaked at about 2.5 Mg ha^{-1} in shallow water table situations, compared with 1.9 Mg ha^{-1} for crops sown in late March in deep water table situations. Hence, deep tillage could be an option for increasing yields for later sown crops.

Application of 120 kg N ha^{-1} increased rainfed lowland rice yields in N omission plots by an average of 1.94 Mg ha^{-1}, with higher increases with shallow than with deep groundwater tables, indicating the interaction between water availability and nitrogen availability. Application of 90 kg K ha^{-1} increased rainfed rice yields in K omission plots by 1.57 Mg ha^{-1}. Farmers' current fertilizer management increased yields in non-fertilized plots by 0.78 Mg ha^{-1}. Application of the recommended 120-22-90 NPK fertilizer increased yields of non-fertilized plots by 1.25 Mg ha^{-1}. These results suggest considerable potential to increase yields of rainfed lowland rice through application of recommended rates of N and K fertilizers, but that there is no need to use compound fertilizers containing P, because of the lack of response to P due to the high indigenous P supply in the study areas.

However, fertilizer response depends on water availability and the erratic nature of rainfall in many of the rainfed environments represents a major risk factor for fertilizer application.

Yield-protecting measures

In Indonesia, timely crop establishment for late wet season crops not only helped in avoiding water limitations, but also in avoiding yield losses due to pest and diseases. The results suggest that identification of optimum planting times is important for narrowing the yield gap in rainfed lowland rice environments.

Farmers' current weeding practices resulted in yield increases of non-weeded plots by 0.69 Mg ha^{-1} across toposequence positions, villages, and seasons, and more intensive weeding did not result in further yield increases.

Conclusions and recommendations

- Combining various methodologies in estimating reference yields provides increased understanding of the constraints in rainfed lowland rice production and the combination of these tools could be applied to other locations in identifying yield constraints and management options to increase production, provided that the necessary experimental data required for such a comprehensive analysis are available.
- There are substantial differences in field hydrology (depth of ponded surface water and depth of the water table, number of days without ponded surface water), exchangeable K, organic C, and clay content among different positions along a toposequence. Differences in other soil properties (N, P, CEC, pH, sand, silt, bulk density), yield, and magnitude of yield increase in farmers' fields due to superimposition of intensive weed control and/or recommended fertilizer application were also observed, but these differences were not consistent across countries, seasons, and years.
- In Indonesia, wide and consistent yield gaps due to water and nutrient (N, K) limitations were estimated, as well as differences in pest (insects, weeds) infestations in the research station and in farmers' fields, suggesting site- and season-specific interventions that could lead to higher rainfed rice production. Yield-increasing measures include variation in planting date, deep tillage, supplementary irrigation and application of N and K fertilizers, while yield-protecting measures include variation in planting date and weed control.

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Summary

More than half of the world's population eats rice and rice is the staple food in Asia. In recent years, the world's population has been growing at 1.2% per year, compared to a growth in rice yield of about 0.7%. Furthermore, the proportion of the total area cropped to rice decreased from 26% in 1980 to 23% in 2004 in Southeast Asia. All these factors are increasing the pressure to raise crop yields, particularly from crops grown under less favorable, such as rainfed, conditions, where current yield levels are well below climatically determined potentials. In Asia, rainfed rice is grown on approximately 59 Mha, 44% of the total rice area. Average yield of rainfed lowland rice is low at 2.1 Mg ha^{-1}, and productivity is generally hampered by uncertain water supply, low soil fertility, and pest (insects, pathogens, weeds) infestation. Pest infestation, nutrient stress, drought, and their interactions often occur simultaneously in rainfed systems. To design management interventions aimed at increasing productivity in rainfed areas, the magnitude of and variation in yield gaps, associated with various constraining factors along toposequences in rainfed lowland areas need to be assessed.

This study aimed at improved understanding of spatial and temporal variations in water status and nutrient availability, and their effects on crop growth and yield of rainfed lowland rice along toposequences in Southeast Asia, as a basis for the design of improved crop management strategies. To address these objectives, the concepts of production ecology were applied to rainfed lowland rice. Statistical and systems analyses, based on a combination of field experiments and simulation modelling were used to quantify the effects of yield-determining, yield-limiting, and yield-reducing factors. The results were used to identify site- and time-specific resource management options along toposequences in sloping rainfed rice areas. Three sets of field experiments were conducted: two in research stations and one in farmers' fields. Experiment 1, on water and tillage effects, was conducted in 1995–96 at Jakenan Experiment Station, Central Java, Indonesia (6°47′ S, 111°12′ E, 8 m above sea level). Experiment 2, on water and fertilizer effects, was also conducted at Jakenan Experiment Station, in 1997–2000. Experiment 3, on the variability of water status, soil chemical and physical properties, crop biomass and yields along toposequences, was conducted in 2000–02 in farmers' fields surrounding the Jakenan Experiment Station, Indonesia and surrounding the Ubon Ratchathani Rice Research Center, Northeast Thailand (15°19′ N, 104°40′ E, 127 m above sea level).

First, yield constraints of rainfed lowland rice at Jakenan Experiment Station were identified, based on statistical analyses of measured crop, soil, and hydrological

characteristics during pest-free seasons, and on systems analysis during seasons when pests could not be adequately controlled by recommended practices. The yield losses in rainfed rice caused by the interactive effects of drought and nutrient stress were quantified, also taking into account the incidence of rice pests. In one (1997-98 wet season) out of six seasons, rainfed rice yields were 20–23% lower than those of irrigated rice. Nitrogen and potassium significantly influenced rice yields and biomass production at Jakenan. Compared to optimal nutrient conditions, average yield reduction due to N omission was 42%, and 33–36% due to K omission. Pests are major threats for late wet-season rice in Jakenan. In two of the three late wet seasons, estimated yield losses due to pests were 56–59%.

Subsequently, the ORYZA2000 model was calibrated and evaluated for rainfed lowland rice. The model was calibrated using the crop, soil, and hydrological characteristics measured in Experiment 1. Model performance was then assessed using the crop, soil, and hydrological characteristics from Experiment 2. The ORYZA2000 model adequately simulated field water depth, soil water tension, above-ground biomass, and grain yield of rice at various levels of fertilizer N under both irrigated and rainfed conditions in the study area. The calibrated model was used to simulate potential yield, which was subsequently used as a reference in analysing yield gaps due to yield-reducing factors (insect pests and pathogens) at the research station and yield-limiting factors in farmers' fields.

The ORYZA2000 model was used to explore potential and rainfed rice yields for shallow, medium, and deep water table scenarios. Simulated potential yields ranged from 3.74 (for early wet season crops sown in October) to 5.53 Mg ha^{-1} (for dry season crops sown in July). The potential yield of dry-season rice was higher than that of wet-season rice because of higher radiation levels during the grain-filling period. Simulated yields of rainfed crops sown from early November to mid-March were significantly affected by water table depth. Rainfed yields reached potential with a shallow water table, but were lower with deep water tables.

ORYZA2000 was also used to assess the effect of water table depth on rice yield under various management interventions (sowing date, tillage, supplementary irrigation and nitrogen fertilization) as a basis for formulation of optimal management recommendations for different water table depths in the rainfed areas of Central Java, Indonesia. Simulated rainfed rice yields sharply declined for crops sown towards the end of the rainy season. This decline in yield of late wet-season rice with late planting emphasizes the importance of identifying the critical planting dates in different water table depth situations. The simulation results indicated that the critical planting date was early April in situations with a shallow water table, compared to mid-March for medium water table depths, and early March for situations with deep water tables.

Water table depth also had a clear impact on responses to tillage, fertilizer application, and supplementary irrigation of rainfed rice sown towards the end of the wet season. In situations with shallow water tables, potential yields could be attained for sowings until late March and deep tillage had no impact on yield. However, when sowing was delayed until late April, deep tillage increased yields by 2.5 Mg ha^{-1}, because of increased capillary rise compared to conventional tillage. In situations with shallow and medium water table depths, application of 120 kg N ha^{-1} resulted in a yield increase over no fertilizer-N application of about 1 Mg ha^{-1} for sowings from November to January, increasing to 1.4 Mg ha^{-1} for later sowings from around early March. With a deep water table, yield was limited by water availability and addition of 120 kg N ha^{-1} resulted in a yield increase of about 0.8 Mg ha^{-1} for early sowings in November and December. With a shallow water table, supplementary irrigation increased yields for sowings from late March onward, increasing for sowings from April onward. For these very late sowings, yield increases ranged from 1.2–3.1 Mg ha^{-1} when 7.5 mm of irrigation water was applied each time the moisture content of the topsoil (0–5 cm) fell below field capacity (I_1); and from 1.4–2.4 Mg ha^{-1} with daily irrigations of 7.5 mm from panicle initiation (PI) till maturity (I_2). In situations with deep water tables, yield responses to irrigation started for sowings in early February, varying from about 0.7 Mg ha^{-1} in I_1 and 0.3–0.5 Mg ha^{-1} in I_2.

Variations in soil properties, hydrological conditions, crop yield and biomass were analysed at different toposequence positions in rainfed rice areas with similar seasonal rainfall levels (Experiment 3). These areas represent the most common rainfed rice cropping system (one rainfed rice crop in Thailand) and the more intensive rainfed rice system (two rainfed rice crops in Indonesia). There were substantial differences in field hydrology (depth of ponded surface water and depth to the water table, number of days without ponded surface water), exchangeable K, organic C, and clay content among toposequence positions. There were also differences in other soil properties (N, P, CEC, pH, sand, silt, bulk density) and in yield, and in the magnitude of yield increase in farmers' fields due to superimposition of intensive weed control and/or recommended fertilizer application among toposequence positions, but these effects were not consistent across countries, seasons, and years.

There was a significant relationship between hydrological conditions and toposequence position: plots at the top of the toposequence were consistently drier than those at the bottom. Yields in plots with the same treatment were statistically similar across toposequence positions in 6 out of 11 combinations of season and control treatment in two countries. However, yield differences in non-fertilized plots were observed across toposequence positions in two (2001–02 early wet, 2002 late wet) out of four seasons in Indonesia and in two (2001 and 2002) out of three wet seasons in

Thailand. Similarly, yield differences across toposequence positions in Indonesia were observed in non-weeded plots in one (2001–02 early wet) out of the four seasons. Yields were generally lower at the higher positions in the toposequences than in the lower positions. Average yield increases due to intensive weed control (0.65 Mg ha^{-1}) or application of recommended fertilizer doses (1.25 Mg ha^{-1}) were similar across toposequence positions. These results indicate that toposequence position can not be used as the sole basis for formulation of recommendations for weed control and fertilizer application. Yield increases over blanket management recommendations across rainfed environments can only be realized by time- and field-specific management practices such as offered by site-specific nutrient management.

Subsequently, yield constraints of rainfed rice in farmers' fields at different toposequence positions were identified. The effects of yield-determining and yield-limiting factors on rice yields at different toposequence positions were quantified using the simulated yield potential as reference. Reference yields under nutrient-limited conditions in rainfed farmers' fields were also estimated based on plant nutrient uptake and theoretical physiological nutrient use efficiencies of rice.

Farmers' rice fields at different toposequence positions showed high spatial and temporal variation in hydrology (350–1446 mm seasonal rainfall, –150 to 50 cm water table depth) and farmers' fertilizer doses (76–166 N, 0–45 P, and 0–51 kg K ha^{-1}). In one (2002 late wet) season, simulated rainfed (or water-limited) rice yields were 28% lower than the simulated yield potential. The simulated yield gap due to water limitation was 52% in one village (Sidomukti), where rainfall was below normal. In 3 out of the 4 villages, the yield gap due to water was wider in the upper toposequence positions than in the lower positions. In the 2001–02 early wet season, the calculated yield gap due N-, P-, and K- deficiency in non-fertilized plots was 55, 20, and 53%, respectively. The yield gap due to N was statistically similar among villages, but wider in upper toposequence positions. On the other hand, the yield gap due to K was substantial (56–66%) in three villages, while in Jadi (where exchangeable K was relatively high) it was rather narrow (28%), and higher in upper toposequence positions. N and K limitations are among the major yield constraints in rainfed lowland rice in farmers' fields in Indonesia.

In the general discussion, the strengths and weaknesses of the methodologies used to estimate reference yields are compared. Yield-limiting and yield-reducing factors are identified by applying these methodologies to rainfed lowland rice at the research station and in farmers' fields. Management interventions aimed at increasing yields in rainfed rice systems that include yield-increasing measures for limiting factors and yield-protecting measures for reducing factors are suggested.

Statistical analyses of measured crop, soil, and hydrological characteristics in multi-location and multi-season experiments reveal differences in the effect of crop management on rice yield at different toposequence positions. However, the experimental approach is expensive and is subject to the vagaries of the weather. Furthermore, the absence of measured reference yield levels makes the yield gap analysis due to limiting and reducing factors difficult in farmers' fields. Therefore, there is a need for indirect methods for calculating reference yields, such as the use of crop models. The goodness-of-fit parameters and the scatter diagrams showed that the ORYZA2000 model adequately simulates yield at various levels of fertilizer N under irrigated and rainfed conditions in the study area. Simulation modelling can be used to quantify site-specific reference yield levels that can not be obtained from field experiments. The use of this approach, however, may be limited by the availability of crop, soil, weather, and management data required in the model. The goodness-of-fit parameters and scatter diagrams showed a relatively close association between estimated (using physiological nutrient use efficiencies) and measured yields in PK (N omission) and NP (K omission) plots. The use of physiological nutrient efficiencies in estimating yields has potential to bridge the findings from field experiments and farmers' fields. However, caution should be exercised in using physiological efficiencies in situations under high indigenous nutrient supply, such as for P in Central Java, Indonesia.

