

Aus dem Institut für Pflanzenernährung und Bodenkunde
der Christian-Albrechts-Universität zu Kiel

**Yield and nitrogen uptake of lowland rice (*Oryza sativa* L.)
in a water-saving ground cover rice production system (GCRPS)
in Beijing, North China**

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TO MY FAMILY

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ABBREVIATIONS

$\delta^{13}\text{C}$	C-13 discrimination value
ANOVA	Analysis Of Variance
AWD	Alternative Wetting and Drying irrigation
CGR	Crop Growth Rate
DrM	Dry Matter
FL	Flowering
GCRPS	Ground Cover Rice Production System
HI	Harvest Index
IAA	Indole Acetic Acid
LAGR	Leaf Area Growth Rate
LAI	Leaf Area Index
LAID	Leaf Area Index Duration
MT	Maximum Tillering stage
NHI	Nitrogen Harvest Index
NUE	Nitrogen Use Efficiency
PFM	Plastic Film Mulching
PI	Panicle Initiation
PSII	Photosystem II
PT	Productive Tillers
SRI	System of Rice Intensification
TGW	Thousand-Grain Weight
TR	Tillering stage
WHC	Water Holding Capacity
WUE	Water Use Efficiency

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CHAPTER 1**GENERAL INTRODUCTION***Rice production in the world*

Rice is the dominant staple food for many countries in Asia and the Pacific, South and North America as well as Africa. In Asia alone, more than 2 billion people obtain 60 to 70 percent of their calories from rice. It is also the most rapidly growing source of food in Africa (FAO, 2003). Rice production is so important for food security of the world that the Food and Agriculture Organization of the United Nations has nominated the year 2004 as the 'International Year of Rice'.

Rice is highly adapted to its environment after a long period of selection and breeding. Rice can be grown under a range of conditions in different climates (Yoshida, 1981). Four main rice ecosystems spread around the world: irrigated rice, rainfed lowland rice, upland rice and flood-prone rice (Maclean et al., 2002). **i** Irrigated rice is grown in banded fields with repetitive irrigation for one or more crops per year. The total harvest area of irrigated rice is about 79 M hectares, about 43 % of it is located in East Asia. China has the largest area of irrigated rice in the world (Dobermann and Fairhurst, 2000). **ii** Rainfed lowland rice grows in banded fields too, but it is characterised by a lack of water control. Hence, it is exposed either to flooding or drought during the growing period. There are about 36 M hectares rainfed lowland rice in the world, while most of them (34 M hectares) are located in the Asian sub-humid subtropics (Dobermann and Fairhurst, 2000), for example in India. **iii** Upland rice is grown with small amounts of external input in unbanded fields and only occupies a relatively small proportion of total rice area (17 M hectares) in Asia, Africa and Latin America (Maclean et al., 2002). The yield of upland rice has increased slowly over the last 30 years and it yields only about 1 ton per hectare on average in most countries. **iv** Flood-prone rice grows in inland and tidal wetland areas where the depth of flood water is greater than 50 cm

throughout the growing period. Flood-prone rice is mainly located in South and Southeast Asia, and is characterised by a small planting area of approximately 12 M hectares and a low yield of about 1.5 ton per hectare (Dobermann and Fairhurst, 2000).

Two major rice species are cultivated in the world. *Oryza sativa* originates from Southeast Asia, while *O. glaberrima* originates from Africa. *O. sativa* is the dominant rice species, which is widely cultivated in Asia, Africa, Europe, America, and Oceania. *O. sativa indica* is widely grown in tropical regions such as Southeast Asia. *O. sativa japonica* is adapted to cooler areas, so it is widely grown in temperate countries, such as the central and northern China, Korea, and Japan.

Rice production in China

China is one of the original centres of rice cultivation. The history of rice cultivation in China could be dated back to 12,000 years before present (Whitehouse, 2003). China is the world's largest rice producer (FAO, 2003), with 20 % of world rice planting area, producing 32 % of rice in the world (FAO, 2003). In China, the area for rice production occupies only 36 % of arable land used for the major cereal crops, and provides 44 % of its grain yield (Tab. 1-1; FAO, 2002)

Table 1-1 Harvest area and production of major cereal crops in China in 2002¹⁾

Crops	Production (Mt)	Harvest area (Ha)
Rice	176,553,000	28,177,000
Maize	123,175,000	24,528,000
Wheat	91,290,240	23,500,060
Sorghum	2,731,000	745,600
Barely	2,470,000	725,000
Millet	2,070,779	1,100,420
Oats	600,000	400,000

¹⁾ Data extracted from FAO online database, 2002.

O. sativa indica is dominant in the south of China, while *O. sativa japonica* is widely grown in the north of China. More than 90 % of the rice area in China is irrigated. The environment in the south-eastern China is more favourable for rice growth because of high temperatures

and sufficient rainfall during the growing period. In the north-eastern China, the rice production suffers from low temperatures and water shortage, but rice quality is better than in other areas (Maclean et al., 2002).

Challenges in Chinese rice production

Growing industry and population consume more resources and more food at the same time, which creates a great challenge to agricultural production. This is highly crucial for rice production because it is a system consuming more water than any other crop (Bouman et al., 2002). The planting area and yield of rice must be kept at a reasonable level because rice is not only a major staple food for the Chinese people but also an integral part of the Chinese culture.

The rice production area has continuously decreased in China (FAO, 2002) because of the competition for labour and resources. The rapidly growing industries attracted many farmers to live and work in cities, which is more profitable than growing crops. The movement of farmers into the cities is more pronounced in the south of China, which is the Chinese major rice production area. Furthermore, industry and households consume more and more water resources, which leads to problems of water scarcity for agriculture in the north of China (Hou and Hunter, 1998) and problems of irrigation with polluted water in the south of China (Fan et al., 2002). An extreme example is Beijing: rice cultivation has been reduced year by year by legislation, and it will be officially terminated at the end of 2007 mainly because of water scarcity in this area (Tang, 2003).

Even though rice yield in China is the highest among all the rice producing countries (FAO, 2003), rice yield needs to be constantly increased to meet the demand without resorting to imports before the per capita rice consumption declines due to dietary diversification and growing population (Maclean et al., 2002). ‘Who will feed China’ was not just an exaggerating appeal in the book of Mr. Brown in 1995, but it illustrates that the situation is

serious and that scientists and politicians have to find solutions to improve food security in the future.

Development of water-saving techniques in rice production systems

More than 90 % of the total rice cultivated in China is irrigated lowland rice with its high water demand (approximately four times higher than for wheat), having a low water use efficiency. This is due to the fact that more than 80 % of all water used in paddy rice is lost unproductively by evaporation (16-18 %), leaching and surface run-off (50-72 %) (Stroosnijder, 1982). Seepage from paddy fields with a free water layer is higher than from water-saturated soils due to the hydraulic pressure (Lu et al., 2000). With respect to water scarcity in China, this type of rice production with ponded water must be improved to save water and to assure food production. In principle this seems to be achievable because of the high amount of unproductive water losses in rice production.

Alternative wetting and drying irrigation (AWD) has been commonly used as a water-saving practise in many countries including China for more than one decade. In this system, the soil is allowed to dry for a few days in-between irrigation events depending on plant developmental stages (Cabangon et al., 2001; Shi et al., 2002). Some success has been reported as far as yield and water demand are concerned (Gani et al., 2002; Li et al., 1994; Lu et al., 2002; Xu et al., 1990). However, unproductive water losses could not be totally avoided by AWD, so the water consumption is still high in AWD since the soils need to be submerged at least during the irrigation period.

Another water-saving alternative to submerged lowland rice is the ‘System of Rice Intensification (SRI)’, which has been developed in Madagascar (Uphoff and Randriamiharisoa, 2002). In SRI, the soil is kept moist by regular irrigation or AWD, but aerated during the vegetative growth phase. A thin layer (1-2 cm) of water is maintained after panicle initiation in SRI. Accompanied by proper field management, in particular weeding, rice yield in SRI has been increased compared to the traditional system in Madagascar

(McHugh et al., 2002) because aerobic conditions promote root growth (Joelibarison, 1998), tiller formation (Uphoff and Randriamiharisoa, 2002), and grain filling (Uphoff, 1999). SRI demonstrated that lowland rice can grow quite well under aerobic conditions after a period of adaptation, at least before its reproductive period.

With the breeding of aerobic rice, the most significant change came along in the development of water-saving rice production in China so far. Aerobic rice is grown in aerobic soils similar to wheat or maize during its entire growing period (Wang and Wang, 1989). Aerobic rice was developed by the genetic recombination of lowland and upland rice varieties from different eco-geographic origins (Wang et al., 2002). By aerobic rice, large amounts of water are saved (Wang et al., 2002), but up to now yield is not as good as in traditional culture systems (Yang et al., 2002). The other shortcoming of aerobic rice is that its market value is lower than lowland rice, as it tastes different, which limits its expansion to larger areas.

The plastic film or straw mulching rice production systems have been developed since 1990 in China. Its original aim was to improve the tolerance to low temperatures by plastic film in the Hubei Province (Shen et al., 1997). This is similar to the success in Japan in the 1960s, but now its benefits for water-saving rice production led to the adoption of this system in China. In plastic film mulching (PFM) also called Ground Cover Rice Production System (GCRPS), lowland rice varieties are used and the soil is kept humid by covering materials. Some groups reported the amount of water saved with this system can be as high as 60-85 % of the need in the traditional paddy systems with no adverse effects on grain yield (Huang et al., 1999). Other groups, however, reported significant yield reductions under such conditions (Borrell et al., 1997; Castillo et al., 1992).

Yield gap and nitrogen utilisation in rice production

According to a recent survey in Asia, rice farmers obtain only 60 % of the potential yield (Dobermann and Fairhurst, 2000). In regions where farmers can afford to use more fertilisers, they make more profits from rice production and achieve higher yields. In poorer regions,

farmers apply only little or no fertiliser, which increases the yield gap. Among different nutrients, nitrogen (N) is most limiting for rice (De Datta, 1981; Yoshida, 1981). However, nitrogen use efficiency (NUE) is quite low in paddy rice production compared to other cereals in Asia (Cassman et al., 1996; IRRI, 1998; Mitsui, 1954). Theoretically, the amount of N fertiliser to be applied to irrigated rice would need to be increased about threefold with the current NUE to increase rice production by 60 %, which is required to meet the demand of the growing population (Cassman and Harwood, 1995).

The low NUE of paddy rice is mainly related to ammonia volatilisation, denitrification, and leaching (Savant and De Datta, 1982). Numerous new techniques have been developed in the last decades to improve the plant N uptake and to reduce N losses, and thus improve NUE. Plant breeders contributed by developing hybrid rice varieties, which are characterised by high ability of N utilisation and high yield (Yang et al., 1999). Also, there is work which focuses on the fertilisation methods in paddy rice systems, such as fertiliser types (Jena, 1999; Norman, et al, 1989), fertilisation timing (Linguist and Sengxua, 2001; Wopereis-Pura, et al., 2002) and fertiliser after recommendation systems (Cassman et al., 1998).

Aims of the experiment

The Ground Cover Rice Production System (GCRPS) permits to save substantial amounts of water while growing traditional lowland rice varieties, that are strongly preferred by consumers in northern China. GCRPS was therefore selected from a range of recently developed water-saving rice production systems for a study aiming at improvements of crop development and at monitoring of the environmental impact of GCRPS. In detail, the crop's reaction to reduced irrigation, the nitrogen dynamics in the soil-plant system, and the nitrogen use efficiency of the rice crop were studied. The two-year field experiments presented here were complemented by a parallel PhD thesis of Kreye (2004), in which the water balance and the effect of GCRPS on greenhouse gas emissions were studied in the same experimental field (Fig. 1-1).

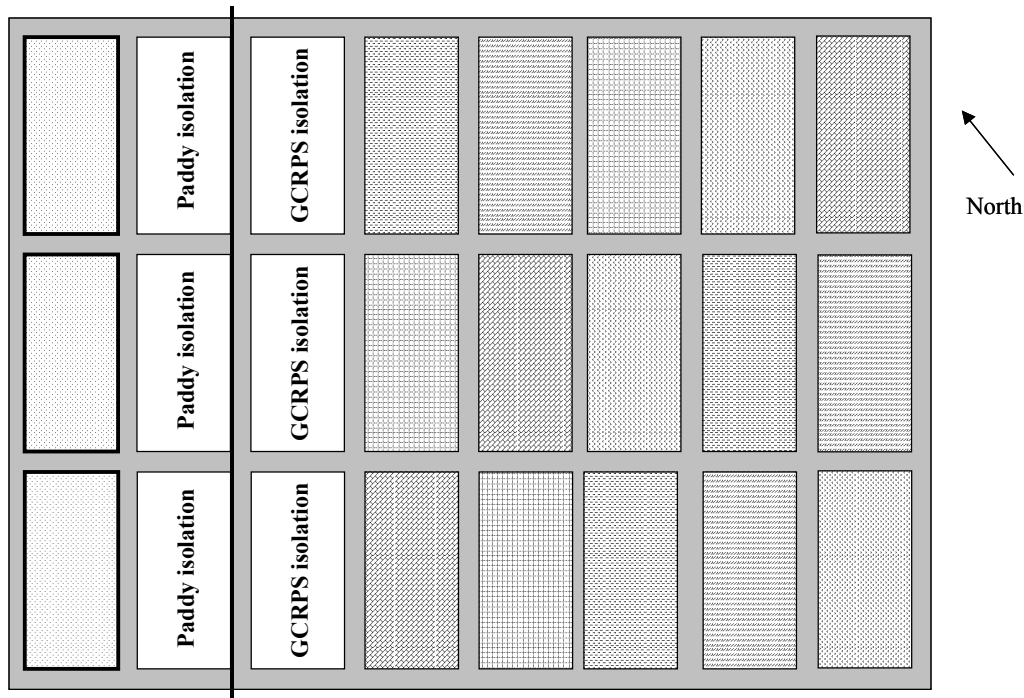


Figure 1-1 Sketch of experimental field set-up on Dongbeiwang experimental station of China Agricultural University in the north-western suburb Dongbeiwang of Beijing.

Paddy control
 GCRPS_{Plastic}
 GCRPS_{Straw}
 GCRPS_{Bare}
 Aerobic rice

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CHAPTER 2**Growth and yield formation of lowland rice (*Oryza sativa* L.) in the water-saving ground cover rice production system (GCRPS)**

Keywords: Rice, Yield, LAI, Tillers, Crop growth rate, Water-use efficiency

Abstract

A new water-saving ‘Ground Cover Rice Production System (GCRPS)’ was evaluated in 2001 and 2002 near Beijing, North China. In GCRPS, lowland rice was cultivated without a standing water layer during the entire growth period. Instead plots were irrigated when soil water tension was below -15 kPa (approx. 90% water holding capacity). In order to prevent soil evaporation the soil surface was covered with 14 µm thick plastic film (GCRPS_{Plastic}) or mulched with straw (GCRPS_{Straw}). In a third GCRPS treatment the soil was left uncovered (GCRPS_{Bare}). These treatments were compared with lowland rice cultivated under traditional paddy conditions (Paddy control). In an additional treatment with bare soil a rice cultivar which has been developed for aerobic rice cultivation (Aerobic rice) was grown. Compared to Paddy control, only 30 to 55% of irrigation water was applied in GCRPS treatments. However, plants in GCRPS were smaller, developed fewer panicles and had a smaller leaf area index compared to Paddy control. Yield was significantly lower in GCRPS_{Bare} and GCRPS_{Straw} compared to Paddy control in both years, while yield in GCRPS_{Plastic} was only 10% lower compared to Paddy control in 2002. Water-use efficiency (WUE, gram grain yield per litre water input) in GCRPS_{Plastic} was higher (0.35) than in Paddy control (0.23). Aerobic rice matured notably earlier than lowland rice, exhibited a significantly higher grain yield compared to GCRPS_{Bare}, and had the highest WUE (0.43) in both years. Grain yield was highly significantly correlated with maximal leaf area index and leaf area index duration.