The wide gap (48%) between potential yield and actual yield using current practices in rainfed farmers' fields suggests considerable scope for yield increase based on the biophysical, socioeconomic, and technical possibilities. The wide and consistent yield gaps due to water and nutrient (N, K) limitations, and pest (insects, weeds) infestations in the research station and in farmers' fields suggest specific interventions that could lead to increased yields. Yield-increasing measures include variation in planting date, deep tillage, supplementary irrigation and application of N and K fertilizers, while yield-protecting measures include variation in planting date and weed control. The degree of adoption of such management interventions and thus the realization of the associated yield, however, depends on investments in infrastructure, on policies and on institutional arrangements that include irrigation or water harvesting facilities, fertilizer subsidies, rice trade and pricing policies, and strong partnerships among the agents of change (researchers, extension workers, farmers, community leaders, policy makers, NGOs).

Combining various methodologies in estimating reference yields provides increased understanding of the constraints to rainfed lowland rice production and could be applied to other locations to identify yield constraints and management options to increase production, provided that the necessary experimental data required for such a comprehensive analysis are available.

Ringkasan

Lebih dari setengah penduduk dunia makan nasi dan nasi merupakan makanan pokok di Asia. Saat ini, laju pertumbuhan penduduk dunia 1,2% per tahun, sedangkan pertumbuhan hasil padi sekitar 0,7% per tahun. Di Asia Tenggara, proporsi areal yang ditanami padi menurun dari 26% pada tahun 1980 menjadi 23% pada tahun 2004. Semua faktor ini menambah tekanan terhadap upaya peningkatan hasil padi terutama dari pertanaman di lingkungan suboptimal tadah hujan. Di Asia, padi sawah tadah hujan terdapat sekitar 59 juta ha, 44% dari luas total pertanaman padi. Hasil rata-rata padi sawah tadah hujan masih rendah yaitu 2,1 ton/ha. Rendahnya hasil tersebut disebabkan oleh ketidakpastian ketersediaan air, rendahnya kesuburan tanah, serangan organisme pengganggu tanaman (OPT). Serangan OPT, cekaman hara, kekeringan, dan interaksinya dapat terjadi secara simultan pada ekosistem sawah tadah hujan. Untuk merancang perbaikan cara pengelolaan lahan tadah hujan, bobot dan keragaman senjang hasil antar toposekuen pada daerah dataran rendah tadah hujan perlu dikaji.

Penelitian bertujuan untuk memperbaiki pemahaman tentang keragaman spasial (ruang) dan temporal (waktu) status air, ketersediaan hara, dan pengaruhnya terhadap pertumbuhan dan hasil tanaman pada ekosistem padi sawah tadah hujan pada toposekuen yang berbeda di Asia Tenggara. Informasi ini selanjutnya digunakan sebagai dasar untuk merancang perbaikan strategi pengelolaan tanaman padi. Untuk tujuan tersebut, konsep ekologi produksi diterapkan pada padi dataran rendah tadah hujan. Analisis statistik dan analisis sistem berdasarkan kombinasi beberapa percobaan lapang dan model simulasi digunakan untuk menghitung pengaruh faktor-faktor penentu-hasil, pembatas-hasil, dan pengurang-hasil, serta mengidentifikasi pilihan-pilihan pengelolaan sumberdaya spesifik waktu dan lokasi sepanjang toposekuen pada areal padi sawah tadah hujan berlereng. Tiga set percobaan lapang dilaksanakan: dua di dalam kebun percobaan dan satu di lahan petani. Percobaan 1 tentang pengaruh air dan pengolahan tanah dilaksanakan pada tahun 1995–96 di Kebun Percobaan Jakenan, Jawa Tengah, Indonesia (6°47’ LS, 111°12’ BT, 8 m dpl). Percobaan 2 tentang pengaruh air dan pupuk dilaksanakan pada tahun 1997–2000 juga di Kebun Percobaan Jakenan. Percobaan 3 tentang keragaman status air, sifat kimia dan fisika tanah, biomas tanaman dan hasil sepanjang toposekuen dilaksanakan pada tahun 2000-02 di lahan petani di sekitar Kebun Percobaan Jakenan, Indonesia dan di sekitar Pusat Penelitian Padi Ratchathani Ubon, Timur Laut Thailand (15°19’ LU, 104°40’ BT, 127 m dpl).

Kendala hasil padi sawah tadah hujan di Kebun Percobaan Jakenan diidentifikasi berdasarkan analisis statistik data pengukuran langsung parameter tanaman, tanah dan air selama musim tanam yang bebas hama. Kendala juga diidentifikasi berdasarkan analisis sistem selama musim tanam yang serangan hamanya tidak bisa dikendalikan dengan praktek-praktek yang direkomendasikan. Kehilangan hasil padi tadah hujan yang disebabkan oleh pengaruh interaksi kekeringan dan cekaman hara juga dihitung dengan mempertimbangkan serangan OPT. Dari enam musim tanam, ada satu musim (gogorancah 1997–98) yang menunjukkan hasil padinya 22–23% lebih rendah daripada hasil padi sawah irigasi. Nitrogen dan kalium berpengaruh nyata pada hasil padi dan produksi biomas di Jakenan. Dibandingkan dengan kondisi hara optimal, penurunan hasil rata-rata tanpa N adalah 42% dan tanpa K 33–36%. OPT merupakan ancaman utama pertanaman padi walik jerami di Jakenan. Pada dua dari tiga musim walik jerami, dugaan kehilangan hasil akibat OPT berkisar 56–59%.

Model ORYZA2000 digunakan untuk kalibrasi dan evaluasi model padi dataran rendah tadah hujan. Model dikalibrasi menggunakan parameter tanaman, tanah dan air yang diukur dari Percobaan 1. Keragaan model dikaji menggunakan data tanaman, tanah dan air dari Percobaan 2. Model ORYZA2000 terbukti layak digunakan untuk simulasi kedalaman air tanah, tegangan air tanah, biomas bagian atas permukaan tanah, dan hasil gabah pada berbagai tingkat pupuk N pada kondisi irigasi dan tadah hujan di areal percobaan. Model digunakan untuk mensimulasi potensi hasil yang digunakan sebagai acuan dalam menganalisis kesenjangan hasil akibat faktor-faktor pengurang-hasil (OPT) di kebun percobaan dan faktor-faktor pembatas hasil di lahan petani.

Model ORYZA2000 digunakan untuk mengeksplorasi potensi hasil dan hasil padi sawah tadah hujan pada skenario muka air tanah yang dangkal, sedang dan dalam. Hasil simulasi potensi hasil padi berkisar antara 3,74 (gogorancah yang ditanam bulan Oktober) dan 5.53 ton/ha (musim kemarau yang ditanam bulan Juli). Potensi hasil padi musim hujan lebih rendah dibandingkan musim kemarau karena lebih tingginya tingkat radiasi surya selama periode pengisian gabah. Simulasi menunjukkan hasil padi tadah hujan yang ditanam awal Nopember hingga pertengahan Maret berbeda nyata antar skenario tiga kedalaman muka air tanah. Hasil padi tadah hujan mencapai tingkat potensinya pada muka air tanah dangkal, dan lebih rendah pada muka air tanah dalam.

ORYZA2000 juga digunakan untuk mengkaji pengaruh kedalaman muka air tanah terhadap hasil padi pada berbagai cara pengelolaan (tanggal tanam, pengolahan tanah, pengairan dan pemberian pupuk N), dan untuk membantu merumuskan rekomendasi pengelolaan optimal untuk kedalaman muka air tanah yang berbeda pada areal tadah hujan di Jawa Tengah, Indonesia. Simulasi menunjukkan bahwa hasil padi sawah tadah hujan turun tajam bila tanaman ditanam mendekati akhir musim hujan. Penurunan hasil padi walik jerami yang ditanam terlambat menunjukkan pentingnya identifikasi tanggal tanam kritis pada kondisi kedalaman muka air tanah yang berbeda. Tanggal tanam kritis untuk pertanaman padi walik jerami dengan muka air tanah dangkal adalah awal April, pertengahan Maret untuk muka air tanah sedang, dan awal Maret untuk muka air tanah dalam.

Kedalaman muka air tanah memiliki dampak yang jelas pada tanggap tanaman terhadap pengaruh pengolahan tanah, pemberian pupuk, dan tambahan air irigasi untuk padi tadah hujan yang ditanam mendekati akhir musim hujan. Pada kondisi muka air tanah dangkal, hasil masih berada pada tingkat potensial untuk padi yang ditanam sampai akhir Maret dan pengolahan tanah dalam tidak berpengaruh terhadap hasil. Namun jika penanaman ditunda sampai akhir April, pengolahan tanah dalam akan meningkatkan hasil mendekati 2,5 ton/ha karena bertambahnya air kapiler. Pada muka air tanah dangkal dan sedang, pemberian 120 kg N/ha meningkatkan hasil sekitar 1 ton/ha dibandingkan perlakuan tanpa N untuk padi yang ditanam antara Nopember dan Januari, dan meningkat 1,4 ton/ha bila ditanam sekitar awal Maret. Pada muka air tanah dalam, hasil padi dibatasi oleh kekurangan air dan pemberian 120 kg N/ha hanya meningkatkan hasil sekitar 0,8 ton/ha untuk padi yang ditanam lebih awal di bulan Nopember dan Desember. Pada muka air tanah dangkal, irigasi tambahan mulai meningkatkan hasil pada padi yang ditanam akhir Maret ke depan dan berpengaruh besar terhadap kenaikan hasil bila penanaman dilakukan bulan April ke depan. Untuk periode tanam akhir ini, hasil meningkat antara 1,2–3,1 ton/ha jika 7,5 mm air irigasi diberikan tiap kali kandungan air tanah lapisan atas (0–5 cm) kurang dari kapasitas lapang (I_1); dan 1,4–2,4 ton/ha bila irigasi harian sebanyak 7,5 mm diberikan sejak fase inisiasi primordia hingga fase masak (I_2); Pada muka air tanah dalam, kenaikan hasil karena pengaruh irigasi mulai terjadi pada padi yang ditanam awal Februari, dengan peningkatan 0,7 ton/ha pada fase I_1 dan 0,3–0,5 ton/ha pada fase I_2.

Keragaman sifat tanah, kondisi hidrologi, hasil tanaman, dan biomas dianalisis pada posisi toposekuen yang berbeda di areal padi sawah tadah hujan dengan curah hujan musiman yang serupa (Percobaan 3). Areal tersebut mewakili areal dengan sistem pertanaman padi tadah hujan pada umumnya (satu pertanaman padi tadah hujan di Thailand) dan areal dengan sistem pertanaman yang lebih intensif (dua pertanaman padi tadah hujan di Indonesia). Ada perbedaan mendasar dalam hidrologi lapang (rata-rata tinggi genangan air dan kedalaman muka air tanah, jumlah hari tanpa genangan air), K-dd, C-organik, kandungan liat bergantung pada posisi toposekuen. Juga terdapat perbedaan pada sifat-sifat tanah yang lain (N, P, KTK, pH, pasir, debu, bobot isi tanah) pada hasil, atau pada bobot kenaikan hasil di lahan petani akibat pengendalian gulma secara intensif dan/atau pemberian pupuk berdasarkan rekomendasi, tetapi pengaruh tersebut tidak konsisten antar negara, musim, dan tahun.

Terdapat hubungan nyata antara kondisi hidrologi dan posisi toposekuen. Petak-

petak yang berada di toposekuen atas secara konsisten lebih kering dibandingkan dengan yang berada di bawah. Hasil pada petakan yang diberi perlakuan sama, secara statistik tidak berbeda nyata antara posisi toposekuen pada 6 dari 11 kombinasi musim dan perlakuan kontrol di 2 negara. Namun, perbedaan hasil pada petak-petak yang tidak dipupuk diamati antar posisi toposekuen pada 2 dari 4 musim di Indonesia (gogorancah 2001–02, walik jerami 2002) dan 2 dari 3 musim di Thailand (musim hujan 2001 dan 2002). Demikian juga, perbedaan hasil diamati pada petak-petak yang tidak disiang pada 1 dari 4 musim pada semua posisi toposekuen di Indonesia (gogorancah 2001–02). Hasil padi pada posisi toposekuen yang lebih tinggi biasanya lebih rendah dibandingkan toposekuen yang lebih rendah. Rata-rata kenaikan hasil (0,65 ton/ha) akibat pengendalian gulma secara intensif atau karena pemberian pupuk berdasarkan rekomendasi (1,25 ton/ha) tidak berbeda nyata antar posisi toposekuen. Ini menunjukkan bahwa posisi toposekuen bukan satu-satunya dasar yang dapat digunakan untuk menentukan keputusan pengendalian gulma dan pemberian pupuk. Perbaikan hasil akibat paket rekomendasi pengelolaan di berbagai lingkungan tadah hujan yang luas, hanya dapat terealisir dengan penerapan pengelolaan spesifik waktu dan tempat seperti yang ditawarkan pada pengelolaan hara spesifik lokasi.

Pengaruh faktor penentu-hasil dan faktor pembatas hasil terhadap hasil padi pada berbagai toposekuen dihitung menggunakan simulasi potensi hasil sebagai acuan. Hasil acuan untuk kondisi hara terbatas juga diestimasi berdasarkan serapan hara tanaman dan efisiensi penggunaan hara fisiologi untuk tanaman padi sawah tadah hujan di lahan petani.