Among yield components, the number of productive tillers had the largest positive effect on yield, while the number of grains per panicle, thousand-grain weight and harvest index remained almost unaffected among treatments, except of significant higher HI of aerobic rice compared to lowland rice cultivars. The experiment demonstrates that GCRPS has a potential to save substantial amounts of water at relatively minor yield penalties.

1. Introduction

Water scarcity is limiting agricultural production in South East Asia in general and in the North China Plain in particular. In this region water deficits may be as high as 1.5 billion cubic meters per year (Hou and Hunter, 1998). This has led to yield reduction (Hou and Hunter, 1998) and a pronounced drawdown of the ground water table (Brown and Halweil, 1998). Furthermore, concurring water demand for industry and urban population forces legal restrictions in agricultural water use, i.e., the arable land allowed for the cultivation of lowland rice with its inherently high water demand has been reduced since 2002 and paddy rice production will be forbidden in Beijing at the end of 2007 (Tang, 2003).

Water demand for lowland rice is approximately four times higher than for other cereals. This is due to the high unproductive water losses (> 80% of water applied) by evaporation (16-18%), surface run-off, and percolation (50–72%) (Stroosnijder, 1982). Hydraulic pressure of the free water layer is contributing significantly to the latter (Lu et al., 2000). Preliminary attempts to reduce water input were made in the USA by growing lowland rice under aerobic conditions with sprinkler irrigation (Westcott and Vines, 1986). Under the prevailing market structures in the United States, the 20-30% of yield loss outweighed the benefits of water-saving, and research was discontinued. However, today in South East Asia water shortage not only increases the costs of production but also severely limits the yield. This is why several water-saving rice production systems are under investigation, such as the alternate wetting and drying irrigation (Tabbal et al., 2002), rice cultivation on raised beds (Ockerby and Fukai,

2001), cultivation of aerobic rice cultivars (Wang et al., 2002), and the Ground Cover Rice Production System, GCRPS (Lin et al., 2002). They are currently considered as promising cultivation systems with moderate yield penalties and substantial savings in water input. Most of these systems still focuses on high-yielding rice production on typical heavy soils, attempting to grow rice under periodically or entirely non-flooded conditions. It is obvious that water-saving production systems will not entirely replace traditional paddy, but in water-scarce environments or under conditions where concurring water demand of non-agricultural users forbids extensive use in agriculture, water-saving rice production systems may be a promising alternative which greatly reduces seepage and evaporation. Current estimates show that such conditions apply to a significant part of the rice growing areas of northern China (Wang and Zhou, 2000).

Although benefits of water-saving rice cultivation in water-limited areas have been illustrated (Shen et al., 1997; Huang et al., 1999; Gani et al., 2002), other experimental evidences suggest moderate to severe yield reduction (Castillo et al., 1992; Borrell et al., 1997) of water-saving cultivation compared to paddy. With lower soil water potentials the elongation of internodes, the number of panicles and the crop growth rate were reduced in comparison to flooded conditions (Lu et al., 2000).

It can be anticipated that the aerobic cultivation affects nutrient availability and physico-chemical properties of the rooting medium. Furthermore, sowing techniques are changed from transplanting to direct sowing, and thus should affect early growth. The pronounced changes in the environmental factors may require the development of rice varieties which are especially 'designed' for aerobic cultivation. In order to investigate the potential benefits of such varieties, aerobic rice (Wang et al., 2002) was included in this experiment. We recorded leaf area and the number of tillers as prominent physiological traits which describe the growth potential of rice plants, as well as grain yield, water consumption, and water-use efficiency of lowland and aerobic rice varieties during a two-year field experiment with the GCRPS.

2. Materials and Methods

2.1. Field management

In 2001 and 2002, a field experiment was conducted at Dongbeiwang Experimental Station (39.95°N; 116.3°E) of the China Agricultural University, Beijing, China. The climatic conditions during the two experimental years are reported in Figure 2-1. Five treatments were compared: **i** Paddy control, with traditional puddling and water supply; **ii** GCRPS_{Plastic}, with plots covered with 14 μm thick transparent plastic film and watered when soil water tension dropped below 15 kPa; **iii** GCRPS_{Straw}, and **iv** GCRPS_{Bare}, with the same management of water supply as in treatment ii but plots covered with semi-decomposed rice straw (1.5 tons ha^{-1}) or without soil cover, respectively. In treatments **i** to **iv**, inbred lowland rice variety Yue Fu was grown. In treatment **v** aerobic rice variety Han Dao 297 was grown under the same conditions as in treatment GCRPS_{Bare}.

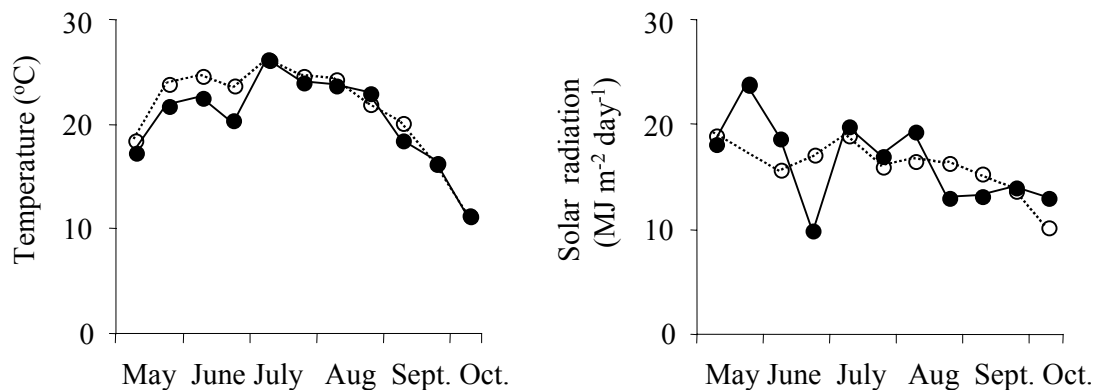


Figure 2-1 Daily air temperature and daily solar radiation during the rice growing period in Beijing in 2001 and 2002 (open and filled symbols, respectively). Each datum point represents the mean of 14 days.

The field was ploughed to 25 cm depth and levelled afterwards in May 2001 and 2002. Following, a basal dressing of 90 kg per hectare of potassium (K_2SO_4) and 90 kg per hectare of phosphorus ($\text{Ca}(\text{H}_2\text{PO}_4)_2$) was applied in both years. A total of 225 kg N per hectare of nitrogen fertiliser was applied in both years. In 2001, the total amount of N was applied as urea, while in 2002 180 kg urea-N plus 45 kg organic-N (rapeseed cake) per hectare were

supplied. In 2001, the 225 kg N per hectare was applied as a basal fertiliser application in GCRPS treatments in 2001, while in Paddy control N was split-applied with amounts of 90 kg, 67.5 kg, and 67.5 kg N three days after transplanting, at tillering and at panicle initiation, respectively. In 2002, GCRPS treatments received a basal dressing of 54 kg N per hectare of urea-N together with 45 kg N organic manure before sowing. 72 kg and 54 kg per hectare urea-N were subsequently applied at tillering and panicle initiation stage, respectively. Urea-N application in Paddy control was as in 2001. We noticed symptoms of micronutrient deficiency of rice cultivated under GCRPS in 2001, and therefore, applied 20 kg per hectare iron (FeSO_4) and 30 kg per hectare manganese (MnSO_4) as basal dressings prior to sowing in 2002.

After basal P and K fertiliser application, paddy plots were flooded and puddled. Sowing of rice in paddy plots took place by transplanting nursery-raised 35 days old plants on May 21 in 2001 and May 19 in 2002. In GCRPS treatments, rice seeds were directly sown before irrigation on May 5 in both years. The planting density in all treatments was 160 plants per square meter with 6 plants per hill in 2001. Due to the risk of lodging, the number of plants per hill in paddy plots was reduced from six to four in 2002, while the number of plants in GCRPS treatments remained at six plants per hill. The spacing of hills was identical in both years with 15 cm and 25 cm between rows, respectively. Plant protection measures included the spraying of herbicide. A special herbicide for rice in upland cultivation, provided by the Department of Crop Science at China Agricultural University, Beijing was used after the first irrigation in GCRPS. Afterwards, hand-weeding was used to control the weeds in GCRPS. Weeds in paddy plots were controlled by hand-weeding during the whole period. Further, a pesticide (Trichlorfon) was sprayed before panicle initiation to avoid the damage of tillers by striped rice borer in 2001 and 2002.

Water was supplied to individual plots by irrigation tubes connected with water meters. In GCRPS treatments, irrigation was scheduled according to tensiometer readings, i.e., water

was applied when soil water tension in 15 cm soil depth exceeded 15 kPa. In paddy plots, a free water table (3-5 cm) was established and maintained after transplanting shock (approximately 7 days after transplanting) until maturity, except for the drainage periods at maximum tillering (44-48 and 50-58 days after transplanting in 2001 and 2002, respectively) and late-maturity stage (105 and 104 days after transplanting in 2001 and 2002, respectively). The total amount of water supplied by irrigation and rainfall was calculated from water meter readings and rainfall gauges installed next to the experimental site. In order to minimise horizontal water flow from Paddy control to GCRPS plots, the former were spatially separated by two lines of isolation plots with 12-meter width and by burying of strong plastic film to a depth of 60 cm below soil surface. All plots were additionally separated by dams of 25 cm height and covered by strong plastic film in order to minimise water flow among plots of GCRPS treatments.

2.2. Plant sampling

Starting four weeks after transplanting and sowing in Paddy control and GCRPS plots, respectively, eight hills (0.3 m²) were harvested in biweekly intervals throughout the growing season. In order to minimise border effects, two rows were left between hills of subsequent harvests. At all harvests, the number of tillers were determined. Samples were separated into stems (including leaf sheaths), green leaves, necrotic leaves, and panicles (when present). Samples were washed with distilled water and oven dried at 70°C to constant weight. Leaf area index (LAI) was calculated from green leaf dry weight and leaf area of sub-samples determined by a scanner (Yu and Lin, 2003). Leaf area index duration (LAID) was calculated as the sum of LAI over time. Leaf area growth rate (LAGR) was calculated as the rate of increase in LAI per unit of time. LAI and crop growth rate (CGR) are presented for the phenological stages from tillering to maximum tillering (TR-MT), from maximum tillering to panicle initiation (MT-PI), and from panicle initiation to flowering (MT-FL). At maturity, yield was determined by harvesting an area of eight m² per plot and adjusted to a moisture

content of 14% of fresh weight. Thousand-grain weight was determined by counting and weighting.

With the exception of Paddy plots, which were isolated from GCRPS treatments (see above), all plots (6 x 12 m) were randomised within three blocks. Despite the restriction in randomisation due to spatial isolation of Paddy plots, the experiment was considered as a one-factorial complete-randomised block design. ANOVA and comparison of treatment means were done separately for years, as the fertiliser management and the planting density was changed from 2001 to 2002. All data were analysed by the GLM procedure of the Statistical Analysis System, version 8e (SAS, 1989).

3. Results

3.1 Dry matter formation

In 2001, dry matter formation of Paddy control over the growing season was significantly higher than that of all GCRPS treatments starting from June 18 (Fig. 2-2). At final harvest, total dry matter of Paddy control was 19.5 tons ha⁻¹ and nearly twice as high compared to that of GCRPS_{Bare} and GCRPS_{Straw} (Tab. 2-1). In 2002, dry matter in treatment GCRPS_{Plastic} was significantly higher compared to treatments GCRPS_{Bare} and GCRPS_{Straw} from July 2 until final harvest. Dry matter of Paddy control was consistently higher compared to GCRPS_{Plastic} but differences were only significant for harvests at July 16 and July 30 of 2002. Final shoot dry matter of Paddy control was 3.5 tons ha⁻¹ higher compared to GCRPS_{Plastic}, though this difference was not statistically significant (Tab. 2-1). Compared to the poor performance of lowland rice in GCRPS_{Bare}, dry matter of aerobic rice was higher in both years.

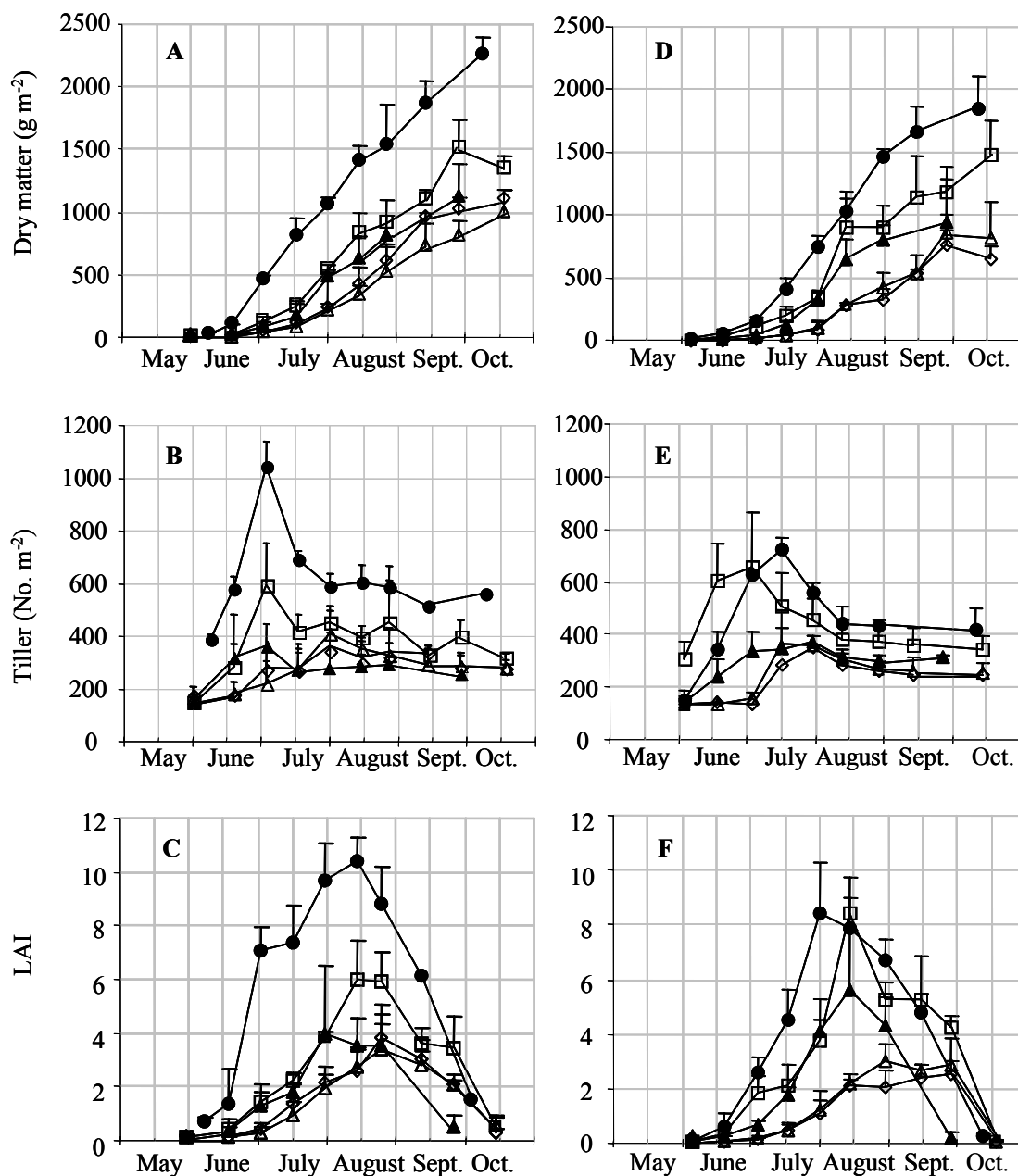


Figure 2-2 Time course of dry matter production, number of tillers and leaf area index (LAI) of GCRPS treatments (GCRPSPlastic, □; GCRPSStraw, Δ; GCRPSBare, ◇; Aerobic rice, ▲) in comparison to Paddy control (●) in 2001 (A, B, C) and 2002 (D, E, F). Each datum point represents the mean of 3 replicates.

Table 2-1 Agronomic grain yield (14% humidity), shoot (Shoot DrM) and straw (Straw DrM) dry matter, harvest index (HI), number of productive tillers, number of spikelets per panicle, number of grains per panicle, percentage of filled spikelets (given in brackets), and thousand-grain weight (TGW) of four GCRPS treatments with reduced water input compared to Paddy control in 2001 and 2002¹⁾

	Yield (t ha ⁻¹)	Shoot DrM (t ha ⁻¹)	Straw DrM (t ha ⁻¹)	HI (%)	Productive tillers (m ⁻²)	Spikelets (panicle ⁻¹)	Grains (panicle ⁻¹)	TGW (g)
<i>2001</i>								
Paddy control	8.5 A	19.5 A	12.2 A	37 BC	562 A	106 A	95 (89) A	20.4 B
GCRPS _{Plastic}	5.9 B	12.6 B	7.6 B	40 B	321 B	102 A	94 (92) A	21.1 B
GCRPS _{Straw}	3.6 C	9.5 BC	6.4 B	32 C	281 B	91 A	70 (79) A	18.0 C
GCRPS _{Bare}	4.2 C	9.3 C	5.7 B	39 B	299 B	93 A	83 (89) A	20.0 BC
Aerobic rice	6.1 B	10.5 BC	5.3 B	50 A	254 B	81 A	74 (93) A	30.8 A
<i>2002</i>								
Paddy control	7.4 A	17.8 A	11.4 A	36 A	419 A	121 A	107 (88) A	21.4 B
GCRPS _{Plastic}	6.8 A	14.3 AB	8.4 A	41 A	343 AB	113 AB	100 (88) A	19.9 B
GCRPS _{Straw}	3.3 B	8.1 C	5.2 B	35 A	250 B	94 B	87 (92) AB	22.4 B
GCRPS _{Bare}	2.9 B	7.5 C	5.0 B	33 A	247 B	90 B	83 (92) B	22.0 B
Aerobic rice	5.7 A	11.4 BC	6.4 B	44 A	304 AB	101 AB	87 (86) AB	27.6 A

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=3$.

Crop growth rate (CGR) of Paddy control was significantly higher compared to other treatments from tillering to maximum tillering stage (TR-MT) in both years (Tab. 2-2). CGR increased during the growth stage from maximum tillering stage to panicle initiation (MT-PI) compared to growth stage TR-MT. Treatments GCRPS_{Straw} and GCRPS_{Bare} had a consistently higher CGR during panicle initiation to flowering (PI-FL) compared to MT-PI in 2001 while the opposite was observed in 2002. Aerobic rice realised a high CGR during PI-FL compared to earlier growth stages in 2001 and exhibited high CGR from maximum tillering to flowering stage in 2002.

Table 2-2 Crop growth rate (CGR, g m⁻² d⁻¹) of Paddy control and GCRPS treatments from tillering to maximum tillering stage (TR-MT), from maximum tillering stage to panicle initiation (MT-PI), and from panicle initiation to flowering (PI-FL) in 2001 and 2002¹⁾

	TR-MT	MT-PI	PI-FL
<i>2001</i>			
Paddy control	17.6 A	26.2 A	21.1 A
GCRPS _{Plastic}	6.6 B	14.5 AB	15.3 A
GCRPS _{Straw}	6.1 B	6.7 B	12.7 A
GCRPS _{Bare}	6.9 B	9.9 AB	16.1 A
Aerobic rice	2.9 B	3.7 B	16.3 A
Mean	8.0	12.2	16.3
<i>2002</i>			
Paddy control	9.5 A	19.2 A	25.8 A
GCRPS _{Plastic}	4.4 B	20.4 A	15.6 BC
GCRPS _{Straw}	3.5 B	13.9 A	8.4 DC
GCRPS _{Bare}	3.0 B	14.4 A	6.7 D
Aerobic rice	4.0 B	16.7 A	18.0 AB
Mean	4.9	16.9	14.9

¹⁾ Figures within each column followed by the same letter are not significantly different, p=0.05, n=3.

Leaf area index (LAI) showed a typical pattern over time with a distinct peak more or less at the middle of the growth period. Consistent with observations presented above, Paddy control and GCRPS_{Plastic} had higher LAI compared to the others, except of Aerobic rice in 2002 which had approximately the same LAI compared to GCRPS_{Plastic} (Fig. 2-2). The increase of LAI over time is due to the formation of new leaves and their subsequent expansion. It can be anticipated that during early growth stages LAI is closely correlated with tiller formation. The difference in sowing time between Paddy control and GCRPS treatments was approximately 18 days (see Material and Methods) and resulted in pronounced differences among treatments in leaf area growth rate (LAGR) at the early growth stage. LAGR of Paddy control was significantly higher compared to GCRPS treatments during TR-MT and was significantly correlated with maximum tiller number (Fig. 2-3).

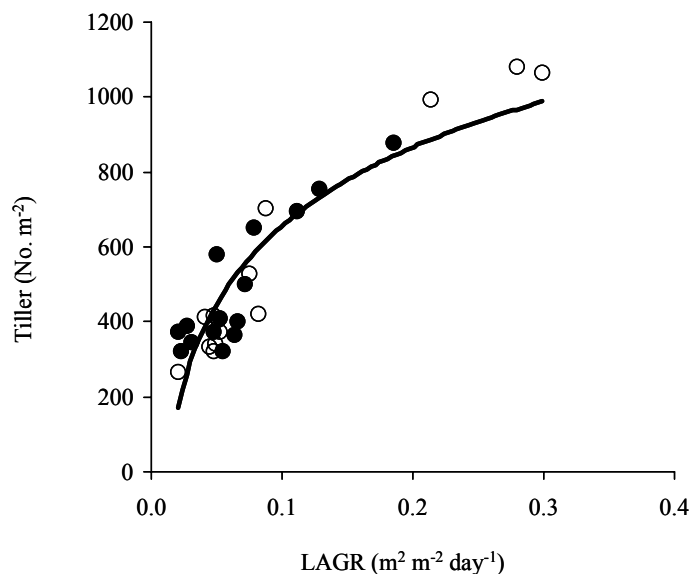


Figure 2-3 Logarithmic correlation between tiller number at maximum tillering stage and leaf area growth rate (LAGR) from tillering to maximum tillering stage (TR-MT) in 2001 and 2002 (open and filled symbols, respectively). $y = 302 \text{ Ln}(x) + 1353$, $R^2 = 0.82$, $n = 30$.

The formation and subsequent disposal of dispensable tillers are regulatory adaptations of the rice plants in response to environmental conditions, including water and nutrient supply, radiation, and temperature. In this experiment treatments had a significant effect on the total number of tillers (Fig. 2-2) and the number of productive tillers at maturity (Tab. 2-1). Paddy control and GCRPS_{Plastic} exhibited the highest number of tillers during early growth stages and a pronounced reduction towards maturity. This reduction was particularly pronounced in 2001. Other treatments exhibited no pronounced dynamic of tiller formation and, consistently in both years, exhibited an increase in tiller number until end of July. No noteworthy reduction in the number of tillers was evident afterwards. The distinct peak in the number of tillers in Paddy control in 2001 most probably was due to the higher number of plants per hill (six and four plants per hill in 2001 and 2002, respectively).

3.2 Grain yield and related traits

In both years, grain yield of Paddy control was significantly higher compared to that of GCRPS_{Straw} and GCRPS_{Bare} the latter which realised remarkably low yields ranging from 2.9 to 3.6 tons ha⁻¹. Compared to Paddy control, yield in GCRPS_{Plastic} was 30 % lower in 2001, while it was only 10 % lower in 2002. Aerobic rice performed significantly better compared

to GCRPS_{Bare} in both years and realised grain yields which were only slightly lower compared to that of lowland rice in treatment GCRPS_{Plastic}. These pronounced differences in grain yield among the investigated management systems were similarly observed for shoot and straw dry matter. The most promising GCRPS treatment with the soil surface covered with plastic film had a significantly lower shoot and straw DrM compared to that of Paddy control in 2001, while shoot and straw DrM was 20% and 26%, respectively, lower in 2002. Both treatments had remarkably constant harvest indices (HI) of roughly 36 % (Paddy control) and 40% (GCRPS_{Plastic}) in both years. Similarly to treatment differences in grain yield, Paddy control exhibited significantly higher shoot and straw DrM compared to GCRPS_{Bare} and GCRPS_{Straw} in both years.

HI in treatments GCRPS_{Bare} and GCRPS_{Straw} varied from 32 to 39 % and were not significantly different from that of other treatments in 2002 while differences in grain yield were highly significant among treatments. Consequently, HI was poorly correlated with grain yield (Tab. 2-3). Substantial genetic effects on HI were evident, as aerobic rice had a higher HI compared to lowland rice treatments. Thousand-grain weight of aerobic rice was significantly higher compared to that of other treatments (Tab. 2-1).

Yield formation in cereals is a complexly co-ordinated process which involves the build-up and subsequent re-assimilation of yield components. These processes are under genetic control and strongly affected by environmental conditions. Compared to growth of rice under Paddy cultivation the GCRPS apparently had distinct effects on relevant yield components: Significance of radiation absorption and, thus, size of photosynthesising leaf canopy is indicated by the highly significant correlation of maximal LAI and leaf area index duration with grain yield (Tab. 2-3). This also holds true for leaf area growth rate from tillering to maximum tillering stage which is closely correlated with tillering rate (Tab. 2-3) and maximal tiller number (Fig. 2-3). Tillering rate during that stage was further closely correlated with number of productive tillers (PT) and grain yield. While treatment differences in PT among

both years were comparably small in all GCRPS treatments (maximal difference roughly 50 PT), Paddy control had clearly less PT in 2002 compared to 2001. This most likely illustrates the effect of reduced planting density on number of PT in 2002 (Tab. 2-1). Surprisingly, correlation of grain yield with the number of spikelets per panicle was poorer compared to parameters mentioned above or in the case of HI (see above) or percentage of filled spikelets not significant at all (Tab. 2-3).

Table 2-3 Correlation coefficient (r) among yield, leaf area growth rate from tillering to maximum tillering stage (LAGR), maximum leaf area index (LAI_{max}), leaf area index duration (LAID), number of productive tillers (PT), number of spikelets per panicle (SP), number of spikelets per square meter (SM), percentage of filled spikelet (PFS), tillering rate (TR, from transplanting to maximum tillering stage), thousand-grain weight (TGW), and harvest index (HI). Data were pooled over treatments and two years, $n=30$.

	Yield	LAGR	LAI_{max}	LAID	PT	SP	SM	PFS	TR	TGW	HI
Yield	--	0.71 ^{***}	0.86 ^{***}	0.84 ^{***}	0.73 ^{***}	0.51 ^{**}	0.77 ^{***}	0.02 ^{ns}	0.80 ^{***}	0.1 ^{ns}	0.38 [*]
LAGR	--	--	0.75 ^{***}	0.88 ^{***}	0.89 ^{***}	0.36 ^{ns}	0.84 ^{***}	-0.20 ^{ns}	0.92 ^{***}	-0.3 ^{ns}	0.13 ^{ns}
LAI_{max}	--	--	--	0.92 ^{***}	0.78 ^{**}	0.60 ^{**}	0.83 ^{***}	-0.06 ^{ns}	0.83 ^{***}	-0.1 ^{ns}	0.08 ^{ns}
LAID	--	--	--	--	0.91 ^{***}	0.56 ^{**}	0.93 ^{***}	-0.07 ^{ns}	0.94 ^{***}	-0.3 ^{ns}	0.06 ^{ns}
PT	--	--	--	--	--	0.46 [*]	0.95 ^{***}	-0.02 ^{ns}	0.87 ^{***}	-0.3 ^{ns}	0.16 ^{ns}
SP	--	--	--	--	--	--	0.70 ^{***}	0.09 ^{ns}	0.41 [*]	-0.3 ^{ns}	0.09 ^{ns}
SM	--	--	--	--	--	--	--	-0.01 ^{ns}	0.84 ^{***}	-0.3 ^{ns}	0.17 ^{ns}
PFS	--	--	--	--	--	--	--	--	-0.05 ^{ns}	0.3 ^{ns}	0.17 ^{ns}
TR	--	--	--	--	--	--	--	--	--	-0.2 ^{ns}	0.03 ^{ns}
TGW	--	--	--	--	--	--	--	--	--	--	0.68 ^{***}
HI	--	--	--	--	--	--	--	--	--	--	--

*, **, and ***: significant at $p=0.05$, $p=0.01$, and $p=0.001$, respectively; ns.: not significant

3.3 Water demand

The amount of irrigation water supplied to GCRPS treatments was substantially lower than in Paddy control in both years. The irrigation amount in GCRPS treatments ranged from 1000 to 1300 mm in 2001 and increased slightly up to 1600 mm in 2002. Aerobic rice received the lowest water amount among GCRPS treatments in both years. Since yield reduction in GCRPS_{Plastic} compared to Paddy control was less pronounced than in the amount of irrigation

water, agronomic water use efficiency (WUE) in terms of grain yield per unit water supplied was higher. The highest WUE was consistently obtained in aerobic rice (Tab. 2-4).

Table 2-4 Water supply (irrigation plus rainfall) and agronomic water-use efficiency (WUE, grain yield per amount of water supply, amount of irrigation plus amount of rainfall) of treatments in 2001 and 2002. Figures in brackets give the percentage of irrigation water supplied relative to that supplied to Paddy control plots. Total amount of rainfall ranged from 280 to 315 mm in 2001 and 400 to 445 mm in 2002, the lower values for short-duration aerobic rice, the highest values for later-maturing GCRPS treatments¹⁾

	2001		2002	
	Water supply (mm)	WUE (g L ⁻¹)	Water supply (mm)	WUE (g L ⁻¹)
Paddy control	4041 (100)	0.23 B	3486 (100)	0.23 BC
GCRPS _{Plastic}	1589 (34)	0.37 AB	2083 (52)	0.33 AB
GCRPS _{Straw}	1506 (32)	0.24 B	2050 (53)	0.16 C
GCRPS _{Bare}	1642 (35)	0.26 B	2082 (54)	0.14 C
Aerobic rice	1346 (29)	0.45 A	1435 (34)	0.40 A

¹⁾ Figures within each column followed by the same letter are not significantly different, p=0.05, n=3.

4. Discussion

The high water demand for lowland rice cultivation is due to high unproductive water losses (> 80% of water applied) by evaporation (16-18%), surface run-off, and percolation (50–72%) (Stroosnijder, 1982). Hydraulic pressure of the free water layer is contributing significantly to the latter (Lu et al., 2000). In order to reduce water input the GCRPS may present one of the promising strategies, which are currently considered for rice producing areas with falling water supply capacity. The comparison of yield and dry matter of Paddy control with several GCRPS treatments revealed substantial water saving of roughly 45 to 70 % (Tab. 2-4) and moderate (GCRPS_{Plastic}) to serious (GCRPS_{Straw} and GCRPS_{Bare}) yield decrease.