Lahan padi petani pada berbagai posisi toposekuen mempunyai keragaman ruang dan waktu dalam hidrologi (350–1446 mm curah hujan musiman, –150–50 cm kedalaman muka air) dan takaran pupuk petani (76–166 N, 0–45 P dan 0–51 kg K/ha). Pada satu musim (walik jerami 2002) hasil simulasi padi tadah hujan 28% lebih rendah daripada potensi hasil simulasi. Senjang hasil pada simulasi diakibatkan oleh kekurangan air sebesar 52% di satu desa (Sidomukti), dimana curah hujan di bawah normal. Pada 3 dari 4 desa, senjang hasil akibat kekurangan air lebih lebar pada posisi toposekuen yang lebih tinggi dibandingkan posisi yang lebih rendah. Pada gogorancah 2001/02, senjang hasil akibat kahat N, P, dan K pada petakan yang tidak dipupuk masing-masing adalah 55, 20, dan 53%. Senjang hasil akibat N tidak berbeda nyata untuk semua desa, tetapi lebih lebar pada posisi toposekuen atas. Di lain pihak, senjang hasil akibat K lebar (56–66%) terjadi di 3 desa, sedangkan di Desa Jadi (dimana K-dd relatif tinggi) senjang hasil agak sempit (28%) dan relatif lebih lebar di bagian toposekuen atas. Kekurangan N dan K merupakan kendala hasil utama padi sawah tadah hujan pada lahan petani di Indonesia.

Kekuatan dan kelemahan dari metodologi yang digunakan untuk estimasi hasil acuan dibandingkan. Faktor-faktor pembatas-hasil dan pengurang hasil diidentifikasi dengan menerapkan metodologi di atas untuk padi dataran rendah tadah hujan di kebun percobaan dan di lahan petani. Cara pengelolaan yang meliputi tindakan peningakatan-hasil untuk faktor pembatas-hasil dan tindakan perlindungan-hasil untuk faktor pengurang-hasil dianjurkan guna memperbaiki produksi padi sawah tadah hujan.

Analisis statistik dari parameter tanaman, tanah, dan air pada percobaan multi lokasi dan antar musim menunjukkan adanya perbedaan pengaruh pengelolaan tanaman pada hasil padi pada posisi toposekuen yang berbeda. Akan tetapi, pendekatan percobaan ini mahal dan rawan terhadap fluktuasi cuaca. Lagipula, tidak adanya tingkat acuan terukur membuat analisis senjang hasil akibat faktor pembatas dan faktor pengurang hasil sulit dilakukan di lahan petani. Oleh karena itu, dibutuhkan metode tidak langsung dalam menghitung hasil acuan, seperti penggunaan model tanaman. Parameter-parameter kebaikan suai dan diagram pencar menunjukkan bahwa model ORYZA2000 cukup dapat mensimulasi hasil pada berbagai tingkat pupuk N pada kondisi irigasi dan tadah hujan di areal percobaan. Model simulasi dapat digunakan untuk menentukan tingkat acuan spesifik lokasi, yang tidak mudah diukur atau tersedia dari percobaan-percobaan lapang. Akan tetapi, penggunaan pendekatan ini dibatasi oleh ketersediaan data tanaman, tanah, iklim, dan pengelolaan yang diperlukan dalam model. Parameter-parameter kebaikan suai dan diagram pencar menunjukkan adanya hubungan yang relatif erat antara hasil padi estimasi (menggunakan efisiensi penggunaan hara fisiologi) dan aktual pada petak-petak dengan PK (tanpa N) dan NP (tanpa K). Penggunaan efisiensi hara fisiologi dalam estimasi hasil berpeluang menjembatani hasil penelitian antara percobaan lapang dan di lahan petani. Namun, kehati-hatian harus diterapkan ketika menggunakan efisiensi fisiologi untuk situasi kahat hara dalam mengestimasi hasil untuk daerah dengan suplai hara tanah yang tinggi, seperti kondisi P tanah di Jawa Tengah, Indonesia.

Kesenjangan hasil yang lebar (48%) antara potensi hasil dan hasil aktual pada cara budidaya petani padi di lahan tadah hujan saat ini menunjukkan bahwa ada peluang yang nyata untuk memperbaiki produksi berdasarkan kemungkinan-kemungkinan biofisik, sosial-ekonomi, dan teknis. Kesenjangan hasil yang lebar dan konsisten akibat kekurangan air dan hara (N, K), dan serangan OPT (hama dan gulma) di kebun percobaan dan di lahan petani menunjukkan tindakan spesifik yang dapat dilakukan untuk memperbaiki produksi sawah tadah hujan. Tindakan meningkatkan-hasil meliputi waktu tanam, pengolahan tanah dalam, tambahan air irigasi, pemberian pupuk N dan K, sedangkan tindakan perlindungan-hasil meliputi waktu tanam dan pengendalian gulma. Akan tetapi, realisasi kenaikan hasil akibat dari perubahan pengelolaan di atas, bergantung pada investasi infrastruktur dan kebijakan yang meliputi irigasi atau fasilitas penangkap air, subsidi pupuk, perdagangan beras dan kebijakan harga, serta kerjasama yang kuat antar agen perubah (peneliti, penyuluh, petani, pemimpin masyarakat, pembuat kebijakan, dan lembaga swadaya masyarakat).

Metodologi yang digunakan untuk estimasi hasil acuan memberikan pemahaman yang jauh lebih besar tentang kendala-kendala untuk produksi padi dataran rendah tadah hujan dan dapat diterapkan untuk lokasi yang lain untuk identifikasi kendala-kendala hasil dan pilihan-pilihan pengelolaan untuk peningkatan produksi.

สรุป

ประชากรโลกมากกว่าครึ่งรับประทานข้าวและข้าวเป็นอาหารหลักในเอเชีย ในปัจจุบัน ประชากรโลกได้เพิ่มขึ้นในอัตรา 1.2 เปอร์เซ็นต์ต่อปีเมื่อเปรียบเทียบกับอัตราการเพิ่มขึ้นของผลผลิตข้าวประมาณ 0.7 เปอร์เซ็นต์ต่อปี นอกจากนี้ในเอเชียตะวันออกเฉียงใต้ อัตราส่วนของพื้นที่เพาะปลูกข้าวทั้งหมดลดลงจาก 26 เปอร์เซ็นต์ในปี 2523 เป็น 23 เปอร์เซ็นต์ในปี 2547 ปัจจัยต่างๆเหล่านี้เพิ่มแรงกดดันในการเพิ่มผลผลิตพืช โดยเฉพาะพืชที่ปลูกในสภาพแวดล้อมที่ไม่เหมาะสม เช่นในสภาพอาศัยน้ำฝนที่มีระดับผลผลิตต่ำกว่าศักยภาพของผลผลิตที่กำหนดโดยภูมิอากาศ (climatically determined potential) ในเอเชีย พื้นที่เพาะปลูกข้าวนาน้ำฝนมีประมาณ 59 ล้านเฮกตาร์ หรือ 44 เปอร์เซ็นต์ของพื้นที่เพาะปลูกข้าวทั้งหมด ผลผลิตเฉลี่ยของข้าวนาน้ำฝนมีค่าต่ำคือ 2.1 ตันต่อเฮกตาร์ ผลผลิตต่ำเนื่องจากความแปรปรวนของน้ำฝน ความอุดมสมบูรณ์ของดินต่ำ การระบาดของศัตรูพืช (แมลง โรค วัชพืช) การขาดธาตุอาหาร ความแห้งแล้ง และปฏิสัมพันธ์ (interactions) ของปัจจัยเหล่านี้มักเกิดขึ้นพร้อมกันในการปลูกพืชในเขตน้ำฝน การวางแผนรูปแบบของการจัดการ (design management interventions) มีเป้าหมายเพื่อเพิ่มผลผลิตในพื้นที่นาน้ำฝน จำเป็นต้องประเมินขนาดและความแตกต่างของผลผลิตที่ได้จริง กับศักยภาพผลผลิต (yield gaps) ที่สัมพันธ์กับปัจจัยจำกัดผลผลิตต่างๆ ตามระดับความสูงต่ำของพื้นที่ที่แตกต่างกัน (toposequences) ในเขตนาน้ำฝน

งานวิจัยนี้มีเป้าหมายเพื่อศึกษาความแปรปรวนของสภาวะน้ำ (water status) และความเป็นประโยชน์ของธาตุอาหารที่มีผลต่อการเจริญเติบโต และผลผลิตของข้าวนาน้ำฝนตามระดับความสูงต่ำของพื้นที่ในเอเชียตะวันออกเฉียงใต้ ซึ่งข้อมูลนี้ใช้เป็นพื้นฐานในการวางแผนการจัดการพืช (crop management strategies) การที่จะบรรลุวัตถุประสงค์นี้ ใช้แนวคิดนิเวศน์วิทยาของการผลิตพืช (production ecology) มาใช้กับข้าวนาน้ำฝน การวิเคราะห์สถิติ (statistical analysis) และการวิเคราะห์ระบบ (systems analysis) ได้จากการทดลองในแปลงนาและการใช้แบบหุ่นจำลอง (simulation modelling) ในการหาอิทธิพลของปัจจัยต่างๆที่กำหนดผลผลิต ปัจจัยที่จำกัดผลผลิต และปัจจัยที่ลดผลผลิต (yield-determining, yield-limiting, and yield-reducing factors) ผลการวิเคราะห์ถูกนำไปใช้เป็นแนวทางเลือกในการจัดการทรัพยากรต่างๆโดยการกำหนดเวลาและพื้นที่ที่เฉพาะเจาะจง (site- and time-specific resource management) ตามระดับความสูงต่ำของพื้นที่ที่มีความลาดเอียงไม่เท่ากันในการปลูกข้าวในเขตน้ำฝน การทดลองในแปลงนา จำนวน 3 ชุดการทดลอง โดยทดลองในสถานีวิจัยจำนวน 2 ชุดการทดลอง และทดสอบในแปลงนาเกษตรกรจำนวน 1 ชุดการทดลอง การทดลองที่ 1 ศึกษาอิทธิพลของน้ำและการไถพรวน ในปี 2538-2539 ที่สถานีทดลอง Jakenan, Central Java, ประเทศอินโดนีเซีย (6°47′ ใต้ 111°12′ ตะวันออก ที่ระดับความสูง 8 เมตรจากระดับน้ำทะเล) การทดลองที่ 2 ศึกษาอิทธิพลของน้ำและปุ๋ย ในปี 2540-2543 ที่สถานีทดลอง Jakenan การทดลองที่ 3 ศึกษาความเป็นประโยชน์ของน้ำ คุณสมบัติทางเคมีและทางกายภาพของดิน มวลชีวภาพ และผลผลิตตามระดับความสูงต่ำของพื้นที่ต่างๆในปี 2543-2545 ในแปลงนาเกษตรกรรอบๆสถานีทดลอง Jakenan

และศูนย์วิจัยข้าวอุบลราชธานี (15°19′ เหนือ 104°40′ ตะวันออก ที่ระดับความสูง 127 เมตรจากระดับน้ำทะเล)

ประการแรก การวิเคราะห์ปัจจัยจำกัดผลผลิต (yield constraints) ของข้าวนาน้ำฝนที่สถานีทดลอง Jakenan ได้จากการวิเคราะห์สถิติโดยใช้ค่าของ ดิน น้ำ และพืชในฤดูที่ไม่มีศัตรูพืชระบาด และได้จากการวิเคราะห์ระบบ (systems analysis)ในฤดูที่ไม่สามารถควบคุมศัตรูพืชโดยวิธีแนะนำ การประเมินความสูญเสียของผลผลิต (yield losses) ในข้าวนาน้ำฝนเนื่องจากปฏิสัมพันธ์ระหว่าง ความแห้งแล้ง และการขาดธาตุอาหาร รวมถึงการระบาดของศัตรูพืช หนึ่งในหกฤดู (ฤดูนาปี 2540/41) ผลผลิตข้าวในแปลงนาน้ำฝนต่ำกว่าผลผลิตข้าวในแปลงที่ได้รับน้ำเต็มที่ 20-23 เปอร์เซ็นต์ ไนโตรเจนและโปแตสเซี่ยมมีอิทธิพลต่อผลผลิต และมวลชีวภาพอย่างมีนัยสำคัญทางสถิติที่สถานีทดลอง Jakenan ในการเปรียบเทียบสภาพการใส่ปุ๋ยที่เหมาะสม ผลผลิตเฉลี่ยลดลงเนื่องจากการขาดไนโตรเจน 42 เปอร์เซ็นต์ และผลผลิตเฉลี่ยลดลงเนื่องจากการขาดโปแตสเซี่ยม 33-36 เปอร์เซ็นต์ การระบาดของศัตรูพืชเป็นปัญหาสำคัญของการปลูกข้าวในปลายฤดูฝนใน Jakenan สองฤดูจากสามฤดูในปลายฤดูฝน ผลผลิตข้าวสูญเสียเนื่องจากศัตรูพืชประมาณ 56-59 เปอร์เซ็นต์

ประการต่อมา ใช้ ORYZA2000 model ในการปรับค่า (calibrate) และการประเมิน (evaluate) แบบหุ่นจำลองของข้าวนาน้ำฝน แบบหุ่นจำลองใช้ค่าของ ดิน น้ำ และพืชจากการทดลองที่ 1 ในการปรับค่า คุณภาพการใช้แบบหุ่นจำลอง (Model performance) ใช้ข้อมูลดิน น้ำ และพืชจากการทดลองที่ 2 ORYZA2000 model สามารถคาดคะเน ค่าความลึกของน้ำในนา (field water depth) ค่าความเครียดของน้ำในดิน (soil water tension) มวลชีวภาพของต้นบนดิน (above-ground biomass) และผลผลิตข้าวที่ใส่ปุ๋ยไนโตรเจนระดับต่างๆ ทั้งในสภาพที่ให้น้ำชลประทานและในสภาพนาน้ำฝนได้ใกล้เคียงความเป็นจริงแบบหุ่นที่ได้จากการปรับค่า (calibrated model) ถูกนำไปใช้ในการจำลองศักยภาพผลผลิต (simulate potential yield) ซึ่งต่อมาใช้ในการเปรียบเทียบ (reference) ในการวิเคราะห์ความแตกต่างของผลผลิตที่ได้จริงกับศักยภาพผลผลิต (yield gaps) เนื่องจากปัจจัยที่ลดผลผลิต (yield-reducing factors (แมลง ศัตรูพืช และโรค)) ในสถานีทดลอง และปัจจัยจำกัดผลผลิต (yield-limiting factors) ในแปลงนาเกษตรกร

ORYZA2000 model ได้ใช้ในการสำรวจศักยภาพผลผลิตและผลผลิตข้าวนาน้ำฝนที่ระดับน้ำใต้ดินตื้น กลางและลึก ศักยภาพผลผลิตจำลอง (Simulated potential yields) มีค่าจาก 3.74 ตันต่อเฮกตาร์ (สำหรับการหว่านข้าวต้นฤดูฝนในเดือนตุลาคม) ถึง 5.53 ตันต่อเฮกตาร์ (สำหรับการหว่านข้าวในฤดูแล้งในเดือนกรกฎาคม) ศักยภาพผลผลิตในฤดูแล้งสูงกว่าในฤดูฝน เนื่องจากพืชได้รับแสงมากกว่าในช่วงการติดเมล็ด ผลผลิตจำลอง (simulated yield) ของข้าวที่หว่านในต้นเดือนพฤศจิกายนถึงกลางเดือนมีนาคมแตกต่างกันเนื่องจากระดับน้ำใต้ดินแตกต่างกัน ผลผลิตข้าวนาน้ำฝนใกล้เคียงศักยภาพผลผลิตเมื่อมีระดับน้ำใต้ดินตื้น แต่ผลผลิตลดลงเมื่อมีระดับน้ำใต้ดินลึก

ORYZA2000 ใช้ในการการประเมินอิทธิพลของระดับน้ำใต้ดินต่อผลผลิตข้าวภายใต้วิธีการจัดการต่างๆ (วันหว่าน การไถพรวน การให้น้ำชลประทานเสริม และการใส่ปุ๋ย

ไนโตรเจน) และใช้เป็นพื้นฐานในการกำหนดคำแนะนำการจัดการระดับน้ำใต้ดินต่างๆในเขตพื้นที่นาน้ำฝนที่เหมาะสมของ Central Java ประเทศอินโดนีเซีย ผลผลิตจำลองของข้าวนาน้ำฝนลดลงอย่างรวดเร็วสำหรับข้าวที่หว่านปลายฤดูฝน การลดลงของผลผลิตของข้าวที่ปลูกปลายฤดูฝนชี้ให้เห็นถึงความสำคัญของการกำหนดวันปลูกวิกฤต (critical planting dates) ที่ระดับน้ำใต้ดินต่างๆ ผลจากแบบหุ่นจำลองชี้ให้เห็นถึงวันปลูกวิกฤตของปลายฤดูฝนคือต้นเดือนเมษายนในหุ่นจำลองเมื่อมีระดับน้ำใต้ดินตื้น เปรียบเทียบกับกลางเดือนมีนาคมเมื่อมีระดับน้ำใต้ดินปานกลาง และต้นเดือนมีนาคมเมื่อมีระดับน้ำใต้ดินลึก ระดับน้ำใต้ดินมีอิทธิพลอย่างชัดเจนต่อการตอบสนองของการไถพรวน การใส่ปุ๋ย และ การให้น้ำชลประทานเสริม ในข้าวนาน้ำฝนที่หว่านปลายฤดูฝน ในหุ่นจำลองที่ระดับน้ำ ใต้ดินตื้นผลผลิตยังคงอยู่ที่ศักยภาพผลผลิตเมื่อหว่านข้าวจนถึงปลายเดือนมีนาคม และ การไถพรวนลึกไม่มีผลต่อผลผลิต อย่างไรก็ตามเมื่อการหว่านข้าวล่าช้าถึงปลายเดือนเมษายนการไถพรวนลึกสามารถเพิ่มผลผลิต 2.5 ตันต่อเฮกตาร์เนื่องจากการเพิ่ม capillary ในดินเมื่อเปรียบเทียบกับการไถพรวนธรรมดา ในหุ่นจำลองสำหรับระดับน้ำใต้ดินตื้น และระดับน้ำใต้ดินปานกลาง การใส่ปุ๋ยไนโตรเจน 120 กก.ไนโตรเจน ต่อเฮกตาร์ให้ผลผลิตสูงกว่าการไม่ใส่ปุ๋ยไนโตรเจนประมาณ 1 ตันต่อเฮกตาร์เมื่อหว่านข้าวในเดือนพฤศจิกายนถึงเดือนมกราคม และให้ผลผลิตสูงกว่าการไม่ใส่ปุ๋ยไนโตรเจนประมาณ 1.4 ตันต่อ เฮกตาร์เมื่อหว่านข้าวล่าถึงต้นเดือนมีนาคม สำหรับระดับน้ำใต้ดินลึกผลผลิตถูกจำกัดเนื่องจากปริมาณน้ำที่มีอยู่ในดินและการใส่ปุ๋ยไนโตรเจน 120 กกไนโตรเจน ต่อเฮกตาร์ทำให้ผลผลิตเพิ่มขึ้นเพียง 0.8 ตันต่อเฮกตาร์เมื่อหว่านข้าวต้นฤดูในเดือนพฤศจิกายนถึงเดือนธันวาคม สำหรับระดับน้ำใต้ดินตื้นการให้น้ำชลประทานเสริมสามารถเพิ่มผลผลิตเมื่อหว่านข้าวตั้งแต่ปลายเดือนมีนาคมเป็นต้นไป และผลผลิตเพิ่มมากขึ้นเมื่อหว่านข้าวตั้งแต่ปลายเดือนเมษายนเป็นต้นไป การหว่านข้าวที่ล่ามากช่วยให้ผลผลิตเพิ่มขึ้น 1.2-3.1 ตันต่อเฮกตาร์เมื่อมีการให้น้ำชลประทาน 7.5 มม.ในแต่ละครั้งเมื่อความชื้นของดินบน (0-5 ซม.) ต่ำกว่าความจุความชื้นสนาม (field capacity) (I_1) และผลผลิตเพิ่มขึ้น 1.4-2.4 ตันต่อเฮกตาร์ เมื่อมีการให้น้ำชลประทาน 7.5 มม.ทุกวันที่ระยะกำเนิดช่อดอก (PI) จนถึงระยะเก็บเกี่ยว (I_2) ในหุ่นจำลองสำหรับระดับน้ำใต้ดินลึกการตอบสนองของผลผลิตต่อการให้น้ำชลประทานเมื่อเริ่มหว่านข้าวต้นเดือนกุมภาพันธ์โดยผลผลิตเพิ่ม 0.7 ตันต่อเฮกตาร์ใน I_1 และผลผลิตเพิ่ม 0.3-0.5 ตันต่อเฮกตาร์ใน I_2

การประเมินความแปรปรวนของ คุณสมบัติทางเคมีและทางกายภาพของดิน สภาพน้ำ มวลชีวภาพ และผลผลิตตามระดับความสูงต่ำของพื้นที่ต่างๆในเขตนาน้ำฝนที่มีปริมาณน้ำฝนใกล้เคียงกัน (การทดลองที่ 3) โดยเป็นตัวแทนของระบบการปลูกข้าวในพื้นที่นาน้ำฝน (การปลูกข้าวนาน้ำฝนในประเทศไทย 1 ฤดูกาล) และเป็นตัวแทนของระบบการปลูกข้าวนาน้ำฝนที่ประณีตมากขึ้น (การปลูกข้าวนาน้ำฝนในประเทศอินโดนีเซีย 2 ฤดูกาล) ความแตกต่างของสภาพน้ำในแปลง (ความลึกของน้ำบนผิวดิน ความลึกของระดับน้ำใต้ดิน จำนวนวันที่ไม่ได้ให้น้ำบนผิวดิน) โปแตสเซียมที่แลกเปลี่ยนได้ อินทรีย์คาร์บอน และปริมาณดินเหนียว (clay content) ขึ้นอยู่กับระดับความสูงต่ำของพื้นที่ สำหรับความแตกต่างของคุณสมบัติของดินอื่นๆ (N, P, CEC, pH, sand, silt, bulk density) และความแตกต่างของผลผลิต และความแตกต่างของขนาดผลผลิตที่เพิ่มขึ้น

(magnitude of yield increase) ในแปลงชาวนา ขึ้นอยู่กับการป้องกันกำจัดวัชพืช และ/หรือ การใส่ปุ๋ยตามคำแนะนำตามความสูงต่ำของพื้นที่ แต่ความแตกต่างนี้ไม่แน่นอนขึ้นอยู่กับประเทศ ฤดูกาล และปี

มีความสัมพันธ์ระหว่างสภาพน้ำ (hydrological conditions) และระดับความสูงต่ำของพื้นที่ โดยแปลงที่อยู่บนพื้นที่ที่สูงกว่าแห้งกว่าแปลงที่อยู่บนพื้นที่ที่ต่ำกว่า ที่ระดับความสูงของพื้นที่ที่เท่ากันผลผลิตจากแปลงที่มีสิ่งทดลอง (treatment) เหมือนกันให้ผลผลิตใกล้เคียงกันใน 6 ฤดูกาลจาก 11 ฤดูกาลใน 2 ประเทศ อย่างไรก็ตาม มีการประเมินความแตกต่างของผลผลิตในแปลงไม่ใส่ปุ๋ยตามระดับความสูงต่ำของพื้นที่ 2 ฤดูกาล (ต้นฝนปี 2544/45 และ ปลายฝน ปี 2545) จาก 4 ฤดูกาลในประเทศอินโดนีเซีย และ 2 ฤดูกาล (ฤดูฝน 2544 และ ฤดูฝน 2545) จาก 3 ฤดูกาลในประเทศไทย ในทำนองเดียวกันมีการประเมินความแตกต่างของผลผลิตในแปลงไม่ป้องกันกำจัดวัชพืช 1 ฤดูกาล (ต้นฝนปี 2544/45) จาก 4 ฤดูกาลตามระดับความสูงต่ำของพื้นที่ในประเทศอินโดนีเซีย แปลงที่อยู่บนพื้นที่ที่อยู่สูงกว่ามักให้ผลผลิตที่ต่ำกว่าแปลงที่อยู่บนพื้นที่ที่ต่ำกว่า ผลผลิตเฉลี่ยเพิ่มขึ้นใกล้เคียงกันเมื่อมีการกำจัดวัชพืช (0.65 ตันต่อเฮกตาร์) หรือการใส่ปุ๋ยตามคำแนะนำ (1.25 ตันต่อเฮกตาร์) ตามระดับความสูงต่ำของพื้นที่ที่ใกล้เคียงกัน ซึ่งผลการทดลองนี้ชี้ให้เห็นว่าระดับความสูงต่ำของพื้นที่ ไม่สามารถใช้เป็นพื้นฐานอย่างเดียวสำหรับการประกาศคำแนะนำ (formulation of recommendations) ในการกำจัดวัชพืชและการใส่ปุ๋ย การเพิ่มขึ้นของผลผลิตโดยใช้คำแนะนำทั่วไป (blanket management recommendations) ในสภาพนาน้ำฝนต้องมาจากผลการวิจัยของการจัดการเฉพาะเวลาและสถานที่ (time- and field-specific management practices) เท่านั้น เช่น โดยการจัดการธาตุอาหารเฉพาะพื้นที่ (site-specific nutrient management)

ประการต่อมา มีการกำหนดปัจจัยจำกัดผลผลิต (yield constraints) ของข้าวนาน้ำฝนในแปลงนาเกษตรกรตามระดับความสูงต่ำของพื้นที่ที่แตกต่างกัน โดยการประเมินอิทธิพลของปัจจัยกำหนดผลผลิตและปัจจัยจำกัดผลผลิต (yield-determining and yield-limiting factors) ตามระดับความสูงต่ำของพื้นที่ โดยใช้ศักยภาพผลผลิตจำลอง (simulated yield potential) เป็นตัวเปรียบเทียบ ศักยภาพผลผลิตที่ใช้ในการเปรียบเทียบ (reference yields) ภายใต้สภาพที่มีธาตุอาหารจำกัดในแปลงนาน้ำฝนของเกษตรกร คำนวณมาจากธาตุอาหารที่พืชใช้ไป (plant nutrient uptake) และประสิทธิภาพการใช้ธาตุอาหารของพืชทางสรีรวิทยาตามทฤษฎี (theoretical physiological nutrient use efficiencies) ของข้าว

แปลงนาเกษตรกรตามระดับความสูงต่ำของพื้นที่แสดงให้เห็นถึงความแปรปรวนของน้ำสูง (ปริมาณน้ำฝนต่อฤดู 350-1446 มม. ความลึกของระดับน้ำใต้ดิน –150 ถึง 50 ซม.) และอัตราปุ๋ยที่เกษตรกรใช้ (ไนโตรเจน 76-166 กก.ต่อ เฮกตาร์ ฟอสฟอรัส 0-45 กก.ต่อ เฮกตาร์ และโปแตสเซี่ยม 0-51 กก.ต่อ เฮกตาร์) ในปลายฤดูฝนปี 2545 ผลผลิตจำลองของข้าวนาน้ำฝน (simulated rainfed (or water-limited) rice yields) ต่ำกว่าศักยภาพผลผลิตจำลอง (simulated yield potential) 28 เปอร์เซ็นต์ ความแตกต่างของผลผลิตจำลอง (simulated yield gap) เนื่องจากการขาดน้ำมีค่า 52