Interestingly, the manner of surface-cover had pronounced effects on yield and related parameters. Yield and WUE in GCRPS_{Plastic} were significantly higher compared to GCRPS treatments with straw mulch or bare soil (Table 2-1, 4). Lowland rice in GCRPS_{Plastic} had significantly higher LAI, more tillers, and tended to have higher CGR and number of productive tillers compared to other GCRPS treatments with lowland rice. Differences in crop

growth rate among GCRPS treatments may be related to differences in soil temperature during the vegetative growth stage. From June 16 to June 30, mean daily soil temperature in two cm depth below the soil surface was 28.9° in GCRPS_{Plastic} compared to 24.8 and 25.3° C in GCRPS_{Straw} and GCRPS_{Bare}, respectively. GCRPS may have severe implications for crop establishment and yield formation, particularly in regions with relatively short growing periods like in Beijing (Fig. 2-1).

One principle difference between the GCRPS and the traditional paddy rice system is related to the planting technique. In most cases, lowland rice is transplanted from the nursery into the field (De Datta, 1981). In GCRPS this is only possible on loamy soils with a high water holding capacity or with a hardpan. Hence in most cases, as in our experiment, direct sowing is applied instead. Since the emergence of seedlings is sensitive to temperatures below 10° C, the low night temperatures in Beijing do not allow sowing before May. In the protected nursery, however, planting is possible approximately 18 days earlier. This gives paddy seedlings an advantage over those in GCRPS. For example, in 2001 the plants of Paddy control at transplanting (May 21) had developed four leaves while those in GCRPS had only two. These effects of transplanting versus direct sowing on early growth are illustrated by the significantly lower CGR of GCRPS treatments compared to Paddy control from tillering to maximum tillering (Tab. 2-2).

A further explanation for significantly higher crop and leaf area growth rate of Paddy control compared to GCRPS treatments is related to putative water management problems in GCRPS. Lowland rice is apparently very sensitive to reduced water availability, at least during the growth stage from sowing to maximum tillering (Castillo et al., 1992; Prasertsak and Fukai, 1997). Rice may even suffer from water stress when grown in flooded paddies (Hirasawa et al., 1992). Apart from xylem cavitation (Stiller et al., 2003), low root radial hydraulic conductivity (Ranathunge et al., 2003) is considered to be responsible for the high sensitivity to small changes in water supply and soil water tension. To our knowledge no information on

the water requirement of aerobic rice is available. This variety is the result of genetic recombination of lowland and upland varieties of different eco-geographic origins (Wang et al., 2002). No difference between upland and lowland varieties in root hydraulic conductivity has been found by Ranathunge et al. (2003) and the performance of aerobic rice in this experiment also gives no indication of superior seedling growth compared to GCRPS treatments with lowland rice. Further work on these aspects is required in order to improve the seedling establishment of rice production systems under aerobic conditions. Most likely, these improvements must make use of genotypic differences in water-stress and cold-resistance, both of which are likely to occur as in all the other crop species. Reduced leaf size and internode length (see appendix, Tab. A1) may be taken as additional indicators (Cabuslay et al., 2002) that plant water status was sub-optimal.

Significant differences between Paddy control and GCRPS in dry matter, number of tillers, leaf area, and grain yield (Fig. 2-2, Tab. 2-1) indicated a moderate to pronounced 'yield' penalty of water-saving rice production systems. These disadvantages may be attenuated if aerobic instead of lowland rice varieties are used. We compared aerobic rice versus lowland rice in GCRPS_{Bare}. The aerobic rice variety revealed a shorter vegetation period and reached maturity one month earlier than the lowland rice variety (144 vs. 172 days after sowing). Although the growth period of aerobic rice was shorter, aerobic rice compared to lowland rice had a higher dry matter and LAI compared to that of GCRPS_{Bare} in both years. Interestingly, neither number of productive tillers nor spikelets per panicle were significantly different between both treatments, leaving thousand-grain weight (TGW) as the major trait responsible for observed differences in grain yield between lowland and aerobic rice. The relatively constant TGW of lowland rice (18 to 22.4 g) over two years (Tab. 2-1) and significantly higher TGW of aerobic rice supports the finding of Yoshida (1981) who illustrated that TGW is mainly determined by genetic effects and relatively unaffected by the environment.

The rice production systems investigated in this experiment did not substantially affect the number of spikelets per panicle, the percentage of filled spikelets and the number of grains per panicle (Tab. 2-1). These parameters and HI were poorly or not significantly correlated with grain yield (Tab. 2-3), while the number of productive panicles was correlated with grain yield. In both Paddy control and GCRPS_{Plastic} the number of productive tillers was in the range considered to be optimal for high productive modern rice varieties (350 – 400 m⁻²), while the lower numbers of panicles in other GCRPS treatments indicates that the number of productive tillers was yield-limiting. The close correlation between the number of panicles and grain yield indicates that sink size contributed significantly to the variation of yield, particularly as the number of grains per panicle remained constant.

Number of tillers is an important morpho-physiological trait for grain yield in rice (Ying et al., 1998; Huang et al., 1999). It is generally believed that tillering is governed by the endogenous phytohormone balance with auxins stimulating and cytokinins weakening apical dominance, i.e., depressing or stimulating tiller formation (Zahir et al., 2001). Several exogenous factors such as transplanting, water supply, and N nutrition impose an effect on tillering. Responsible factors are unknown and difficult to discuss on the basis of our field experiments. However, some factors, which may contribute to this phenomenon shall be considered briefly. **i)** The transplanting procedure itself may stimulate tiller formation possibly by causing mechanical root damage which itself induced formation of numerous laterals (Forsyth and van Staden, 1981), and increased synthesis of cytokinins (Peres and Kerbauy, 1999). **ii)** It is well known from practical agriculture that water management imposes a pronounced influence on tillering. In order to prevent the formation of large numbers of unproductive tillers, paddy fields are drained after the active tillering stage (mid-season drainage). To our knowledge the involved mechanisms have not been thoroughly investigated. However, since it is known that water management affects endogenous cytokinin (Tao et al., 2002) and IAA content (Fan et al., 2002), it may be anticipated that this is causally

responsible. **iii)** The effect of nitrogen on tillering is more complex because water management affects not only the amount of available N due to its effect on mineralisation/immobilisation (Savant and De Datta, 1982) but also the dominant N form. In paddy NH_4^+ is the dominant N form (Savant and De Datta, 1982), NO_3^- is only stable in the oxidized rhizosphere (Shen, 1969), in GCRPS NO_3^- clearly dominates over NH_4^+ (Kronzucker et al., 1998). Although paddy rice can utilise either N form (Kronzucker et al., 2000), the N form, especially in the seedling stage, does affect plant growth and development. For example, if NO_3^- is the dominant N form, nitrogen uptake (Lin et al., 2004) and plant growth is depressed and so is tillering (Brueck et al., unpublished). A causal relation between the effect of the N form on ethylene synthesis (Barker et al., 1999), cytokinins synthesis (Walch-Liu et al., 2000), and tillering is anticipated.

More than 80% of the total variance in grain yield among the treatments could be explained by leaf area index duration and maximal LAI. This indicates that light interception and, thus, the availability of assimilates but not its partitioning is limiting yield. The fact that HI was unaffected may be taken as an indirect support for such an assumption (Tab. 2-1). Moreover, LAI was closely correlated with the number of panicles and leaf area growth rate was highly significantly correlated with tillering rate. These results illustrate a pronounced effect of management practices on LAI and tillering rate. The results further suggest that assimilate availability from maximum tillering to flowering stage exert significant control on final grain yield. Further work on sink size and the formation of generative organs should include more thorough investigations of light interception and planting density, the former parameter being relevant for defining source size optimisation, the latter most probably relevant for the adjustment of unintentional shading (Singh, 1994), which must have occurred considering the high LAI established in this experiment and may affect tiller number (Zhong et al., 2002).

The number of productive tillers is further determined by the tillering potential, which is affected by several environmental factors, of which nitrogen has a prominent role (Yoshida,

1981). Sufficient nitrogen supply enables maintenance of green leaf area after heading and thereby contributes to active photosynthesis available for grain production (Yoshida, 1981; Kropff et al., 1993). Low shoot N content in plants of treatments GCRPS_{Bare} and GCRPS_{Straw} (see chapter 3) certainly contributed to poor dry matter production and tiller formation and shorter tiller longevity (Ishizuka and Tanaka, 1969). Nevertheless, the high N supply in 2001 and the split N application during the second year, as well as the comparably high CGR (Tab. 2-2) from maximum tillering stage to flowering (Ying et al., 1998; Laza et al., 2001) supports the argumentation that effects of N form and water supply on hormonal regulation are more likely explanations for the low tiller formation potential of GCRPS compared to Paddy control.

Conclusion

The ground-cover rice production system (GCRPS) has the potential to reduce water input at relatively minor yield penalties and increases water-use efficiency. The surface-covering with plastic film appears to be superior compared to bare soil treatment or straw mulch application. This is partly due to the increase of soil temperature during early growth stages. The yield depression in GCRPS compared to Paddy control is likely to be due to both, sub-optimal water availability and effects of N form on tiller formation. Grain yield was highly correlated with plant canopy size (LAI and maximal LAI). This indicates that light interception and assimilate availability are prominent factors which contribute to yield formation, at least in the colder climate of Beijing. Aerobic rice exhibited a higher HI and thousand-grain weight compared to lowland rice and may be better suited for GCRPS. The investigated GCRPS requires further improvements in planting density and nitrogen management.

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CHAPTER 3**Plant nitrogen uptake dynamics and nitrogen use efficiency in the water-saving GCRPS**

Keywords: Lowland rice, Nitrogen, Nitrogen use efficiency, GCRPS, ^{15}N fertiliser recovery

Abstract

The new water-saving ‘Ground Cover Rice Production System (GCRPS)’ was evaluated in a two-year field experiment (2001 and 2002) near Beijing, North China. With GCRPS, lowland rice varieties are cultivated without a standing water layer during the entire growth period. Instead, the soil is irrigated to Ψ_{soil} above -15 kPa and covered either by 14 μm thick plastic film (GCRPS_{Plastic}) or straw (GCRPS_{Straw}) in order to reduce evaporation. The N nutritional status of rice plants grown in GCRPS was dominated by an unexpectedly pronounced N deficiency. Nitrogen fertiliser use efficiency (NUE) as well as N accumulation in the aboveground biomass of rice plants in GCRPS were lower than in Paddy control. Even with the application of the N fertiliser in three splits in 2002, only approximately 20% of all applied N fertiliser was taken up into the aboveground biomass of GCRPS plants. Nitrate leaching in GCRPS was severe and became the main pathway of N losses, which directly reduced nitrogen uptake and nitrogen fertiliser use efficiency of plants. It has also to be anticipated that apart from reduced N availability, the dominant form of N in GCRPS, nitrate, also had a negative impact on plant growth and N acquisition. Improvements in N uptake and hence NUE can probably be achieved by further adaptation of fertilisation to the special needs in GCRPS.

1. Introduction

Nitrogen is the most important nutrient for rice, and its deficiency occurs almost everywhere unless nitrogen is applied as a fertiliser (Yoshida, 1981; De Datta, 1981). To reach the potential yield target, more and more N fertiliser has been applied in paddy fields in recent years. The total amount of N fertiliser applied to irrigated rice needs to increase about threefold with the current nitrogen use efficiency (NUE) to increase rice production by 60%, which is required to meet the demand of the population growth (Cassman and Harwood, 1995). However, the NUE of paddy rice has remained quite low (30-40%) for decades compared to other crops in Asia (Mitsui, 1954; Cassman et al., 1996; IRRI, 1998). More N input is obviously not ideal because it economically lowers benefits and ecologically harms the environments.

The low NUE of paddy rice is related to ammonia volatilisation, denitrification, leaching, ammonium fixation, immobilization, and runoff (Savant and De Datta, 1982). Most of the fertiliser N is lost through the first three processes. Submerged rice fields are particularly prone to NH_3 volatilisation, as the floodwater pH shows a large diurnal fluctuation: during the day it may rise to value of 9 or even higher (pK_a of $\text{NH}_4^+=9.24$) because of the photosynthetic activity of algae lowering the dissolved CO_2 content (Mikkelsen et al., 1978). Hence, about 50% of the applied urea N can be lost through ammonia volatilisation, while probably less than 10% of the applied urea N is lost through gaseous emissions through denitrification (De Datta et al., 1991). Under different soil conditions and with different fertilisation methods, N loss through leaching ranges from 10 to 60% of the applied N (Craswell and Vlek, 1979).

New techniques have been developed in recent years to reduce N losses and improve NUE. Some rice varieties, which are characterised by high capacity of N uptake and utilisation, have been developed (Yang et al., 1999). More groups work on developing new fertilisation methods, such as the type of fertiliser (Norman et al., 1989; Jena, 1999), the timing of fertilisation (Linguist and Sengxua, 2001; Wopereis-Pura et al., 2002), and N application after

recommendations (Cassman et al., 1998). There are also reports of using covering of the water surface by azolla to reduce NH_3 volatilisation in paddy systems (De Macale et al., 2002). By these techniques, the NUE in the paddy rice production systems was improved, but the values are still low compared to other aerobic crops (Cassman et al., 1996). It is difficult to avoid gaseous emissions and leaching from the traditional rice production systems because of the special conditions of the standing water layer and the reductive conditions in paddy soil.

The 'Ground Cover Rice Production System (GCRPS)' has been developed in order to reduce water consumption in rice production. By GCRPS, lowland rice varieties are grown under non-submerged soil conditions during the entire vegetation period, but the ground is covered by plastic film or plant straw to keep the soil water content at 90% water holding capacity (Lin et al., 2002). Due to the changes in water regime, the N transformation in the soil and the N acquisition of the plants may be affected in the new GCRPS. However, the research on similar systems focuses mainly on water-saving (Cheng et al., 1999), yield stability (Shen et al., 1997), and temperature effect (Xia et al., 1997), few works studying the nitrogen dynamics in the system are reported.

In this paper, we present the results on plant N uptake, soil N conditions, and nitrogen use efficiency of GCRPS in two years (2001 and 2002) in Beijing, aiming at a understanding of N dynamics and nitrogen fertiliser use efficiency of lowland rice in the new rice production system.

2. Materials and methods

A two-year field experiment (2001, 2002) was conducted in the Dongbeiwang experimental station (39.95°N and 116.3°E) of China Agricultural University, Beijing, China. The soil type of the experimental field was Cambisol (FAO soil classification; Gong et al., 1994) with light loamy texture. The total soil N content was 0.13% and soil C content was 2.47% in the rooting depth from 0 to 60 cm. The total rainfall during the vegetation periods (from May 1 to

October 15) was 313mm and 445mm in 2001 and 2002, respectively (see chapter 2 for details of climate data). The saturated hydraulic conductivity of the soil ranged from 29 cm per day to 166 cm per day (Kreye, 2004).

The experiment was a one-factorial block design including three replications (Fig. 1-1). Except plots in Paddy control, all plots (6 m x 12 m) of the other treatments were randomised within each block of non-submerged growing conditions. Five treatments were compared: **i** Paddy control, **ii** GCRPS_{Plastic}, cultivated at $\Psi_{\text{soil}} > -15$ kPa, covered with a 14 μm plastic film, **iii** GCRPS_{Straw}, as in the previous treatments but utilising semi-decomposed rice straw (1.5 tons ha^{-1}) as mulch material, **iv** GCRPS_{Bare}, as before but without mulch, **v** Aerobic rice, grown as in the previous treatment. For treatments **i** to **iv** the inbred lowland rice variety Yue Fu was used. A specially adapted aerobic rice variety Han Dao 297 was grown in treatment **v**. For field preparation, the soil was ploughed to 25 cm depth, and one week later harrowed and levelled under non-submerged conditions after basal fertilisation. Then in the paddy plots, the field was submerged, and levelled again to produce a compacted mud layer for transplanting (see chapter 2 for details in field managements).