เปอร์เซ็นต์ในหมู่บ้าน Sidomukti ซึ่งมีปริมาณน้ำฝนต่ำกว่าปกติ ใน 3 จาก 4 หมู่บ้าน ความแตกต่างของผลผลิตที่ได้จริงกับศักยภาพผลผลิต (yield gap) เนื่องจากน้ำมีค่าสูงในพื้นที่ที่มีระดับความสูงที่สูงกว่ามากกว่าบนพื้นที่ที่มีระดับความสูงต่ำกว่า ต้นฤดูฝนปี 2544/45 การคำนวณความแตกต่างของผลผลิตเนื่องจากการขาดธาตุไนโตรเจน ฟอสฟอรัส และโปแตสเซี่ยมในแปลงที่ไม่ใส่ปุ๋ยมีค่า 55 20 และ 53 เปอร์เซ็นต์ ตามลำดับ ความแตกต่างของผลผลิตเนื่องจากการขาดไนโตรเจนให้ผลใกล้เคียงกันระหว่างหมู่บ้านต่างๆ แต่มีค่าสูงขึ้นเมื่อพื้นที่มีระดับความสูงมากขึ้น ในทางตรงข้ามความแตกต่างของผลผลิตเนื่องจากการขาดโปแตสเซี่ยมมีค่อนข้างมาก (56-66%) ใน 3 หมู่บ้าน ในขณะที่หมู่บ้าน Jadi (การแลกเปลี่ยนของโปแตสเซี่ยมในดินค่อนข้างสูง) มีความแตกต่างของผลผลิตค่อนข้างต่ำ (28%) และมีค่าสูงขึ้นเมื่อพื้นที่ทีมีระดับความสูงที่มากขึ้น การขาดไนโตรเจนและการขาดโปแตสเซี่ยมเป็นปัจจัยจำกัดผลผลิตที่สำคัญของการปลูกข้าวนาน้ำฝนในประเทศอินโดนีเซีย

การวิจารณ์ผลทั่วไป กล่าวถึงจุดแข็งและจุดอ่อนของวิธีการที่ใช้ในการประเมินศักยภาพผลผลิตสำหรับการเปรียบเทียบ (reference yields) มีการประเมินปัจจัยที่จำกัดผลผลิต (yield-limiting factor) และปัจจัยที่ลดผลผลิต (yield-reducing factor) โดยใช้วิธีการดังกล่าวในการประเมินข้าวนาน้ำฝนในสถานีทดลองและแปลงนาเกษตรกรในประเทศอินโดนีเซีย คำแนะนำในเรื่องการจัดการวิธีการเพิ่มผลผลิตในข้าวนาน้ำฝนคือการใช้วิธีการจัดการเพื่อเพิ่มผลผลิตสำหรับปัจจัยที่จำกัดผลผลิต (yield-increasing measures for limiting factors) และการใช้วิธีการจัดการป้องกันผลผลิตสำหรับปัจจัยที่ลดผลผลิต (yield-protecting measures for reducing factors)

การวิเคราะห์สถิติ ของลักษณะ ดิน น้ำ และพืชของการทดลองในหลายสถานที่และหลายฤดูกาล แสดงให้เห็นถึงความแตกต่างของอิทธิพลของการจัดการพืชต่อผลผลิตข้าวตามระดับความสูงต่ำของพื้นที่ที่แตกต่างกัน อย่างไรก็ตาม การทดลองแนวทางนี้ (experimental approach) มีราคาแพงและได้รับผลกระทบจากความไม่แน่นอนของภูมิอากาศ นอกเหนือจากนี้ การที่ไม่ได้วัดค่าศักยภาพผลผลิต (reference levels) โดยตรงทำให้การวิเคราะห์ความแตกต่างของผลผลิตที่ได้จริงกับศักยภาพผลผลิต (yield gap) ที่เนื่องมาจากปัจจัยที่จำกัดผลผลิตและปัจจัยที่ลดผลผลิตเป็นไปได้ยากในแปลงนาเกษตรกร เพราะฉะนั้นจึงใช้วิธีการคำนวณศักยภาพผลผลิตในการเปรียบเทียบ (reference yields) โดยการใช้แบบหุ่นจำลองพืช (crop models) ผลจาก goodness-of-fit parameters และ scatter diagrams แสดงให้เห็นว่า แบบหุ่นจำลอง ORYZA2000 สามารถจำลองผลผลิตที่ระดับต่างๆของการใส่ปุ๋ยไนโตรเจนภายใต้สภาพการให้น้ำและภายใต้สภาพนาน้ำฝน ณ สถานที่ที่ทำการศึกษาได้เป็นอย่างดี แบบหุ่นจำลองสามารถใช้เพื่อกำหนดระดับศักยภาพผลผลิตในพื้นที่เฉพาะ (site-specific reference levels) ที่ไม่สามารถวัดได้ในแปลงทดลอง การใช้แนวทางนี้อาจมีข้อจำกัดด้วยข้อมูลของ ดิน พืช และ ภูมิอากาศ และต้องการการจัดการข้อมูลในแบบหุ่นจำลอง ค่าที่ได้จาก goodness-of-fit parameters and scatter diagrams แสดงให้เห็นถึงความสัมพันธ์ที่ค่อนข้างใกล้ชิดระหว่างค่าที่ได้จากการคำนวณ (โดยใช้ประสิทธิภาพการใช้ธาตุอาหารของพืชทางสรีรวิทยา (physiological nutrient use efficiencies)) และ

สรุป

ค่าผลผลิตที่วัดได้จริงในแปลงที่ใส่ปุ๋ยฟอสฟอรัสและโปแตสเซี่ยม (ไม่ใส่ปุ๋ยไนโตรเจน) และแปลงที่ใส่ปุ๋ยไนโตรเจนและฟอสฟอรัส (ไม่ใส่ปุ๋ยโปแตสเซี่ยม) การใช้ประสิทธิภาพการใช้ธาตุอาหารของพืชทางสรีรวิทยาในการประเมินผลผลิตสามารถเชื่อมความสัมพันธ์ระหว่างผลการทดลองในแปลงทดลองและผลการทดสอบในแปลงเกษตรกร อย่างไรก็ตาม การใช้ประสิทธิภาพทางสรีรวิทยาในสภาพที่ธาตุอาหารมีจำกัด (physiological efficiencies for nutrient-limited situations) ควรระมัดระวังเมื่อใช้ในกรณีที่ดินมีธาตุอาหารสูง ดังเช่นกรณี ดินมีฟอสฟอรัสสูงใน Central Java ประเทศอินโดนีเซีย

การที่ผลผลิตแตกต่างกันมาก (48%) ระหว่างศักยภาพผลผลิตและผลผลิตที่ได้จริง (yield gap) โดยใช้วิธีการจัดการปัจจุบันของเกษตรกรในเขตน้ำฝนแสดงให้เห็นถึงขอบเขตของการเพิ่มผลผลิตบนพื้นฐานของ ชีวกายภาพ (biophysical) เศรษฐสังคม (socioeconomic) และ ด้านเทคนิค ความแตกต่างกันของผลผลิตมีค่ากว้างเนื่องมาจากการขาดน้ำและธาตุอาหาร (ไนโตรเจนและโปแตสเซี่ยม) และการระบาดของศัตรูพืช (แมลง และวัชพืช) ในสถานีทดลองและในแปลงนาเกษตรกรชี้ให้เห็นว่า การจัดการเฉพาะ (specific interventions) นำไปสู่การเพิ่มผลผลิตข้าวนาน้ำฝนได้ การใช้วิธีการจัดการเพื่อเพิ่มผลผลิต (yield-increasing measures) โดยวิธีการจัดการวันปลูก การไถพรวนลึก การให้น้ำชลประทานเสริม การใส่ปุ๋ยไนโตรเจนและโปแตสเซี่ยม ในขณะที่การใช้วิธีการจัดการป้องกันผลผลิต (yield-protecting measures) โดยวิธีการจัดการวันปลูกและการจัดการวัชพืช ระดับการยอมรับวิธีการจัดการต่างๆ และการตระหนักถึงผลผลิตที่สัมพันธ์กัน ขึ้นอยู่กับ การลงทุนและนโยบาย และ การจัดการในสถาบันต่างๆ ในสังคม รวมถึงสวัสดิการทางด้านการชลประทาน ปุ๋ยราคาถูก นโยบายด้านการค้าข้าว และราคา และร่วมมือแข็งแกร่งระหว่างหน่วยงานต่างๆ (นักวิจัย นักส่งเสริมการเกษตร เกษตรกร ผู้นำชุมชน ผู้วางแผนนโยบาย และ องค์กรพัฒนาเอกชน)

การรวมวิธีการที่ใช้ในการประเมินศักยภาพผลผลิตสำหรับการเปรียบเทียบ (reference yields) หลายๆวิธีการเข้าด้วยกันช่วยให้เข้าใจถึงข้อจำกัดในการผลิตข้าวนาสวนนาน้ำฝน และสามารถนำไปปรับใช้ในท้องถิ่นอื่นๆ เพื่อกำหนดปัจจัยที่จำกัดผลผลิตต่างๆ และใช้เป็นแนวทางเลือกในการจัดการเพื่อเพิ่มผลผลิต มีเงื่อนไขว่าต้องมีข้อมูลการทดลองที่จำเป็นเพียงพอเพื่อวิเคราะห์ในเชิงกว้างและลึก (comprehensive analysis) ได้

Kabuuran

Mahigit sa kalahati ng mga tao sa mundo ay kumakain ng bigas at ang bigas ang pangunahing pagkain sa Asya. Kamakailan lamang, ang populasyon ng mundo ay tinatayang lumalago ng 1.2% kada taon ngunit ang pagtaas ng ani ay 0.7% lamang kada taon. Bukod doon, ang bahagi ng kabuuang lupa na tinataniman ng palay ay bumaba mula 26% noong 1980 hanggang 23% noong 2004 sa timog-silangang Asya. Lahat nang ito ay nagpaigting sa pangangailangan na pataasin ang ani lalo na yaong mga itinatanim sa mga lugar na ang kondisyon ay hindi pabor sa pagkakaroon ng mataas na ani, kung saan ang ani ay mas mababa sa potensiyal na apektado ng klima. Sa Asya, tinatayang may 59 milyong ektarya o 44% ng kabuuang lupa para sa palayan ay umaasa sa sahod-ulan. Ang karaniwang ani ay mababa lamang na umaabot sa 2.1 tonelada kada ektarya. Ang sanhi nito ay maraming bagay gaya ng walang katiyakang tubig, hindi matabang lupa, at mga peste (insekto, mga organismong nagdudulot ng sakit, at damo). Ang mga peste, kakulangan ng sustansiya sa lupa, tagtuyot, at ang kanilang interaksiyon ay sabay-sabay na nagaganap sa mga palayang sahod-ulan. Upang makapagplano ng mga paraan para madagdagan ang ani ng mga palayang sahod-ulan, kailangang malaman kung gaano kalaki at gaano nagbabago ang kakulangan sa ani sa iba’t-ibang bahagi ng lupa ng iba’t-ibang palayan sa kapatagan na umaasa sa sahod-ulan.

Ang pag-aaral na ito ay naglalayon na maunawaan ang mga pagkakaiba ng estado ng patubig at sustansiya ng lupa sa iba’t-ibang lugar at panahon at ang epekto nito sa paglaki at ani ng sahod-ulan na palay sa iba’t-ibang bahagi ng bukid sa timog-silangang Asya. Ang impormasyong ito ay naging batayan ng pagpaplano ng mga paraan upang mapabuti ang pangangalaga ng halaman. Upang makamit ang mga layuning ito, ang mga konsepto ng ekolohiya ng produksiyon (concepts of production ecology) ay ginamit sa palayang sahod-ulan. Ang mga pagsusuring estadistika at pagsusuri ng sistema (systems analysis) ay ginamit sa pinagsanib na eksperimento sa bukid at modelong pagtutulad bilang basehan upang malaman at matantiya ang epekto ng mga bagay na nagtatakda, naglilimita, at nagpapababa ng ani (yield-determining, -limiting, and -reducing factors). Ang mga resulta ng pag-aaral ay ginamit upang matukoy ang mga paraan ng pangangalaga sa likas yaman na angkop sa iba’t-ibang lugar at panahon sa kaitaasan hanggang sa kababaan ng lupang dahilig. Tatlong pangkat ng eksperimento ang ginawa: dalawa sa himpilan ng pananaliksik at isa sa bukid ng magsasaka. Ang unang eksperimento ay ginawa noong 1995–96 sa Jakenan Experiment Station, Central Java, Indonesia (6°47′ S, 111°12′ E, 8 metro mula sa taas ng dagat) at ito ay pag-aaral sa epekto ng patubig at pagbubungkal. Ang ikalawang eksperimento tungkol sa epekto ng patubig at abono ay ginawa rin sa Jakenan noong 1997–2000. Ang pangatlong eksperimento ay isang pagsusuri sa pagkakaiba-iba ng estado ng patubig, mga katangiang kemikal at pisikal ng lupa, bigat ng halaman (bayomas) at ani sa iba't-ibang posisyon sa bahagdan na pagkakasunud-sunod sa lupa (toposequence). Ito ay ginawa noong 2000–02 sa mga tanimang bukid ng mga magsasaka na nakapaligid sa Jakenan Experiment Station sa Indonesia at sa nakapaligid sa Ubon Ratchathani Research Center sa Thailand (15°19′ N, 104°40′ E, 127 metro mula sa taas ng dagat).

Una, ang mga hadlang sa masaganang ani sa palayang sahod-ulan sa Jakenan Experiment Station ay natukoy base sa pagsusuring estadistika ng mga tuwirang pagsukat sa mga pananim, lupa, at tubig sa panahon na walang peste sa bukirin, at *systems analysis* sa panahon na ang peste ay di gasinong makontrol kahit ng mga rekomendadong kaparaanan. Ang kabawasan o kawalan ng ani ng sahod-ulan na palay na bunga ng interaksiyon ng tagtuyot at kakulangan sa sustansiya ay tinantiya, habang tinitingnan din ang pagkakaroon ng peste sa linang. Sa isa sa anim na panahon (1997-98 maagang tag-ulan), ang ani sa palayang sahod-ulan ay mababa ng 20–23% kaysa palayang maganda ang patubig. May malaking epekto ang nitroheno (N) at potasyo (K) sa ani at bayomas sa Jakenan. Kung ikukumpara sa pinakamagandang kundisyon ng nutrisyon, ang karaniwang pagbaba ng ani dahil sa kawalan ng N ay 42%, at 33-36% naman ay dahil sa kawalan ng K. Ang mga peste ay isang malaking panganib para sa palay na itinanim sa bandang huli ng tag-ulan sa Jakenan. Ang dalawa sa tatlong panahon ng huling tag-ulan ay nagkaroon ng 56–59% pagbaba ng ani dahil sa peste.

Kasunod ang kalibrasyon at pagtatasa ng modelong ORYZA2000 para sa palay na angkop sa bukid-kapatagan at sahod-ulan. Ang modelong pagtutulad ay kinalibra na gamit ang mga datos tungkol sa halaman, lupa, at patubig na kinuha sa unang eksperimento. Ang pagsasakatuparan ng modelo ay sinuri na gamit ang mga impormasyon tungkol sa halaman, lupa, at patubig na galing sa ikalawang eksperimento. Maayos na naitulad ng modelong ORYZA2000 ang lalim ng tubig sa bukid, tensiyon ng tubig sa lupa, bayomas na nasa ibabaw ng lupa, at ani ng butil ng palay sa iba't-ibang antas ng abonong N sa kondisyong sahod-ulan at may patubig sa lugar na pinag-aralan. Ang kalibradong modelo ay ginamit upang tantiyahin ang potensiyal na ani na kailangan naman para masuri ang mga agwat sa ani dahil sa mga bagay na nagpapababa nito (insekto at organismo na nagdudulot ng sakit) sa himpilan ng pagsusuri at mga bagay na naglilimita sa ani sa bukid ng mga magsasaka.

Ginamit ang ORYZA2000 na modelo upang tingnan ang potensiyal at aktuwal na ani ng sahod-ulan na palayan sa 3 kundisyon – mababaw, kainaman, at malalim na antas ng tubig sa ilalalim ng lupa. Ang nakalkulang potensyal na ani ay mula 3.74

(para sa maagang tanim noong tag-ulan ng Oktubre) hanggang 5.53 tonelada kada ektarya (sa tanim noong tag-araw ng Hulyo). Ang potensiyal na ani ng palay na itinanim noong tag-araw ay mas mataas kaysa ani ng palay na itinanim noong tag-ulan dahil sa mas mataas na antas ng enerhiyang dulot ng liwanag ng araw (radiation levels) sa panahon ng pagbubutil. Ang aning kinalkula gamit ang OYZA2000 para sa halamang sahod-ulan na itinanim noong unang araw ng Nobyembre hanggang kalagitnaan ng Marso ay naapektuhan nang malaki ayon sa lalim ng tubig sa lupa. Naabot ang aning potensiyal sa mababaw na tubig ngunit ito ay mas mababa doon sa mga lugar na malalim ang tubig.

Ang ORYZA2000 ay ginamit para makita ang epekto sa ani ng lalim ng tubig sa lupa sa harap ng iba't-ibang paraan ng pangangalaga (araw ng paghahasik, paraan ng pagbubungkal, pagbibigay ng suplementong patubig, at pagpapataba sa pamamagitan ng N) at upang makatulong na makapagbalangkas ng pinakamagandang rekomendasyon para sa iba't-ibang lalim ng tubig sa lupa para sa palayang sahod-ulan sa Central Java, Indonesia. Malaki ang ibinaba ng ani sa sahod-ulan na palay na kinalkula gamit ang ORYZA2000 noong malapit nang matapos ang panahon ng tag-ulan. Ito ay nagpapakita ng kahalagahan ng kaalaman tungkol sa mga kritikal na petsa ng pagtatanim sa harap ng pabago-bagong lalim ng tubig sa lupa. Ang mga kritikal na petsa ay unang araw ng Abril (para sa nahuling tanim sa tag-ulan na mababaw ang tubig), kalagitnaan ng Marso (para sa kainamang babaw ng tubig), at mga unang araw ng Marso (para sa malalim na tubig sa lupa).

Ang antas ng tubig sa ilalim ng lupa ay may malinaw na epekto sa pagtugon sa pagbubungkal, paglalagay ng abono, at karagdagang patubig sa palay (sahod-ulan) na itinanim sa bandang huling panahon ng tag-ulan. Sa mababaw na tubig sa ilalim ng lupa, ang ani ay nasa potensiyal para sa paghahasik hanggang sa mga huling araw ng Marso; ang malalim na pagbubungkal ay walang epekto sa ani. Ngunit kung ang paghahasik ay naantala hanggang sa mga huling araw ng Abril, ang malalimang paglilinang ay nakapagbigay ng mas mataas na ani na umabot sa 2.5 tonelada kada ektarya dahil sa mas malakas na daloy ng kapilar (increased capillary rise) kung ikukumpara sa nakaugaliang paraan ng pagbubungkal. Sa mababaw at kainamang lalim ng tubig sa lupa, ang pag-aabono ng 120 kilong N kada ektarya ay nagbigay ng karagdagang ani na 1 tonelada kada ektarya kaysa doon sa walang N nang ang binhi ay inihasik mula Nobyembre hanggang Enero, na tumaas at umabot sa 1.4 tonelada kada ektarya nang ang huling paghahasik ay ginawa noong mga unang araw ng Marso. Sa kondisyong malalim ang tubig sa lupa, ang ani ay nalimitahan ng kawalan ng tubig at ang paglalagay ng 120 kilong N kada ektarya ay nagresulta sa dagdag na ani na umabot lamang sa 0.8 tonelada kada ektarya sa mga binhing inihasik noong Nobyembre at Disyembre. Sa mababaw na tubig sa ilalim ng lupa, pinarami ng karagdagang patubig ang ani nang ang paghahasik ay nagsimula noong mga huling araw ng Marso pasulong at mas malalaking dagdag na ani ang nakuha ng paghahasik noong Abril pasulong. Para dito sa mga masyado ng huling paghahasik, ang dagdag na ani ay umabot ng 1.2–3.1 tonelada kada ektarya nang 7.5 mm na patubig ay ibinigay tuwing ang tubig sa pang-ibabaw na lupa ay naging mababa pa sa itinakdang kapasidad (I_1); ito ay naging 1.2–2.4 tonelada kada ektarya nang ang irigasyon araw-araw ay 7.5 mm mula paglilihi ng palay hanggang sa paggulang (I_2). Kapag malalim ang tubig sa lupa, ang pagtugon ng halaman ayon sa patubig ay naobserbahan noong mga unang araw ng Pebrero, at ang dagdag na ani ay nasa 0.7 tonelada kada ektarya sa I_1 at 0.3−0.5 tonelada kada ektarya sa I_2.

Ang pagbabago-bago sa mga katangian ng lupa, mga kondisyong may kinalaman sa pamamalagi at pagkilos ng tubig, ani ng pananim, at bayomas ay sinuri sa iba't-ibang posisyon sa *toposequence* sa mga palayang umaasa sa sahod-ulan na may magkaparehong talaan ng pag-ulan (Eksperimento 3). Ang mga lugar na ito ay kumakatawan sa pangkaraniwang sistema ng pagtatanim sa palayang sahod-ulan (isang taniman sa Thailand) at sa mas masinsinang sistema (dalawang taniman sa Indonesia). May mga mahahalagang pagkakaiba sa pamamalagi at pagkilos ng tubig sa mga bukirin (lalim nang naipong tubig sa ibabaw ng lupa at lalim ng tubig sa ilalim ng lupa, bilang ng araw na walang naipong tubig sa ibabaw ng lupa), K na puwedeng ipagpalit (exchangeable K); organikong karbon; at nilalamang lupang malagkit (clay) na ayon sa posisyon sa lupa. Mayroon ding pagkakaiba sa ibang katangian ng lupa [N, posporus (P), CEC, pH, buhangin (sand), banlik (silt), bultong kasinsinan (bulk density)]; sa ani; at sa laki ng karagdagang ani sa bukid ng mga magsasaka dahil sa paggamit ng matinding paraan ng pagkontrol sa damo at mga iminungkahing dami ng abono; ngunit di pare-pareho ang mga epekto nito sa iba't-ibang bansa, panahon, at taon.

May mahalagang kaugnayan ang kondisyon ng pamamalagi o pagkilos ng tubig sa *toposequence*: ang mga taniman sa itaas ng *toposequence* ay laging mas tuyo kaysa sa mga hanay na nasa ibaba ng *toposequence*. Ang mga ani sa mga taniman na may magkatulad na pagsubok ay pareho lamang sa punto ng estadistika sa lahat ng posisyon sa *toposequence* ay totoo sa anim sa 11 tambalan ng panahon na pagsubok at ang kontrol sa dalawang bansa. Subali't ang kaibahan ng ani sa mga walang-abonong taniman ay naobserbahan sa iba't-ibang posisyon sa *toposequence* sa 2 (2001–02 maagang tag-ulan, 2002 huling tag-ulan) sa 4 na panahon sa Indonesia at sa 2 (2001 at 2002) sa 3 tag-ulan sa Thailand. Gayundin naman, may pagkakaiba sa ani na nakita sa mga hanay (plot) na hindi inalisan ng damo sa 1 (2001–02 maagang tag-ulan) sa 4 na panahon sa iba't-ibang posisyon sa *toposequence* sa Indonesia. Ang mga posisyon sa itaas ay may mas mababang ani kaysa sa mga posisyon sa ibaba. Ang karaniwang dagdag na ani dahil sa matinding pagsupil sa damo (0.65 tonelada kada ektarya) o ang rekomendadong paglalagay ng abono (1.25 tonelada kada ektarya) ay magkatulad sa lahat ng posisyon sa *toposequence*. Ito ay nagpapatunay na hindi lamang posisyon sa *toposequence* ang magagamit na solong basehan sa pagkontrol ng damo at paglagay ng pataba. Ang pagpapataas ng ani na higit sa pangkalahatang rekomendasyon sa lahat ng lugar na umaasa sa sahod-ulan ay maari lamang matamo sa pamamagitan ng pamamahala na naaayon sa partikular na panahon, at sa partikular na bukid. Isang halimbawa nito ay "pamamahala ng nutrisyon ayon sa partikular na lugar" (site-specific nutrient management).

Kasunod ang pagtukoy ng mga bagay na naglilimita sa ani ng palay sa mga bukid ng magsasaka sa iba't-ibang posisyon sa *toposequence*. Ang epekto ng mga bagay na ito na nagtatakda at humahadlang sa ani ay pinag-aralan base sa iba't-ibang posisyon sa *toposequence* na gamit bilang basehan na ani na kinalkula sa pamamagitan ng ORYZA2000. Ang batayan na ani sa ilalim ng kundisyong kulang sa sustansiya ay tinantiya rin base sa pagkuha ng halaman ng pagkain (sustansiya) at ang ipinapalagay na pampisiolohikal na kagalingan ng paggamit ng sustansiya ng palay (physiological nutrient use efficiency) sa mga bukirin ng magsasaka na umaasa sa ulan.

Ang mga bukid ng mga magsasaka na nasa iba-ibang posisyon sa *toposequence* ay nagpakita ng malaking pagkakaiba sa lugar at panahon sa aspeto ng pagmamalagi o pagkilos ng tubig (350–1446 mm panahonang patak-ulan, –150 hanggang 50 cm lalim ng tubig sa lupa) at sa dami ng abono na ginamit (76–166 N, 0–45 P, and 0–51 kilong K kada ektarya). Sa isang panahon (2002 huling tag-ulan), ang aning tinantiya gamit ang modelo (na may limitasyon sa tubig) ay mababa ng 28% sa tinatantiyang potensyal na ani. Ang tinantiyang agwat sa ani na dulot ng limitasyon sa tubig ay 52% sa isang nayon (Sidomukti), na kung saan ang ulan ay mas kaunti kung ihahambing sa normal. Tatlo sa apat na nayon ang may mas malaking agwat sa ani (dahil sa tubig) sa itaas na posisyon sa *toposequence* kaysa sa ibabang posisyon. Noong 2001–02 sa panahong maaga ang tag-ulan, ang tinayang agwat sa ani dahil sa kakulangan ng N, P, at K sa mga tanimang walang abono ay 55, 20, at 53%, ayon sa pagkakasunud-sunod. Ang agwat sa ani dahil sa N ay pare-pareho sa mga nayon base sa estadistikang panukat, ngunit mas malaki ang agwat sa mga posisyong nasa itaas ng *toposequence*. Sa kabilang banda, ang agwat sa ani dahil sa K ay malaki (56–66%) sa tatlong nayon, habang sa Jadi (kung saan maraming *exchangeable K*), ang agwat ay maliit (28%) at mas mataas ito sa posisyong nasa bandang itaas ng *toposequence*. Ang limitasyon sa N at K ang mga pangunahing hadlang upang matamo ang masagang ani sa palayang sahod-ulan na inaalagaan ng mga magsasaka sa Indonesia.

Sa kabuuang talakayan, ang mga kalakasan at kahinaan ng mga kaparaanang ginamit upang malaman ang mga batayang ani ay pinaghambing. Ang mga bagay na humahadlang at nagpapababa ng ani ay natukoy sa pamamagitan ng paggamit ng mga paraang ito sa palayang sahod-ulan sa himpilan ng pananaliksik at bukid ng magsasaka. Ang pamamagitang pampangasiwaan na sumasaklaw sa mga hakbang na magpapalaki ng ani (para sa mga naglilimita ng ani) at magsasanggalang sa ani (para sa mga bagay na nagpapababa ng ani) ay iminungkahi upang pagbutihin ang produksiyon sa sahod-ulan na palayan.