Nitrogen fertiliser use efficiency (NUE) was determined by the ^{15}N dilution method (Barraclough, 1991). One ^{15}N mini-plot (2 m x 2 m) was located in each of the main plots and fertilised with ^{15}N labelled urea (2 at % and 1.5 at % in 2001 and 2002, respectively). To avoid ^{15}N loss from the mini-plot, a 40 cm-height metal frame was buried to 25 cm soil depth without disturbing the soil inside the mini-plot. The location of the ^{15}N mini-plot was changed to another site of the main plot in the second year to avoid contamination with ^{15}N from previous applications.

Phosphorus (90 kg ha^{-1}) as $\text{Ca}(\text{H}_2\text{PO}_4)_2$ and potassium (90 kg ha^{-1}) as K_2SO_4 were applied as basal fertilisers in both years. Different nitrogen fertilisation methods were used in the two years to improve the nitrogen use efficiency. In both years, 225 kg N per hectare nitrogen fertiliser was applied. In 2001, the total amount of N was applied as urea, while in 2002 it was

180 kg urea-N plus 45 kg organic-N per hectare. In 2001, the 225 kg N per hectare was entirely applied as a basal fertiliser in GCRPS, while in Paddy control it was split applied with rates of 90 kg, 67.5 kg, and 67.5 kg N three days after transplanting, at tillering stage, and at panicle initiation stage, respectively. In 2002, urea N was split applied, while organic manure (rapeseed cake) was applied as a basal fertiliser in all treatments. In GCRPS, 54 kg N per hectare urea was applied together with organic manure as basal fertilisers before sowing. 72 kg and 54 kg N (urea) per hectare were subsequently applied at tillering and panicle initiation stage, respectively. In Paddy control, organic manure was applied before submergence, the first urea-N dressing was given 3 days after transplanting, and then at tillering stage and panicle initiation stage. Iron (20 kg ha^{-1}) as FeSO_4 and manganese (30 kg ha^{-1}) as MnSO_4 were applied to GCRPS as basal fertilisers to alleviate the micronutrient deficiency which was observed in 2001.

Intermediate harvests were done in biweekly intervals starting four weeks after sowing in GCRPS and after transplanting in Paddy control. For this purpose, an area of 0.3 m^2 ($50 \text{ cm} \times 60 \text{ cm} = 8$ hills) in each plot was harvested, leaving 2 lines as borders between two subsequent harvests. ^{15}N plant samples were taken in ^{15}N -mini plots biweekly in 2001 and monthly in 2002. Soil samples for the determination of mineral nitrogen (N_{min}) were taken biweekly using an auger. ^{15}N soil samples were also taken from 0-20 cm, 20-40 cm, 40-60 cm and 60-90 cm soil depths at final harvest to determine the N fertiliser residues in the soil.

Plant samples were washed by distilled water, oven dried until weight constancy and finely ground in a ball mill (MM2000, Retsch), and then analysed by an elemental analyser (EA1108, Fisons Instrument) for N content, or by a mass spectrometer (Delta C, Finnigan, MAT) for ^{15}N abundance. Soil samples were stored in an icebox immediately after sampling, and taken to the laboratory for soil mineral N extraction according to the method of Houba et al. (1986). The measurement of soil mineral N was done by an auto-analyser (AA3, BRAN&LUEBBE, Norderstedt, Germany). ^{15}N -soil samples were first air-dried and ground

by hands (to pass 1mm sieve), then finely ground in a ball mill (MM2000, Retsch), and analysed by a mass spectrometer (Delta C, Finnigan, MAT). All data were analysed by the GLM procedure of the SAS (Statistical Analysis System) statistical package (SAS, 1989).

3. Results

In both years, shoot dry matter production (Shoot DrM) was significantly lower in all GCRPS treatments compared to Paddy control (Tab. 3-1). Straw and grain yield were affected to a similar extent as Shoot DrM. Yields in GCRPS_{Plastic} were 30% and 10% lower than in Paddy control in 2001 and 2002, respectively. The lowest yield was obtained with GCRPS_{Straw} and GCRPS_{Bare}, while yield of the Aerobic rice grown under the same growing condition as GCRPS_{Bare} resembled GCRPS_{Plastic} yield.

Table 3-1 Dry matter production (kg ha⁻¹) of GCRPS and Paddy control in two years¹⁾

	2001			2002		
	Shoot DrM	Straw DrM	Grain DrM	Shoot DrM	Straw DrM	Grain DrM
Paddy control	19515 A	12192 A	7323 A	17811 A	11459 A	6352 A
GCRPS _{Plastic}	12656 B	7614 B	5042 B	14268 AB	8444 A	5824 A
GCRPS _{Straw}	9483 BC	6405 B	3078 C	8106 C	5228 B	2877 B
GCRPS _{Bare}	9373 C	5741 B	3631 C	7502 C	5039 B	2463 B
Aerobic rice	10521 BC	5285 B	5236 B	11351 BC	6443 B	4907 A

¹⁾ Figures within each column followed by the same letter are not significantly different, p=0.05, n=3

In comparison to Paddy control, the uptake of nitrogen into the above ground biomass was generally lower in GCRPS (Fig. 3-1) in both years. Among all GCRPS treatments, GCRPS_{Plastic} revealed the highest N uptake. Until harvest, the aerobic rice (Aerobic rice) accumulated significantly more N in total shoot dry matter than GCRPS_{Bare} and GCRPS_{Straw}. In 2001, the differences between Paddy control and GCRPS_{Plastic} were more pronounced than in 2002 (Tab. 3-1). In both years, the shoot nitrogen content of all GCRPS treatments was clearly lower than in Paddy control, especially after PI stage significant differences occurred in both years (Tab. 3-2). At final harvest, N content in the grain of GCRPS_{Plastic} significantly

lower than other treatments, and N content in straw had similar tendency (Tab. 3-2). Since this was accompanied by lower dry matter production as compared to Paddy control (Tab. 3-1), it is anticipated that the N acquisition limited growth. The Aerobic rice made a remarkable exception, i.e., nitrogen content and N accumulation were much higher than in GCRPS_{Bare} (Tab. 3-2, Fig. 3-1). Analogous to N accumulation, differences in N contents among treatments were larger in 2001 than in 2002 (Tab. 3-2), which has to be seen on the background of the differences in the fertilisation schedules of the two years. In both years, the partitioning of nitrogen within the plants was unaffected by the treatments, i.e., nitrogen harvest index (NHI) was about 50% (Tab. 3-3).

Table 3-2 Nitrogen content in rice shoot (% DrM) at different developmental stages¹⁾

	Tillering	PI	Flowering	Harvest	
				Straw	Grain
<i>2001</i>					
Paddy control	3.25 A	2.23 A	1.70 A	0.93 A	1.41 A
GCRPS _{Plastic}	3.17 A	1.45 B	1.20 B	0.60 B	1.16 B
GCRPS _{Straw}	2.57 A	1.53 B	1.02 B	0.82 A	1.33 A
GCRPS _{Bare}	2.55 A	1.36 B	0.97 B	0.61 B	1.23 A
Aerobic rice	3.05 A	1.72 AB	1.23 B	0.74 A	1.40 A
<i>2002</i>					
Paddy control	3.29 A	2.31 B	1.37 B	0.89 B	1.59 A
GCRPS _{Plastic}	3.63 A	1.70 C	1.21 B	0.73 B	1.25 B
GCRPS _{Straw}	3.18 A	1.42 C	1.57 B	1.12 AB	1.46 A
GCRPS _{Bare}	3.18 A	1.49 C	1.66 AB	1.29 A	1.55 A
Aerobic rice	3.51 A	3.02 A	2.01 A	1.00 AB	1.48 A

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=3$

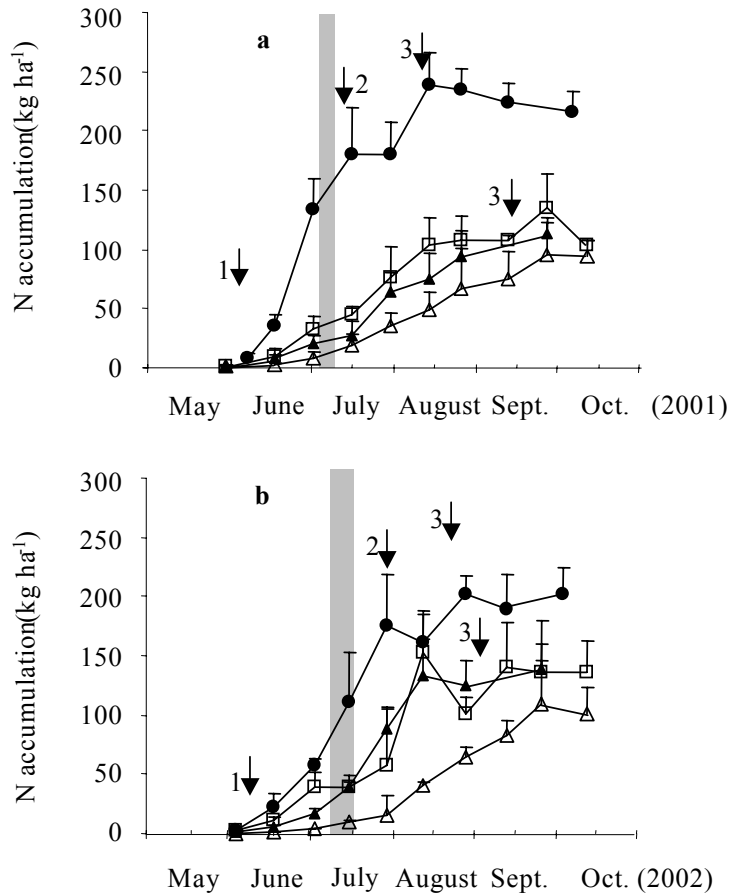


Figure 3-1. Nitrogen accumulation in the shoot of GCRPS plants compared to Paddy control

● Paddy control □ GCRPS_{Plastic} ▲ GCRPS_{Straw} ▲ Aerobic rice
 1: tillering, 2: PI, 3: flowering;
 gray bars indicate drainage period in Paddy control

Table 3-3 Biomass nitrogen and nitrogen harvest index (NHI) in rice shoots at final harvest¹⁾

	2001				2002			
	Total N (kg ha ⁻¹)	Grain N (kg ha ⁻¹)	Straw N (kg ha ⁻¹)	NHI	Total N (kg ha ⁻¹)	Grain N (kg ha ⁻¹)	Straw N (kg ha ⁻¹)	NHI
Paddy control	216 A	103 A	113 A	0.48 C	202 A	101 A	101 A	0.50 AB
GCRPS _{Plastic}	104 BC	59 BC	46 B	0.56 B	135 AB	73 AB	62 A	0.55 A
GCRPS _{Straw}	94 BC	41 D	53 B	0.44 C	101 B	43 B	58 A	0.41 AB
GCRPS _{Bare}	80 C	45 CD	35 B	0.56 B	103 B	38 B	64 A	0.37 B
Aerobic rice	113 BC	74 B	39 B	0.65 A	139 AB	73 AB	67 A	0.54 A

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=3$

In comparison to Paddy control, fertiliser derived nitrogen made a surprisingly small contribution to the N uptake of the plant shoots in all GCRPS treatments, especially in 2001

when the entire fertiliser N dose (225 kg ha^{-1}) was given as a single dressing (Fig. 3-2). Only approximately 5% and 25% of the total N in the shoot was derived from N fertiliser at harvest in GCRPS in 2001 and 2002, respectively, while in Paddy control more than 40% of the total shoot N came from fertiliser in both years.

In Paddy control, most soil nitrogen was present as NH_4^+ , while in GCRPS NO_3^- was the dominant N form (Fig. 3-3 and 3-4). Surprisingly, four weeks after fertilisation in GCRPS in 2001, only approximately 30% of the applied fertiliser nitrogen was detectable in the soil horizon of 0-60 cm, and almost all of it was present as NO_3^- (Fig. 3-3, 3-4). Since the hydraulic conductivity of the soil was high, frequent irrigation was required to maintain the Ψ_{soil} above -15 kPa. There was a loose negative correlation of soil NO_3^- -N content and the amount of irrigation water given (see appendix, Fig. A1), so NO_3^- leaching was probably a major pathway for N losses and hence largely responsible for the extremely low N fertiliser use efficiency (NUE) in all GCRPS treatments (Tab. 3-4).

In 2002, with the improved fertilisation scheme, the soil nitrate-N content was maintained at a relatively higher level until panicle initiation (PI) stage (Fig. 3-3) in GCRPS. Hence, both NUE (Tab. 3-4) and the amount of fertiliser-derived nitrogen in the aboveground biomass (Fig. 3-2) were improved compared to 2001. In Paddy control, the increase of NO_3^- -N content in soil profile (Fig 3-3d, e) was a clear evidence of the mineralisation of organic matter after mid-season drainage (from July 8 to July 16) and during harvest drainage (after September 1).