Ang pagsusuring estadistika sa mga kinuhang datos ng halaman, lupa, at tubig mula sa mga eksperimentong ginawa sa maraming lugar at iba't-ibang panahon ay nagpakita ng mga kaibhan ng epekto sa pangangalaga sa tanim sa bawat posisyon sa *toposequence*. Subali't ang paraang pang-eksperimento ay magastos at madaling maimpluwensiyahan ng pabago-bagong panahon. Bukod doon, ang kawalan ng paghahambingan ay nakakapagpahirap sa pagsusuri ng mga bagay na hadlang sa masaganang ani sa mga lugar na sinasaka. Kung kaya't kinakailangang gumamit ng mga hindi tuwirang paraan para makalkula ang paghahambingang ani, katulad ng pagbalangkas ng modelo ng pananim. Ang mga ginamit na panukat gaya ng bagay na naghahayag ng pagkakatugma (goodness-of-fit) at mga krokis ng paghiwa-hiwalay (scatter diagram) ay nagpakita na ang ORYZA2000 ay may sapat na kakakayahang tumantiya ng tamang ani sa palayan na may iba-ibang antas ng pag-aabono (N) maging sa kondisyong sahod-ulan o maayos ang patubig. Ang pagmomodelo upang magaya ang situwasyon at mailarawan ang maaring mangyari ay pwedeng gamitin upang maitakda ang partikular na antas (referensiya) o basehan sa mga di madaling sukatin o di agad nakukuha sa mga eksperimento sa bukid. Ang paggamit ng paraang ito ay mahahadlangan ng kawalan ng datos na kailangan (datos tungkol sa tanim, lupa, panahon o klima, o pangangalaga) ng modelo. Ang *goodness-of-fit* at *scatter diagram* ay nagpahayag ng malapit na pagkakaugnay ng tinantiyang ani base sa kagalingan ng paggamit ng sustansiya ng palay (physiological nutrient use efficiency) at ng aktuwal na ani sa mga *plot* na may PK (walang N) at may NP (walang K). Ang paggamit ng *physiological nutrient use efficiency* ng palay sa pagtakda ng ani ay may potensiyal na kakayahang mapagdugtong ang mga resulta ng pag-aaral sa mga ginawang eksperimento sa himpilan ng pananaliksik at sa mga bukid ng magsasaka. Gayunpaman, may mga babalang kailangang hakbang na dapat gawin kung ginagamit ito para sa situwasyon na may kakulangan sa sustansiya ngunit may mataas na tustos ng sustansiyang katutubo (high indigenous nutrient supply) tulad ng kondisyon sa P sa lupa sa Central Java, Indonesia.

Ang malaking agwat (48%) sa pagitan ng potensiyal at aktuwal na ani na gamit ang kasalukuyang pamamaraan sa mga palayang sahod-ulan ay nagmumungkahi na may magandang pagkakataon para lalong pahusayin ang produksiyon ayon sa mga posibilidad na may kinalaman sa sistemang biyolohikal at pisikal, sosyal at ekonomikal, at teknikal. Ang malaki at di pabago-bagong agwat ng ani dahil sa limitasyon ng tubig at sustansiya (N, K) at impestasyon ng peste sa himpilan ng pananaliksik at mga bukid ng magsasaka ay naghahayag ng tiyak na pamamagitan upang mapagbuti ang produksiyon sa palayang sahod-ulan. Ang mga hakbang na pampataas ng ani ay ang pagtatanim sa tamang panahon, malalimang pagbubungkal, karagdagang patubig, paglalagay ng abonong N at K, samantalang ang mga pananggalang na hakbang ay ang pagtatanim sa tamang panahon at pagsupil sa damo. Ang pagkakamit ng dagdag na ani ay depende sa pamumuhunan para sa imprastraktura at mga polisiya na tulad ng ukol sa irigasyon o mga pasilidad para makakuha ng tubig, tulong na salapi para sa abono, polisiya sa pangangalakal ng bigas at presyo, at matibay na pakikipag-ugnayan sa mga ahente ng pagbabago [mga mananaliksik, mga nagtatrabaho sa ekstensiyon, magsasaka, mga lider ng komunidad, tagagawa ng polisiya, mga organisasyon na di pang-gobyerno (NGOs)].

Ang mga pamamaraang ginamit sa pagtaya ng pinagbasehang ani ay nagbibigay ng malawak na pagkakaunawa sa mga bagay na nakakahadlang sa produksiyon ng palay sa mga lugar na sahod ulan, at maari din itong isagawa sa iba pang lugar upang malaman ang mga hadlang sa masagang ani at mga pamimilian sa pamamahala upang palaguin ang produksiyon.

Samenvatting

Rijst wordt door meer dan de helft van de wereldbevolking gegeten en is het hoofdbestanddeel van het menu in Azië. De laatste jaren is de wereldbevolking toegenomen met gemiddeld 1,2% per jaar, terwijl de rijstopbrengsten (per ha) toenamen met gemiddeld 0,7%. Verder is het aandeel rijst in het landbouwareaal in zuidoost Azië tussen 1980 en 2004 afgenomen van 26 tot 23%. Deze ontwikkelingen maken het nodig te streven naar hogere opbrengsten van rijst, vooral onder minder gunstige omstandigheden, zoals in regenafhankelijke systemen, waar de huidige opbrengsten ver beneden de door het klimaat bepaalde potenties liggen. In Azië wordt ongeveer 59 Mha regenafhankelijke rijst verbouwd, i.e. ongeveer 44% van het totale rijstareaal. De gemiddelde opbrengst van rijst in regenafhankelijke laaglandsystemen is 2,1 Mg ha^{-1}, en de productiviteit wordt beperkt door een onzekere watervoorziening, lage bodemvruchtbaarheid en het optreden van ziekten, plagen en onkruiden. Nutriëntengebrek, droogte en aantasting door ziekten en plagen komen vaak tegelijkertijd voor in regenafhankelijke rijstsystemen. Om teeltmaatregelen gericht op het verhogen van de opbrengst te kunnen ontwerpen, is inzicht nodig in de grootte en de variatie van opbrengstdervingen die optreden als gevolg van beperkende factoren.

Deze studie was gericht op het vergroten van inzicht in de variabiliteit in tijd en ruimte van de beschikbaarheid van water en nutriënten, en het effect daarvan op groei en opbrengst van rijst, om op grond daarvan verbeterde teeltsystemen te ontwerpen in regenafhankelijke laaglandsystemen op hellende terreinen (toposequenties) in zuidoost Azië. Om dit doel te realiseren is gebruik gemaakt van productie-ecologische concepten. Statistische en systeemanalytische analyses zijn toegepast, gebaseerd op veldproeven en simulatiemodellen, om de effecten van opbrengstbepalende, -beperkende en -reducerende factoren te kwantificeren. De resultaten zijn gebruikt om tijd- en plaatsafhankelijk gewasmanagement opties te identificeren voor rijstverbouw op toposequenties.

Er zijn drie series veldproeven uitgevoerd, twee op proefstations en één op praktijkpercelen. Experiment 1, gericht op onderzoek naar de effecten van water en grondbewerking, is uitgevoerd in 1995–96 op Jakenan Proefstation, Midden Java, Indonesië (6°47′ S, 111°12′ E, 8 m boven zeeniveau). Op Midden Java duurt het regenseizoen (langjarig gemiddelde regenval is 1550 mm) van november tot juni, met een piek in januari. Dit biedt de mogelijkheid twee rijstgewassen na elkaar te verbouwen, een ‘vroeg-regenseizoen’ gewas (november–maart) en een ‘laat-regenseizoen’ gewas (maart–juni). Experiment 2, gericht op onderzoek naar de effecten van water en kunstmest, is eveneens uitgevoerd op Jakenan Proefstation in de periode

1997–2000. Experiment 3, gericht op onderzoek naar de variabiliteit van waterhuishouding, bodemchemische en -fysische factoren, drogestofproductie en opbrengsten van rijst over toposequenties, is uitgevoerd in de periode 2000–02 op praktijkpercelen van boeren rondom Jakenan Proefstation en rondom Ubon Ratchathani Rijstonderzoekscentrum, noordoost Thailand (15°19′ N, 104°40′ E, 127 m boven zeeniveau). In noordoost Thailand duurt het regenseizoen van november tot juni en wordt gewoonlijk één rijstgewas verbouwd.

Eerst zijn de opbrengstbeperkende factoren voor regenafhankelijke rijst op Jakenan Proefstation geïdentificeerd op basis van statistische analyses van gemeten gewas- bodem- en hydrologische karakteristieken in seizoenen waarin het gewas ziekten- en plagenvrij was, en op basis van systeemanalytische analyses voor seizoenen waarin dat niet het geval was. De opbrengstverliezen als gevolg van de interactieve effecten van water- en nutriëntengebrek zijn gekwantificeerd, rekening houdend met de invloed van ziekten en plagen. In één van de zes groeiseizoenen (1997–98) waren de opbrengsten van regenafhankelijke rijst 20–23% lager dan die van geïrrigeerde rijst. Stikstof en kali hadden een significant effect op de korrelopbrengst en totale drogestofproductie in Jakenan. De opbrengstdervingen, als gevolg van het niet toedienen van stikstof en kali, waren 42%, en 33–36% in vergelijking met de situatie met optimale nutriëntenvoorziening. Ziekten en plagen vormen een serieuze bedreiging voor rijstgewassen, die laat in het regenseizoen verbouwd worden in Jakenan. In twee van de drie ‘laat-regenseizoen’ gewassen was de geschatte opbrengstderving als gevolg van ziekten en plagen 56–59%.

Het gewasgroeimodel ORYZA werd gekalibreerd en gevalideerd voor regenafhankelijke laaglandrijst. Het model is gekalibreerd met behulp van gewas- bodem- en hydrologische karakteristieken gemeten in Experiment 1. Vervolgens is het model gevalideerd op basis van de gegevens gemeten in Experiment 2. De door ORYZA2000 gesimuleerde waarden van de waterstand, de bodemwaterpotentiaal, de bovengrondse drogestofproductie en de rijstopbrengst kwamen goed overeen met de gemeten waarden, bij verschillende stikstofkunstmestgiften, zowel voor geïrrigeerde als voor regenafhankelijke omstandigheden. Het gevalideerde model is vervolgens gebruikt om potentiële opbrengsten te berekenen, die zijn gebruikt als referentiewaarden bij de analyse van opbrengstdervingen als gevolg van opbrengstreducerende (ziekten en plagen) factoren op het proefstation en opbrengstbeperkende factoren op praktijkpercelen.

Het model ORYZA2000 is ook gebruikt om potentiële en regenafhankelijke opbrengsten te berekenen voor verschillende scenario’s met drie grondwaterstanden. De gesimuleerde potentiële opbrengsten bij een hoge grondwaterstand varieerden van 3,74 Mg ha^{-1} (voor gewassen geteeld in het begin van het natte seizoen, geplant in oktober) tot 5,53 Mg ha^{-1} (voor gewassen geteeld in het droge seizoen, geplant in juli). Echter, bij diepere grondwaterstanden ware de opbrengsten in het droge seizoen extreem laag (< 0,5 Mg ha^{-1}). Potentiële opbrengsten waren hoger voor gewassen geteeld in het late regenseizoen dan voor gewassen geteeld in het vroege regenseizoen, vanwege de hogere stralingsniveaus tijdens de periode van korrelvulling. De gesimuleerde opbrengsten van gewassen geteeld onder regenafhankelijke omstandigheden in de periode begin november tot midden maart hingen sterk af van de grondwaterstand.

ORYZA2000 is eveneens gebruikt om het effect van de grondwaterstand te analyseren op rijstopbrengsten bij verschillende teeltmaatregelen (plantdatum, grondbewerking, supplementaire irrigatie en stikstofbemesting). Deze analyses dienen als basis voor het formuleren van aanbevelingen voor optimale teeltsystemen voor gebieden met verschillende grondwaterstanden in de regenafhankelijke systemen van Midden Java in Indonesië. De gesimuleerde opbrengsten onder regenafhankelijke omstandigheden namen scherp af voor laat in het regenseizoen geplante gewassen. De sterke opbrengstdaling bij later planten in het 'late-regenseizoen' benadrukken het belang van het vaststellen van de 'kritische' plantdatum voor verschillende grondwaterstanden. De simulatieresultaten lieten zien dat voor ondiepe grondwaterstanden begin april de kritische plantdatum is, vergeleken met midden en begin maart voor situaties met respectievelijk gemiddelde en diepe grondwaterstanden.

De grondwaterstand had ook een duidelijk effect op de opbrengstrespons op grondbewerking, kunstmesttoediening en supplementaire irrigatie van regenafhankelijke rijst geplant tegen het eind van het regenseizoen. In situaties met een ondiepe grondwaterstand realiseerden gewassen geplant tot eind maart nog potentiële opbrengsten, en had diepploegen geen invloed. Echter wanneer er eind april geplant werd, leidde een diepe grondbewerking tot een opbrengstverhoging van 2,5 Mg ha^{-1}, als gevolg van meer capillaire opstijging dan bij conventionele grondbewerking.

In situaties met een (relatief) ondiepe grondwaterstand leidde toediening van 120 kg N ha^{-1} tot een opbrengstverhoging van ongeveer 1 Mg ha^{-1}, vergeleken met de controle voor gewassen geplant tussen november en januari, oplopend tot 1,4 Mg ha^{-1} voor gewassen geplant rond begin maart. Met een diepe grondwaterstand was de opbrengst waterbeperkt, en leidde toediening van 120 kg N ha^{-1} tot een opbrengstverhoging van ongeveer 0,8 Mg ha^{-1} voor gewassen geplant in november en december. Met een ondiepe grondwaterstand leidde supplementaire irrigatie tot toenemende opbrengsten voor gewassen geplant vanaf begin maart, oplopend voor gewassen geplant vanaf april. Voor deze later geplante gewassen varieerde de opbrengstverhoging van 1,2 tot 3,1 Mg ha^{-1} wanneer 7,5 mm water werd toegediend zodra het vochtgehalte van de bovengrond (0–20 cm) beneden veldcapaciteit kwam (I_1) en van 1,4 tot 2,4 Mg ha^{-1} bij dagelijkse toediening van 7,5 mm in de periode van aanleg van de pluim (PI) tot het eind van de afrijping (I_2). In situaties met een diepe grondwaterstand begonnen gewasopbrengsten positief te reageren op irrigatie vanaf een planttijd in begin februari, variërend van ongeveer 0,7 Mg ha^{-1} in I_1 en 0,3–0,5 Mg ha^{-1} in I_2.