Table 3-4 Nitrogen use efficiency (%) in 2 years by ^{15}N isotope method^{1) and 2)}

	2001 ³⁾	2002
Paddy control	47.0 A	42 A
GCRPS _{Plastic}	2.4 B	19 BC
GCRPS _{Straw}	1.3 C	13 C
GCRPS _{Bare}	1.8 BC	----
Aerobic rice	2.3 B	28 B

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=3$

²⁾ $\text{NUE} (\%) = 100 \times \left(\frac{\text{amount of } ^{15}\text{N}\text{-labelled fertiliser recovered in aboveground biomass } [\text{mg N m}^{-2}]}{\text{total amount of } ^{15}\text{N}\text{ labelled fertiliser applied } [\text{mg N m}^{-2}]} \right)$

³⁾ Statistical analysis after LOG transformation

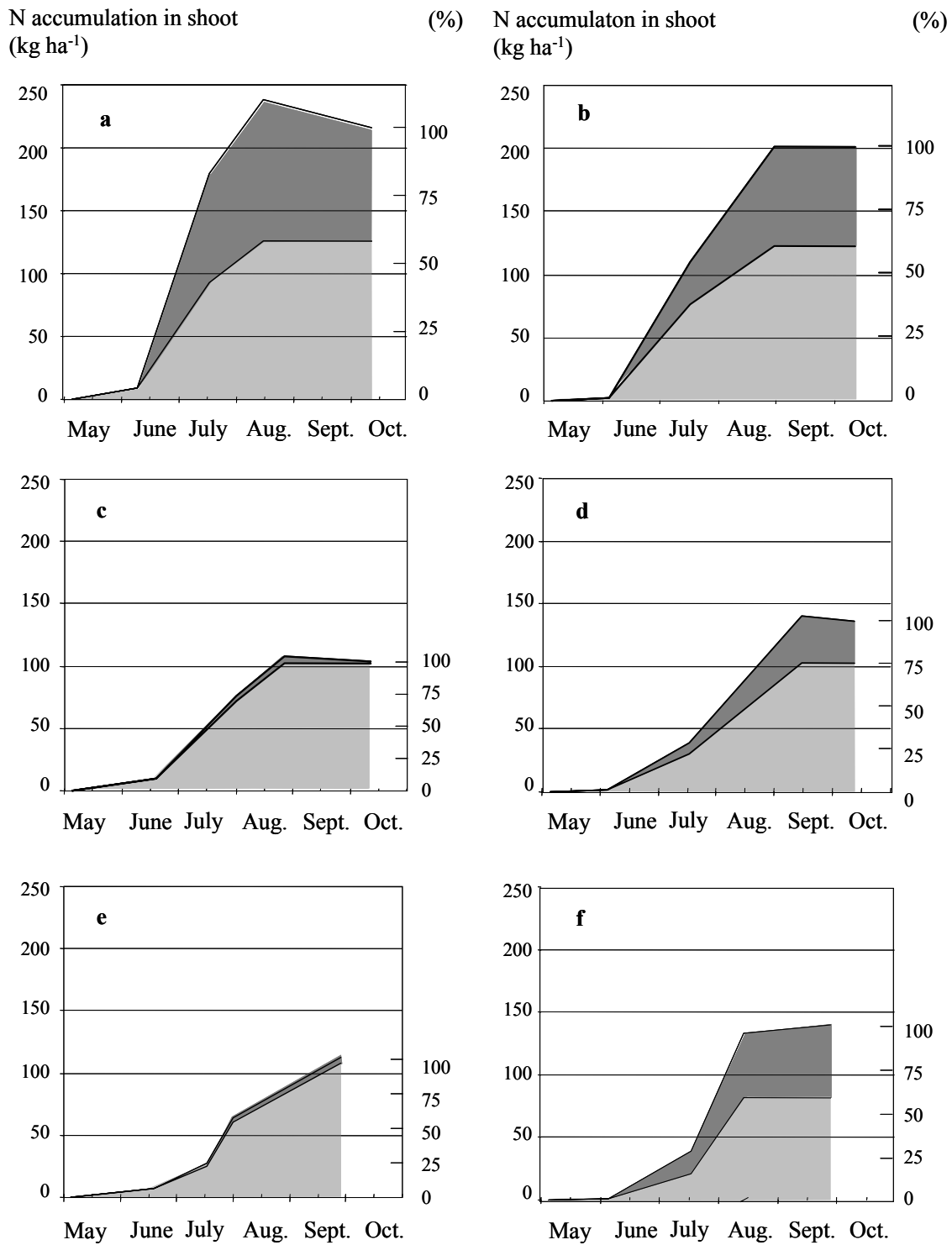


Figure 3-2 Time course of N uptake into aboveground biomass differentiated into soil and fertiliser-derived N as calculated from ¹⁵N uptake
 a: Paddy control, 2001; b: Paddy control, 2002;
 c: GCRPS_{Plastic}, 2001; d: GCRPS_{Plastic}, 2002;
 e: Aerobic rice, 2001; f: Aerobic rice, 2002.
 ■ Fertiliser N □ Soil N

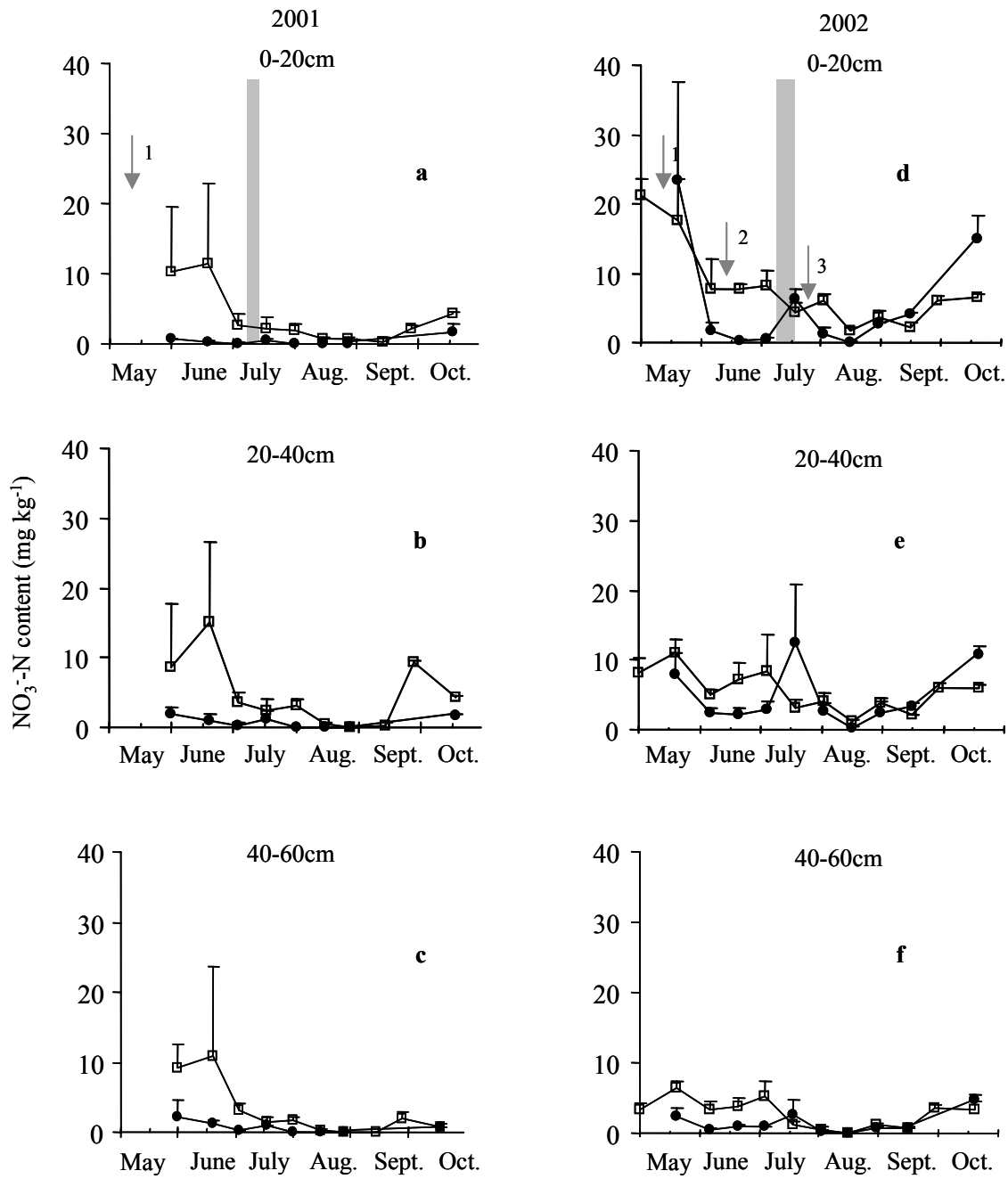


Figure 3-3 Time course of soil NO₃-N content in 3 different soil depths

Gray arrows indicate fertilisation in GCRPS_{Plastic}

1: nitrogen basal dressing, 2: nitrogen tillering dressing, 3: nitrogen PI dressing

Vertical gray bars indicate drainage period in Paddy control.

● Paddy control □ GCRPS_{Plastic}

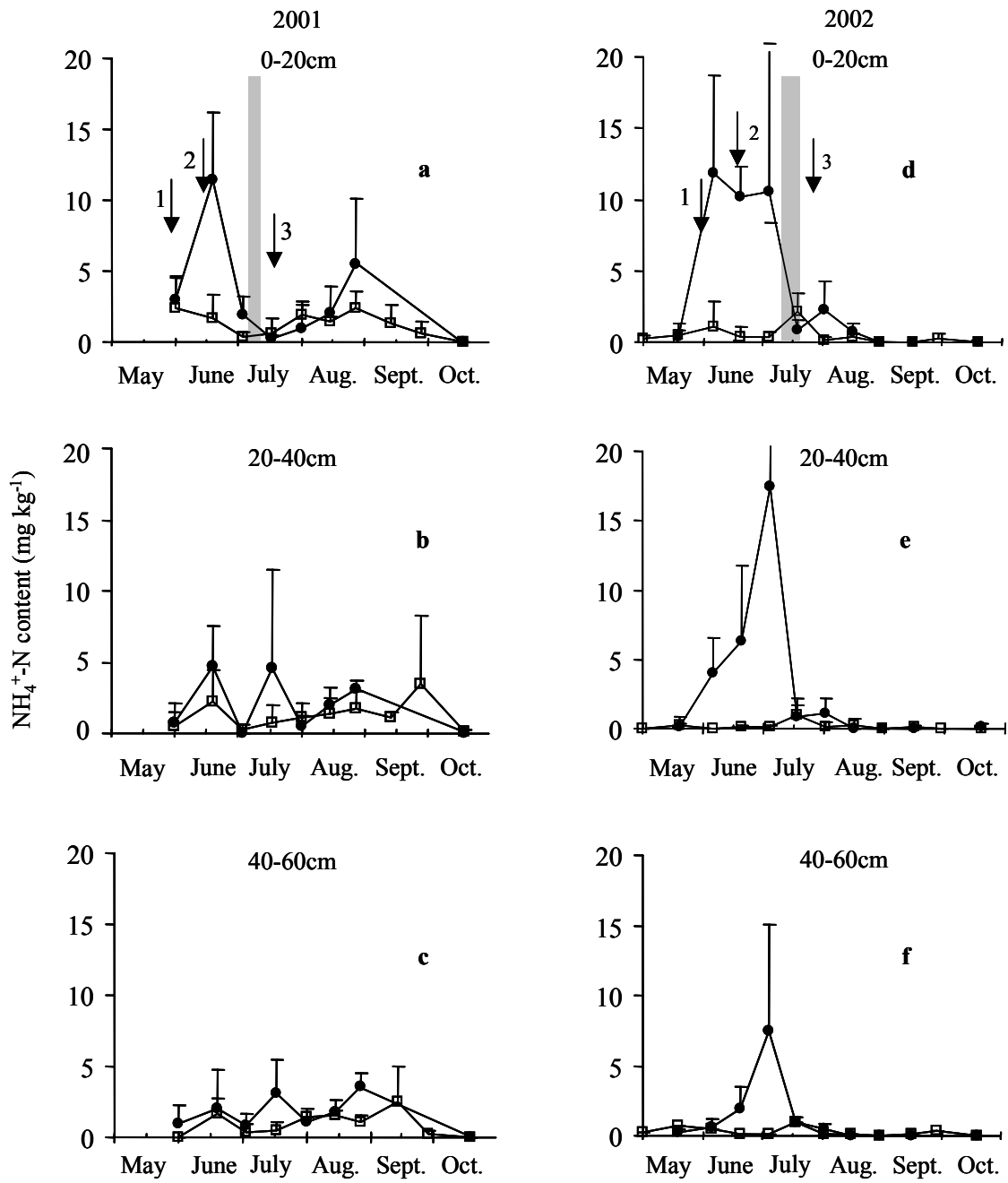


Figure 3-4 Time course of soil $\text{NH}_4^+\text{-N}$ content in 3 different soil depths

Black arrows indicate fertilisation in Paddy control

1: nitrogen basal dressing, 2: nitrogen tillering dressing, 3: nitrogen PI dressing

Vertical gray bars indicate drainage period in Paddy control.

● Paddy control □ GCRPS_{Plastic}

4. Discussion

The large differences in rice grain yield, observed in the comparison of GCRPS with traditional lowland rice production (Tab. 3-1), were closely related to the tremendous differences observed in nitrogen dynamics of the two systems. For optimum yield, a N uptake into aboveground biomass of approximately 18 kg N per ton grain yield is needed (Yoshida, 1981; Dobermann and Fairhurst, 2000), hence, under the conditions of Beijing with a yield level of about 6750 kg per hectare, about 130 kg N per hectare in aboveground biomass (at least 70 kg N per hectare in grain) is necessary for an optimum yield. In the present experiment, plants in GCRPS took up significantly less nitrogen over the entire growing period than in Paddy control (Fig. 3-1). In all GCRPS treatments, N harvest in the grain and aboveground biomass were clearly below 70 kg and 130 kg per hectare, respectively. In 2002, plant N uptake was improved by splitting the N fertiliser into three dressings. Nevertheless, the plant nitrogen content remained below the critical limit ($> 2\%$ of shoot DrM) for active photosynthesis after PI stage (Tab. 3-2). Therefore, there is little doubt that plant N uptake was one of the major limitations for aboveground biomass development and subsequent grain production in GCRPS, and it also led to the low NUE.

Typically, NUE is low in paddy rice (Cassman et al., 1996), which is caused by various loss processes, especially ammonia volatilisation and nitrification-denitrification (De Datta, 1995). Ammonia volatilisation is particularly important in submerged rice fields because the floodwater pH may rise to high values during the day, exceeding the pK_a of NH_4^+ (9.24) as photosynthetic algae remove CO_2 from the water (Mikkelsen et al., 1978). Contrary to our expectations, under non-submerged conditions of GCRPS, the NUE was significantly lower than in Paddy control (Tab. 3-3). The amount of residual fertiliser N in the soil at harvest was very low, making up less than 0.7% of the applied N in both years (see appendix, Tab. A2). The low fertiliser N recovery in plant and soil also documented the large fertiliser N losses by leaching or gaseous emissions in GCRPS, where aerobic processes were dominant.

Under the more aerobic conditions of GCRPS, urea hydrolysis was probably very fast (Savant et al., 1985), so it seems typical to find maximum soil NH_4^+ concentrations shortly, e.g., 3 days after urea application, before rapid nitrification depletes the pool again (Dowling, 1998), therefore chances for NH_3 volatilisation can be seen as low under conditions of GCRPS, where the cover by plastic film or straw additionally restricts gaseous NH_3 loss. However, denitrification was probably a relevant process under the micro-aerophilic conditions of GCRPS (Jetten, 2001). Among the products of denitrification, N_2O contributed less than $4 \text{ kg N ha}^{-1}\text{a}^{-1}$ to the N balance of GCRPS in both years (1.7 % of applied N; see Kreye, 2004). Even when considering the wide range of reported ratios of N_2O and NO to N_2 (Cai et al., 2001; Davidson, 1993), the total amount of gaseous N losses by nitrification-denitrification may have reached a range of 30 % of the applied fertiliser N, which still cannot explain the gap in the N balance observed in this study.

The dominant N form in the soil of GCRPS plots was nitrate (Fig. 3-3 and 3-4), which is very mobile in the soil. So in the soil of GCRPS, nitrogen can easily be taken up by plants, but it is also highly susceptible to leaching (Nishio et al., 1994; Torbert et al., 1992). As in GCRPS a high amount of urea was applied as basal fertiliser before plant emergence (225 kg ha^{-1} in 2001 and 54 kg ha^{-1} in 2002), nitrate leaching was high and became the major N loss in GCRPS (see appendix Fig. A1). Plant nitrogen uptake was low at the beginning of plant establishment, so a large share of nitrate was leached to deeper soil layers, where it could not be reached by plant roots (Sveda et al., 1992). At later growth stages, the plant development was evidently limited by insufficient N supply, and as most fertiliser N was washed into deep horizons of the soil, a rapid plant uptake of indigenous soil N was then observed (Fig. 3-2). This also resulted in a pronounced depletion of soil NO_3^- in the rooting horizon in GCRPS (Fig. 3-3). In 2002, nitrogen fertiliser was split into three dressings, so the N losses were lower (Fig. 3-3), which was also reflected by the higher plant N uptake (Fig. 3-1) and by the better plant growth (see chapter 2) compared to GCRPS in 2001. However, the plant growth

and N uptake became slower after maximum tillering when the soil NO_3^- content decreased (Fig. 3-3d, Tab. 3-2).

According to the general concept of lowland rice's nitrogen nutrition, NH_4^+ is seen as the favourable N form (Wang et al., 1993). Also, results from nutrient solution experiments demonstrated that lowland rice produced more dry matter with NH_4^+ nutrition than with NO_3^- nutrition, although there was no difference in the N uptake rate with the two forms (Kronzucker et al., 2000; Lin et al., 2004). During both experimental years, NO_3^- was the dominant N form in GCRPS (Fig. 3-3 and 3-4) and in both years rice plant development was clearly affected in GCRPS. Whether or not NO_3^- nutrition is the original cause of the observed growth effect, cannot be explained by our experiment. It can be speculated, that plant growth and nitrogen acquisition were affected by hormonal imbalance caused by almost pure NO_3^- nutrition in young growth stages (see also Barker et al., 1999; Walch-Liu et al., 2000).

Different timing of N fertilisation resulted in significantly different NUE in GCRPS over 2 years (Tab. 3-2). However, even in 2002, the NUE in GCRPS was still much lower than expected, which resulted from extensive leaching. The major cause of leaching has to be seen in the soil texture and the lack of a soil layer with low hydraulic conductivity. The percolation rate was as high as 1500 mm per season in the experimental field (Kreye, 2004). Consequently, leaching losses were high in the sandy-loam soil at the experimental station. Reduction of the basal fertiliser dressing and application of fertiliser at crucial stages such as mid-tillering and PI will improve NUE. Furthermore, soils with heavier texture might be more suitable for GCRPS, because they require less irrigation and will also have lower N losses by leaching.

To reduce fertiliser N leaching and improve plant N uptake in GCRPS, fertiliser N should be applied following the plant's need in the different developmental stages. Hence, the crucial N acquisition period of lowland rice varieties must be well understood for an appropriate timing of fertilisation in GCRPS. Although N is required throughout the growth period, the largest requirement is between the early to mid-tillering and PI stages (Dobermann and Fairhurst,

2000), which was also found in our experiment (Fig. 3-1). Sufficient nitrogen nutrition at the stage of panicle initiation, e.g., leaf N content higher than 2 %, was identified as important to ensure high photosynthetic activity after heading, as also seen from leaf colour, which then permits high photosynthetic activity required for high-yielding rice production (Yoshida, 1981). N deficiency (Tab. 3-2) at this stage has probably caused irreversible negative effects on tiller formation (see chapter 2) and dry matter production in GCRPS in 2001 (Tab. 3-1), because N content in plants at this stage is crucial for tiller longevity (Ishizuka and Tanaka, 1969). In 2002, fertiliser top dressing at PI has clearly increased N uptake in GCRPS. So tiller formation and yield were significantly improved (see chapter 2).

N content in the aboveground biomass determines not only the grain yield but also the grain quality. High N content relates to high protein content in the grain (Borrell et al., 1999), which is desirable for raising the protein intake of human beings. This is also the reason why the so-called 'High-protein Rice' has been under investigation (China Daily, 2002). However, it was reported that the taste of milled rice negatively related to protein content, i.e., the greater the protein content, the worse the taste (Blakeney et al., 2001). The average range of protein content in milled rice is about 7-9 % of dry weight (Juliano, 1993), while lower than 6.2 % of protein content is supposed to be good taste (Blakeney et al., 2001). In Japan, northern China and Europe, good taste rice is preferred to high-protein rice when people could obtain enough protein from other resources. In GCRPS_{Plastic}, the grain N content was significantly lower than Paddy control (Tab. 3-2), while yield only slightly reduced in 2002 (Tab. 3-1). This shows the possibility of better taste in the milled rice of GCRPS_{Plastic} as compared to Paddy control, which will probably become one of the profits out of the new water-saving rice production system. On the other hand, sufficient N is necessary for a good yield, hence, proper N fertiliser doses and timing are needed to match both the yield demands and taste demands simultaneously.

In conclusion, the N nutritional status of rice plants grown in GCRPS was dominated by an unexpectedly pronounced N deficiency. Even with application of the N fertiliser in three splits in 2002, only approximately 20 % of all applied N fertiliser was taken up into the aboveground biomass of GCRPS plants. Nitrate leaching was severe in GCRPS and became the main pathway of N losses. It has also to be anticipated that apart from reduced N availability, the dominant form of N in GCRPS, nitrate, also had a negative impact on plant growth and N acquisition. Improvements in N uptake and hence NUE can probably be achieved by further adaptation of fertilisation to the special needs in GCRPS. In detail, further splitting of fertiliser N – which would be economically feasible at present labour costs –, the use of urea super-granules, urease or nitrification inhibitors can be seen as promising strategies in this field. Elaboration of soil criteria, i.e., soil texture and hydraulic conductivity will also make an important contribution, so field sites can be selected, that allow to grow rice in GCRPS with lower drainage and leaching rates.

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CHAPTER 4**Effects of soil humidity on the growth and N, Mn, Fe uptake of lowland rice (*Oryza sativa* L.) when planting under plastic film covered condition**

Keywords: Soil humidity, Lowland rice, Growth, Nutrient uptake, Plastic film

Abstract

A pot experiment was conducted under controlled greenhouse conditions to study the effect of soil humidity on the growth and N, Mn, Fe uptake of lowland rice with plastic film cover for seven weeks. Five treatments were compared: **i** Paddy control, **ii** GCRPS_{Plastic} – saturated, **iii** GCRPS – 90 % water holding capacity (WHC), **iv** GCRPS_{Plastic} – 70 % WHC, and **v** GCRPS_{Plastic} – 70 % WHC + organic manure.

The highest dry matter production and the highest numbers of tiller were observed with lowland rice grown under saturated soil condition (GCRPS_{Saturated}), the optimum N, Mn and Fe acquisition was measured with GCRPS_{Saturated}, while both traditional Paddy control and the other more aerobic conditions showed either higher or lower nutrients uptake. In the pot experiment, there was no indication that water stress or N deficiency limited the plant growth, only Mn nutrition showed clear differences. Low soil redox potentials favoured the reduction of Mn oxides to Mn (II) and increased plant Mn availability. The experiment provides evidence that GCRPS_{Plastic} combined with highly saturated soil conditions allows to save water and obtain optimum rice crop development, without problems of micronutrient (e. g. Mn) deficiency.

1. Introduction

Among the new water-saving rice production systems, plastic film covered rice (or GCRPS, Lin et al., 2002) was introduced in 2000 and it was demonstrated that it can successfully save water, while the rice grain yield still reaches a competitive level (see chapter 2). However, the new system still encountered some problems, such as the delayed plant establishment, smaller leaves, lower number of tillers, higher N losses, and Mn deficiency compared to the traditional paddy system. These have limited the system, so maximum yield was not achieved up to now.

Reduced irrigation in GCRPS limited tillering and leaf enlargement possibly because of a water deficit. However, the results from Lu et al (2000) did not show a significant reduction of tiller formation when lowland rice was grown at soil water tensions between 0 and 20 kPa, although the stomatal resistance was increased at higher soil water tensions. Whether or not the reduced soil humidity directly affected tillering of GCRPS in the field remained open, since the soil humidity in GCRPS was close to the field capacity.

The other effect of the lacking water layer is that soil redox potential increases. More oxygen is available and increases the soil redox potential. The available form of nitrogen changes to NO_3^- , which in contrast to NH_4^+ , is highly mobile in the soil. Mn(II) is oxidised to Mn(III) or Mn(IV), becoming the dominant manganese forms, which have a much lower plant availability.

It is reported that the nitrogen content in the leaf determined the formation (Zhong et al., 2003) and longevity of tillers (Ishizuka and Tanaka, 1969). Since the capacity of rice to take up NO_3^- and NH_4^+ is almost the same (Kronzucker et al., 2000), the low N uptake in GCRPS plants was supposed to be the result of severe NO_3^- leaching in the system due to the sandy-loam soil texture (see chapter 3). The change in the available N form under aerobic conditions could also have affected plant growth in GCRPS as discussed in chapter 2.

Moreover, Mn deficiency in GCRPS plants occurred in our field experiment in 2001 and 2002, while this was not found with lowland rice grown in submerged Paddy control. Little work on the relationship between tillering and manganese deficiency of rice has been published, but Mn deficiency at early growth periods has been reported to limit tiller formation of other upland cereals like barley and wheat (Aspinall, 1961; Karamanos et al., 1985). Mn deficiency under aerobic conditions might be one of the reasons to explain the reduced plant height, leaf area and the number of tillers in GCRPS.

We carried out a pot experiment under greenhouse conditions to study the effects of soil humidity on plant growth and N, Mn, Fe uptake at early developmental stages (seedling stage and tillering stage) with plastic film covering.

2. Materials and methods

A pot experiment was conducted in the greenhouse of the Institute of Plant Nutrition and Soil Science of Kiel University from May 14 to July 2, 2003. Five treatments including 4 replicates were tested: **i** Paddy control, **ii** GCRPS_{Plastic} – saturated, **iii** GCRPS_{Plastic} – 90 % water holding capacity (WHC), **iv** GCRPS_{Plastic} – 70 % WHC, and **v** GCRPS_{Plastic} – 70 % WHC + organic manure. Water management started after visual symptoms of transplanting shock had disappeared (9 days after transplanting). In Paddy control, a 3-cm water layer was constantly maintained after transplanting shock. In the other treatments, the soil surface was covered by plastic film without a standing water layer, and the amount of irrigation water needed was determined by daily weighing of the pots.

The soil type of the experiment was the Cambisol of Dongbeiwang Experimental Station, China Agricultural University, Beijing (FAO soil classification; Gong et al., 1994), the same as in the field experiment. Fertilisers were applied at a rate of 100 mg nitrogen (N) per kg soil as urea, 66 mg phosphorus (P) per kg soil as Ca(H₂PO₄)₂, 166 mg potassium (K) per kg soil as K₂SO₄, and 200 mg magnesium (Mg) per kg soil as MgSO₄. Urea-N was applied in 3 split dressings to all pots after transplanting, while the other fertilisers were mixed with 10 kg air

dried soil in each pot as basal fertilisers. The soil redox potential was measured every day by two platinum redox electrodes in each pot (Phene, 1986), beginning at the onset of the different irrigation treatments (9 days after transplanting).

The inbred lowland rice variety (Yue Fu), that was also grown in the field experiment, was used. Pre-germinated seeds were cultivated in sand for one week, then 20 plants (1.5 leaves) were transplanted into each pot at a regular spacing. Eight plants in each pot were harvested at the early tillering stage (20 days after the onset of the irrigation treatment), the other eight plants were harvested at the end of the tillering stage (40 days after the onset of the irrigation treatment). At each harvest, the first expanded leaf in the middle line of each pot was cut for measuring the $\delta^{13}\text{C}$ ‰ by a stable isotope mass spectrometry (Delta C, Finnigan, MAT). Plant shoots were cut for measuring plant height, the number of tillers, fresh weight and dry weight. One sub-sample was ground, then digested in HNO_3 at 185°C in a digestion autoclave (Loff field Analytik, Neu Eichenberg, Germany) for Fe, Mn content (AAS; PU9200, Philips). Another sub-sample was finely ground by a ball mill (MM2000, Retsch) to measure N content by elemental analyser (EA1108, Fisons Instrument) of the plant shoots. All data were analysed by the GLM procedure of the SAS (Statistical Analysis System) statistical package (SAS, 1989).

3. Results and discussion

Lowland rice is traditionally grown in submerged, irrigated rice fields in northern China. The introduction of GCRPS provides a promising alternative way to grow rice, which is urgently needed in large regions, i.e. the region of Beijing, where submerged paddy rice production will be banned by regional legislation after 2007. Although the grain yield of GCRPS, especially with the plastic film covered GCRPS system, was nearly comparable with traditional paddy rice (see chapter 2), there is still a need to fully reach the yield potential of this new system.

Full water saturation of the soil permitted best rice growth

Plants grown with plastic film soil cover and fully water saturated (GCRPS_{saturated}) soil showed the highest dry matter production of all compared treatments. This held especially true for the later stage of tillering (Tab. 4-1), so in contrast to results obtained in the field experiment, these growth conditions permitted even better plant development than Paddy conditions. In more aerobic soil, such as 90 % WHC and 70 % WHC, tillering was clearly reduced compared to submerged or saturated conditions in the pot experiment (Tab. 4-1). This is in line with results obtained in the field experiment as presented earlier (see chapter 2). The major difference among treatments was the soil redox potential of the soil, which was measured by soil redox electrodes in the pot experiment (Tab. 4-2). As indicated by the measured redox potentials, the oxygen level in the soil had a clear effect on the form of nutrients, hence their availability to and uptake by plants.

Table 4-1 Growth of lowland rice grown under submerged conditions (Paddy control) or with plastic film soil cover under different soil humidity regimes¹⁾

	June 12 2003			July 2 2003		
	Plant height	Tiller ²⁾	Shoot DrM	Plant height	Tiller ²⁾	Shoot DrM
	(cm)	(No. pot ⁻¹)	(g pot ⁻¹)	(cm)	(No. pot ⁻¹)	(g pot ⁻¹)
Paddy control	64.5 A	42 B	8.19 B	68.8 B	37 A	19.10 C
GCRPS _{saturated}	64.6 A	53 A	11.37 A	69.7 AB	38 A	24.87 A
GCRPS _{90% WHC}	57.6 B	35 C	6.98 C	73.7 AB	31 B	22.55 B
GCRPS _{70% WHC}	52.7 C	29 D	5.44 D	74.6 A	30 B	21.47 B
GCRPS _{70% WHC} + manure	52.9 C	30 D	5.36 D	73.7 AB	27 B	17.61 C

¹⁾ Figures within each column followed by the same letter are not significantly different, p=0.05, n=4

²⁾ Statistical analysis after LOG transformation

Growth reduction was not directly related to water deficiency

In GCRPS, reduced irrigation and less available water might have been detrimental to plants by directly affecting the plant water status. If so, the $\delta^{13}\text{C}$ of leaf carbohydrates should show symptoms of water deficit. When water stress increases, plants reduce their water loss by closing stomata, which in turn also reduces CO_2 diffusion between the intercellular space and

the atmosphere. Thus isotopic fractionation declines, i.e. more $^{13}\text{CO}_2$ is then fixed by Rubisco than under normal conditions, so the $\delta^{13}\text{C}$ increases (Boutton, 1991; Farquhar and Lloyd, 1993; O'Leary, 1993). For C_3 crops like rice, $\delta^{13}\text{C}$ values more positive than $-27 \delta^{13}\text{C} \text{ ‰}$ indicate water deficit (Clay et al., 2001). $\delta^{13}\text{C}$ was therefore measured in this pot experiment, results are shown in Table 4-2. As $\delta^{13}\text{C}$ showed only a very small trend at the first sampling day, there is no evidence for stress that might have led to reduced stomatal conductance in GCRPS. Also, at the end of tillering (July 2) shoot dry matter (DrM) production and the number of tillers were not significantly lower with reduced soil water content (70 % WHC) compared to 90 % WHC (Tab. 4-1). These results underline the view, that the growth limitation with GCRPS observed in the field experiments resulted from nutritional disorders rather than from direct damage by the water deficit.

Table 4-2 Effect of soil humidity on soil redox potentials and $\delta^{13}\text{C}$, reflecting plant stomatal conductance¹⁾

	Irrigation amount (kg pot ⁻¹)	Redox potential ²⁾ (mV)	$\delta^{13}\text{C}$ ³⁾ (‰ PDB)	$\delta^{13}\text{C}$ ⁴⁾ (‰ PDB)
Paddy control	32	-233	-30.2 C	-28.8 C
GCRPS _{saturated}	20	-80	-29.8 BC	-28.0 A
GCRPS _{90 % WHC}	15	498	-29.7 BC	-28.3 AB
GCRPS _{70 % WHC}	13	462	-29.1 A	-28.4 ABC
GCRPS _{70 % WHC + manure}	12	340	-29.5 AB	-28.7 BC

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=4$

²⁾ Readings of one day, but representative for the whole period.