Variaties in bodemeigenschappen, hydrologische condities, korrelopbrengsten en bovengrondse drogestofproductie zijn geanalyseerd voor verschillende posities op een toposequentie in twee gebieden waar regenafhankelijke rijstteelt plaatsvindt met vergelijkbare neerslaghoeveelheden (Experiment 3). Deze gebieden zijn representatief voor de meest voorkomende regenafhankelijke rijstproductiesystemen: één regenafhankelijk gewas per jaar in Thailand en twee regenafhankelijke gewassen per jaar in Indonesië. Op de verschillende posities binnen de toposequentie werden substantiële verschillen waargenomen in veldhydrologie (diepte van de waterlaag op het veld, grondwaterstand, aantal dagen zonder waterlaag), uitwisselbaar kalium, organisch C en kleigehalte. Er werden ook verschillen waargenomen in andere bodemeigenschappen (totaal N, totaal P, kationenuitwisselcapaciteit, zand- en leemgehalte, volumedichtheid), en in opbrengst en de mate van opbrengstverhoging als gevolg van een intensieve onkruidbestrijding en/of toediening van aanbevolen kunstmestgiften. Deze verschillen waren echter niet consistent over landen, seizoenen en jaren.

De hydrologische condities waren significant gecorreleerd met de positie binnen de toposequentie: percelen boven aan de toposequentie waren altijd droger dan die beneden aan de toposequentie. In 6 van de 11 combinaties van seizoen en controlebehandeling in de twee landen waren de opbrengsten op percelen met dezelfde behandeling statistisch niet verschillend voor verschillende posities binnen de toposequentie. Er werden echter verschillen in opbrengst waargenomen tussen nietbemeste percelen op verschillende posities binnen de toposequentie in twee (2001–02 ‘vroeg regenseizoen’, 2002 ‘laat regenseizoen’) van de vier seizoenen in Indonesië en in twee (2001 en 2002) van de drie natte seizoenen in Thailand. Er werden ook opbrengstverschillen waargenomen tussen niet-gewiede percelen op verschillende posities binnen de toposequentie in Indonesië in één (2001–02 ‘vroeg regenseizoen’) van de vier seizoenen. De opbrengsten waren in het algemeen lager voor de posities op de top dan aan de voet van de toposequentie. De gemiddelde opbrengstverhoging als gevolg van intensieve onkruidbestrijding (0,65 Mg ha^{-1}) of toediening van de aanbevolen hoeveelheid kunstmest (1,25 Mg ha^{-1}) waren vergelijkbaar op de verschillende posities binnen de toposequentie. Deze resultaten geven aan dat positie binnen de toposequentie niet het enige criterium kan zijn voor formulering van aanbevelingen voor onkruidbestrijding en/of kunstmesttoediening. Opbrengstverhogingen ten opzichte van de opbrengst bij standaardaanbevelingen kunnen alleen worden gerealiseerd bij gebruik van tijd- en plaatsafhankelijke teeltmaatregelen, zoals toegepast bij plaatsspecifiek nutriëntenbeheer.

Opbrengstbeperkingen voor regenafhankelijke rijst op percelen van boeren zijn vervolgens geïdentificeerd. De effecten van opbrengstbepalende en opbrengstbeperkende factoren op de opbrengst van rijst op verschillende posities binnen de toposequentie zijn gekwantificeerd op basis van de gesimuleerde potentiële opbrengsten. Referentieopbrengsten onder nutriëntenbeperkte omstandigheden in regenafhankelijke rijst op praktijkpercelen zijn geschat op de basis van nutriëntenopname en theoretische fysiologische nutriëntengebruiksefficiënties voor rijst.

De percelen van boeren op verschillende posities binnen de toposequentie vertoonden een grote variabiliteit in zowel ruimte als tijd, zowel in hydrologische condities (350–1446 mm jaarlijkse regenval, –150 tot +50 cm 'grondwaterstand') als in toegediende hoeveelheid kunstmest (76–166 N, 0–45 P, and 0–51 kg K ha^{-1}). In één seizoen (2002 'laat regenseizoen') waren de gesimuleerde regenafhankelijke opbrengsten 28% lager dan de gesimuleerde potentiële opbrengsten. De gesimuleerde opbrengstderving als gevolg van watergebrek was 52% in één dorp (Sidomukti) waar de regenval significant lager dan normaal was. In drie van de vier dorpen was de opbrengstderving als gevolg van watergebrek groter voor percelen bovenaan de toposequentie dan voor percelen in lagere posities. In het 'vroege regenseizoen' 2001–02 was de berekende opbrengstderving als gevolg van N-, P- en K-gebrek in nietbemeste percelen respectievelijk 55, 20 en 53%. De opbrengstderving als gevolg van N-gebrek was statistisch niet verschillend voor de verschillende dorpen, maar wel groter voor posities bovenaan de toposequentie. Anderzijds was de opbrengstderving als gevolg van K-gebrek substantieel (56–66%) in drie van de vier dorpen, terwijl die in Jadi (waar het gehalte aan uitwisselbaar K relatief hoog was) laag (28%) was, en hoger voor posities bovenaan de toposequentie. N- en K-gebrek behoren dus tot de meest belangrijke opbrengstbeperkende factoren in regenafhankelijke rijstverbouw op praktijkpercelen in Indonesië.

In de algemene discussie worden sterke en zwakke punten van de gevolgde methodes voor het schatten van referentieopbrengsten met elkaar vergeleken. Opbrengstbeperkende en -reducerende factoren zijn geïdentificeerd voor regenafhankelijke rijst, geteeld op zowel proefstations als praktijkpercelen. Er worden teeltmaatregelen aanbevolen om tot hogere opbrengsten te komen in deze regenafhankelijke systemen, zowel voor de beperkende als voor de reducerende factoren.

Statische analyses van gemeten gewas-, bodem- en hydrologische karakteristieken in op meerdere locaties en in verschillende seizoenen uitgevoerde proeven laten zien dat de effecten van teeltmaatregelen op rijstopbrengsten verschillen voor verschillende posities binnen de toposequentie. Dergelijke experimenten zijn echter duur en tijdrovend, terwijl de variabiliteit in weersomstandigheden interpretatie van de resultaten bemoeilijkt. Daarnaast is het ontbreken van referentieopbrengsten een beperking bij het analyseren van de effecten van opbrengstbeperkende en opbrengstreducerende factoren op praktijkpercelen. Er bestaat dus behoefte aan indirecte methoden om die referentieopbrengsten te berekenen, zoals het gebruik van gewasgroeimodellen. De berekende 'goodness-of-fit' parameters en de spreidingsdiagrammen laten zien dat voor Indonesië het model ORYZA2000 bevredigende resultaten geeft bij het simuleren van opbrengsten bij verschillende niveaus van kunstmesttoediening, zowel onder geïrrigeerde als onder regenafhankelijke condities. Gewasgroeimodellen kunnen worden gebruikt om plaatsspecifieke referentieopbrengsten te berekenen die niet in veldproeven kunnen worden vastgesteld. Het gebruik van gewasgroeimodellen wordt echter beperkt als de benodigde gegevens met betrekking tot de bodem, het gewas en/of het weer niet beschikbaar zijn. De 'goodness-of-fit' parameters en de spreidingsdiagrammen laten een goede samenhang zien tussen de geschatte opbrengsten (gebruikmakend van fysiologische nutriëntengebruiksefficiënties) en de gemeten opbrengsten op proefveldjes waar geen stikstof (PK) en kali (NP) werd toegediend. Gebruik van fysiologische nutriëntengebruiksefficiënties biedt in principe de mogelijkheid om waarnemingen op proefvelden en in praktijkpercelen aan elkaar te koppelen. Voorzichtigheid is echter geboden bij gebruikmaking van deze efficiënties in situaties waar de beschikbaarheid van nutriënten uit natuurlijke bronnen hoog is, zoals voor P op Midden Java in Indonesië.

Het grote (48%) verschil tussen de potentiële en actuele opbrengsten onder huidig beheer op de praktijkpercelen suggereert dat er aanzienlijke mogelijkheden zijn om de opbrengsten te verhogen gezien de biofysische, socio-economische en technische mogelijkheden. De grote en consistente opbrengstdervingen als gevolg van beperkingen in de beschikbaarheid van water en nutriënten (N, K) en ziekten, plagen en onkruiden, zowel op de proefvelden als op praktijkpercelen, suggereren dat specifieke teeltmaatregelen zouden kunnen leiden tot hogere opbrengsten. Opbrengstverhogende maatregelen omvatten aanpassingen in plantdatum, diepploegen, supplementaire irrigatie en N- en K-kunstmestgiften, terwijl maatregelen die de oogstzekerheid vergroten zouden kunnen bestaan uit aanpassingen in plantdatum en onkruidbestrijding. De mate waarin dergelijke maatregelen ook inderdaad door boeren zullen worden toegepast en hogere opbrengsten worden gerealiseerd hangt mede af van investeringen in infrastructuur, beleidsmaatregelen en institutionele regelingen, zoals irrigatiefaciliteiten, systemen voor wateropslag, subsidies op kunstmest, de handel in rijst, prijsmaatregelen, en een sterke samenwerking tussen verschillende belanghebbenden, zoals onderzoekers, voorlichters, boeren, lokale leiders, politici en NGOs.

Het combineren van verschillende methoden om de referentieopbrengsten te bepalen heeft het inzicht vergroot in de beperkingen bij de verbouw van rijst in regenafhankelijke systemen. Deze methodes zouden ook kunnen worden toegepast in andere systemen, maar een absolute voorwaarde is dat de experimentele gegevens die nodig zijn, ook beschikbaar zijn.

List of selected papers of the author

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Boling, A.A., Bouman, B.A.M., Tuong, T.P., Murty, M.V.R., Jatmiko, S.Y., 2007. Modelling the effect of groundwater depth on yield-increasing interventions in rainfed lowland rice in Central Java, Indonesia. Agric. Syst. 92, 115-139.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (5.6 credits)

- Site-specific water and nutrient management in rainfed rice across the toposequence

Writing of Project Proposal (7 credits)

- Site-specific water and nutrient management in rainfed rice across the toposequence (2001)

Post-Graduate Courses (2.8 credits)

- Operational tools for regional land use analysis; PE&RC, Mansholt Institute (2001)
- ORYZA2000 training course; IRRI, WUR (2003)

Deficiency, Refresh, Brush-up and General Courses (2.8 credits)

- Simulation of ecological processes; Plant Production Systems (2001)
- Simulation of crop growth; Plant Production Systems (2001)

Competence Strengthening / Skills Courses (3.4 credits)

- Modular course on public speaking; IRRI, International Toastmaster's Club (2005 and 2006)

Discussion Groups / Local Seminars and Other Scientific Meetings (5.9 credits)

- PE&RC discussion group 4: Plant and Crop Ecology (2001)
- CWE and PPS lunch seminars (2006-2007)
- IRRI Thursday seminar (2001-2006)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (0.3 credits)

- PE&RC day on scientific agenda: who pulls the string (2006)

International Symposia, Workshops and Conferences (6.4 credits)

- Water-wise in rice production; IRRI, Los Baños, Philippines (2002)
- 4th International crop science congress; Brisbane, Australia (2004)
- World rice research conference; Tsukuba, Japan (2004)

Curriculum vitae

Anita Areola Boling was born on 1 December 1962 in Mabini, Pangasinan, Philippines. She graduated from the University of the Philippines Los Baños with the degrees in BSc in Agricultural Engineering in 1985 and MSc in Agrometeorology, minor in Agronomy, in 1991. To enhance her knowledge, she took specialized agrometeorology courses conducted by the Philippine Atmospheric, Geophysical, and Astromical Services Administration (PAGASA) in 1986 and Israel Meteorological Service in 1994, in cooperation with the World Meteorological Organization (WMO). She also attended the training on Environmental Characterization in Chinsurah Rice Research Station, India in 1992. Furthermore, she attended the course on the ORYZA2000 model conducted at the International Rice Research Institute (IRRI) in 2003.

In 1986, she passed the Agricultural Engineering Board examination given by the Professional Regulation Commission and the Career Service Eligibility examination by the Civil Service Commission.

She worked at the IRRI Climate Unit as a Student Assistant under the Rice-weather project in 16 countries in 1984–85; and as a Graduate Assistant under the projects on Agroclimatic databank in 13 rice-growing countries and Philippine agroclimatic classification in 1987–90. She joined the Water Science Section of IRRI as Research Assistant in 1991, rose into ranks, and became Associate Scientist in 2006. Since 1991, she has been assisting Senior Scientists in conceptualizing, planning, and implementing experiments and surveys on water management, and in analysing the agroclimatological data needed for spatial and temporal drought characterization and the promising production systems for increased cropping intensity in rainfed lowland rice ecosystems. Since then, she has been actively involved in an interdisciplinary research approach through collaborative research within IRRI and with the National Agricultural Research and Extension Systems (NARES).

In 2000, she was awarded a scholarship under the IRRI-Wageningen University and Research Centre sandwich PhD programme. The research output under this scholarship is summarized in this thesis.

Funding

Funding for this research was obtained from the International Rice Research Institute (IRRI) and Wageningen University and Research centre (WUR) Sandwich PhD programme. Research was carried out under the framework of Rainfed Lowland Rice Consortium which was later renamed as Consortium for Unfavorable Rice Environments. Field experiments were co-funded by the Ubon Rice Research Center in Ubon Ratchathani, Thailand and Jakenan Experiment Station, Central Java, Indonesia.