³⁾ The youngest expanded leaf sampled during active tillering (June 12).

⁴⁾ The youngest expanded leaf sampled at the end of tillering stage (July 2).

Nitrogen content of rice shoot was not the key factor for growth reduction at reduced soil humidity

Under field conditions, the N accumulation in plant shoots of the Paddy control treatment was always higher than in any form of GCRPS (see chapter 3). A striking contrast was found in the pot experiment. The N content of the youngest fully expanded leaf and also the total N uptake into the plant shoot of Paddy control plants were significantly lower than those in plastic film covered treatments (Tab. 4-3 and Fig. 4-1). This confirms recent reports (Kirk,

2001; Kronzucker et al., 2000) that lowland rice can utilise NO_3^- very well, so plants should be able cover their N need by NO_3^- under aerobic conditions, as long as sufficient NO_3^- availability is given. Furthermore, these results give evidence that lower number of tillers observed with GCRPS_{plastic} in the field was not totally related to N deficiency, since here with GCRPS 90 % WHC and 70 % WHC, the numbers of tillers were lower than in paddy control, while leaf N content and N uptake were higher (Tab. 4-1). So these results suggest that it should be possible to greatly improve the nitrogen use efficiency of GCRPS, when NO_3^- leaching can be reduced like in this pot experiment. Then of course the importance of other N loss processes, like ammonia volatilisation and denitrification may change. The results of this experiment therefore indicate that GCRPS should probably be used with soils of a higher clay content or a hardpan, where N loss by leaching is low.

Table 4-3 Nutrient uptake of lowland rice (aboveground biomass) grown under submerged conditions (Paddy control) or with plastic film soil cover under different soil humidity regimes¹⁾

	June 12 2003			July 2 2003		
	Mn	Fe ²⁾	N ³⁾	Mn ²⁾	Fe	N ³⁾
	(mg kg ⁻¹)	(mg kg ⁻¹)	(%)	(mg kg ⁻¹)	(mg kg ⁻¹)	(%)
Paddy control	1152 A	168 A	3.42 B	1092 A	88 AB	2.07 C
GCRPS _{saturated}	818 B	161 A	3.58 B	737 B	133 A	2.10 C
GCRPS _{90 % WHC}	166 C	151 A	4.45 A	68 C	91 AB	2.75 B
GCRPS _{70 % WHC}	140 C	150 A	4.63 A	43 D	107 AB	2.95 AB
GCRPS _{70 % WHC} + manure	121 C	171 A	4.52 A	32 D	72 B	3.01 A

¹⁾ Figures within each column followed by the same letter are not significantly different, $p=0.05$, $n=4$

²⁾ Statistical analysis after LOG transformation

³⁾ Data from the youngest expanded leaves

However, while the effect of N forms in the different systems was not in focus of this experiment, their effect also needs to be considered in understanding the reaction of lowland rice to reduced humidity in GCRPS. In a study using the same rice variety, maximum growth and tillering were found with mixed nitrogen supply (NO_3^- plus NH_4^+). This was followed by sole NH_4^+ supply, and plants showed poor growth with exclusive NO_3^- supply, even though

there was no difference in the total N uptake of either N form by lowland rice (Lin et al., 2004). So the optimal plant development under saturated soil conditions (Tab. 4-2) was probably caused by the NH_4^+ supply. The physiological effect of these N forms on the development of lowland rice still needs further study.

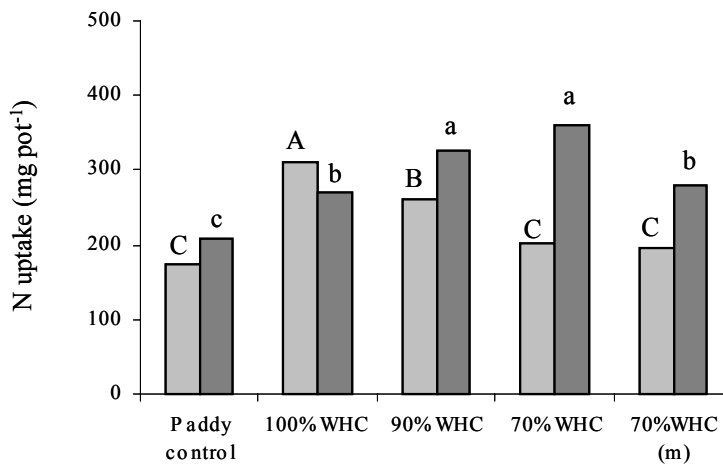


Figure 4-1 N accumulation in shoots of lowland rice grown under submerged conditions (Paddy control) or with plastic film soil cover under different soil humidity regimes. Statistical analysis of data was made within each sampling date, figures followed by the same letter are not significantly different, $p=0.05$, $n=4$
 □ 12th of June ■ 2nd of July

Mn deficiency under more aerobic conditions was related to the lower number of tillers

Clearly sub-optimal Mn concentrations were found in plants grown in GCRPS_{Plastic} in the field experiment (Fig. 4-2a). The Mn contents measured in GCRPS plants were lower than the critical Mn concentration of 20 mg Mn kg^{-1} for most of the 2001 growing period. The tremendous difference of Mn content between plants grown in Paddy control and GCRPS_{Plastic} is probably an important finding that might explain the large differences in plant growth and tiller formation observed in the two cultivation systems. Mn is involved in photosynthesis, respiration, nitrogen metabolism, lignin and phenols synthesis, hormones, and lipid synthesis of higher plants (Campbell and Nable, 1988). Growth limitation in GCRPS might result from reduced photosynthetic activity as particularly during younger developmental stages, the photosynthetic activity is very sensitive to Mn deficiency (Terry and Ulrich, 1974). Reduced

tiller formation may also result from Mn deficiency, which has been reported to affect the plant's auxin balance (Horst and Marschner, 1978; Morgan et al., 1976). Based on these hypotheses, manganese fertiliser was applied in 2002, aiming at improving growth and tiller formation. So in 2002, shoot Mn content increased to the lower limit of the optimal concentration of 50 mg Mn kg⁻¹ (Fig. 4-2b). Nevertheless it remained far below concentrations measured in Paddy control, thus growth and the number of tillers were significantly lower than in Paddy control (see chapter 2). In the field it seems to be difficult to alleviate Mn deficiency by fertilisation, since all forms of Mn are rapidly oxidised to Mn(III) or Mn(IV), when soil redox potentials are higher than 400mV (pH 7) under aerobic conditions (Brümmer, 1974) and lowland rice is not able to utilise these forms of Mn. So a rice cultivation system with nearly saturated soil conditions without a free water layer seems to be the most suitable way to grow lowland rice under water-saving conditions. Excessive loss of water is avoided, while the soil redox potential remains at low levels, keeping the soil's Mn in a highly mobile form, that is available to rice (Mandal and Mitra, 1982). The pot experiment confirmed this view, as measured Mn contents in plants of Paddy control and saturated conditions were in a different order of magnitude than those of plants grown under more aerobic conditions. Also, the number of tillers was higher (Tab. 4-3). It should be mentioned that in this pot experiment the Mn content of paddy plants was even higher than the critical Mn toxicity level, which may have contributed to somewhat reduced growth of paddy plants in the second phase of the experiment (Tab. 4-1).

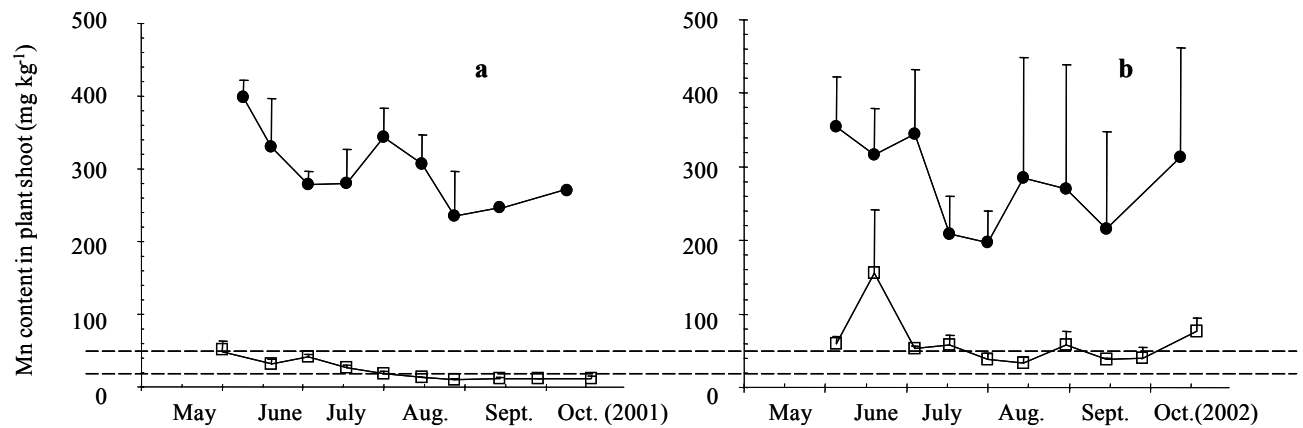


Figure 4-2 Mn content in shoots of lowland rice grown under submerged conditions (Paddy control) or with plastic film soil cover under different soil humidity regimes (field experiment). Error bars indicate 1 standard deviation ● Paddy control □ GCRPS, 90%WHC

Mn is the catalyst needed for oxygen evolution of photosystem II (PSII) (Burnell, 1988). Four Mn atoms are located in the active centre of a hydrolytic Mn-protein acting as a charge accumulator facilitating H₂O oxidation (Marschner, 1995). Lack of Mn in PSII will directly cause a reduction of photosynthetic activity. Moreover, Mn is also important for the structural integrity of chloroplast lamella and chlorophyll (Burnell, 1988). Reductions in chlorophyll content caused by Mn deficiency are commonly found in many crops (Ohki, 1985; Agarwala et al., 1991; Singh et al., 2001). As a consequence, the numbers of PSII units per unit leaf area are reduced and this is followed by the reduction of net photosynthesis rate (Henriques, 2003). Since photosynthesis accomplishes the central provision of the plant with assimilates and energy (Campbell and Nable, 1988), its reduction caused by Mn deficiency retards plant establishment and reduces dry matter production (see Tab. 4-1). In this, our results match findings of other groups (Agarwala et al., 1991; Longnecker et al., 1991).

Mn deficiency is also known to decrease tillering (Ohki, 1984; Longnecker et al., 1991), which was also found in our experiment (Tab. 4-1), where the Mn contents of plant shoots were significantly lower with more aerobic conditions (Tab. 4-3). This effect might have been caused by a lack of assimilates from photosynthesis, but also a direct effect of Mn on tiller

initiation cannot be ruled out. A causal relationship between Mn content and auxin level has been reported (Morgan et al., 1976), and the effect was seen to be mediated by the effect of Mn on the level of indole acetic acid (IAA) oxidase (breakdown of IAA) and by its activity as a cofactor of IAA synthesis (Burnell, 1988). Moreover, auxins regulate the apical dominance (Marschner, 1995), thus tillering might have been affected when Mn deficiency induced a hormonal imbalance (Burnell, 1988). It has been found that not only apical root elongation, but also lateral root emergence and elongation were inhibited by Mn deficiency (Abbott, 1967), so it can be speculated that tiller initiation of lowland rice might have been inhibited in a similar way.

In the present experiment, more irrigation water was needed under fully saturated soil conditions than in GCRPS₉₀ % WHC (Tab. 4-2) but the number of tillers was higher (Tab. 4-1). Higher numbers of tillers would probably have led to a higher grain yield, thus at harvest, water use efficiency would have been equal and nutrient productivity would have been maximised under saturated conditions. However, in the field it is often difficult to constantly keep saturated conditions even with the help of plastic film. So by application of organic manure, another way to keep the soil redox potential low was tested, as it is known that the application of organic manure increased the plant available Mn content in the soil (Mandal and Mitra, 1982). In the present experiment, the soil redox potential was reduced by the application of organic manure (Tab. 4-2), however the effect was not sufficient to avoid Mn deficiency at the low soil humidity of 70 % WHC. Future work may identify the optimum combination of larger amounts of manure and slightly more humid conditions in the soil, alleviating Mn deficiency with maximum water savings.

The Fe content measured in plant shoots was not affected by the different production systems tested either in the field (see appendix, Fig. A1) or in the pot experiment (Tab. 4-3). There was no clear interaction between Mn uptake and Fe uptake as it was found by other groups

(van der Vorm and van Diest, 1979), which is probably related to the different soil conditions in this study.

Conclusion

In the pot experiment, water stress and N deficiency were identified not to constrain good plant growth, while there was clear evidence for an interaction with Mn nutrition. Low soil redox potentials, as observed in saturated soils, favour the reduction of Mn oxides to Mn(II), which is then available for plant uptake. Hence, cultivation of lowland rice in soils with nearly saturated conditions using plastic film cover will not only save water but also improve plant growth and tillering through improved Mn availability.

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SUMMARY

Rice is the dominant staple food for many countries in Asia and the Pacific, South and North America as well as Africa. Among them, China is not only the largest rice producer in the world but also one of the countries with longest rice cultivation history.

In China, more than 90% of rice is produced in irrigated lowlands and it is characterised by high water demand. The amount of water needed to produce 1 kg of grain is with 2000 – 3000 litre three to four times higher than for any other cereals. Due to the fact that more than 80% of water used in paddy rice is lost unproductively by evaporation (16-18%), leaching and surface run off (50–72%), the water use efficiency in paddy system is quite low. Competition for water resources among paddy rice production, industry and domestic demand becomes more and more critical because of the fast urbanisation in the last decades in China.

Also, nitrogen use efficiency is low in irrigated lowland rice because about 50% of the applied nitrogen may be lost through ammonia (NH₃) volatilisation. The submerged rice fields are particularly prone to NH₃ volatilisation, as the floodwater pH shows large diurnal fluctuation: during daytime it may rise to values of 9 or even higher (pK_a of NH₄⁺ = 9.24) because of photosynthetic activity of algae lowering the dissolved CO₂ content.

On this background, the traditional paddy rice system needs to be adapted to produce more rice with less water and less fertiliser input by reducing unproductive water and fertiliser losses. In this work, the new water-saving ‘Ground Cover Rice Production System (GCRPS)’ was evaluated. With GCRPS, lowland rice varieties are cultivated without a standing water layer during the entire growth period. Instead, the soil is irrigated to approximately field capacity and mulched either with plastic film or straw in order to reduce evaporation.

A two-year field experiment (2001 and 2002) and a pot experiment (2003) under controlled greenhouse conditions were conducted. The objectives of the experiments were to contribute to the understanding of growth and yield formation of lowland rice, to evaluate nitrogen dynamics in plants and soil as well as N fertiliser use efficiency in the different systems.

In the field experiments, the amount of irrigation water was significantly reduced by GCRPS (45-70% of Paddy control), and water use efficiency was improved accordingly. However, plant growth and yield were limited. Plants in GCRPS were smaller, developed less panicles and lower LAI compared to Paddy control. Under good conditions in 2002, yield was 10% lower in GCRPS_{Plastic} than in Paddy control, which was strongly related to leaf area index duration ($R^2=0.84$), showing clear source limitation of the system. Among yield components, the number of productive tillers had the largest effect on yield ($R^2=0.73$), while the number of grains per panicle and thousand-grain weight remained almost unaffected. What may be interpreted is sink limitation. The apparent contradiction arises from the fact that the amount of available carbohydrates hampers the number of tillers. The reduced tiller formation in GCRPS coincided with nutrient disorders, i.e., nitrogen deficiency and manganese deficiency in the field in 2001. In non water logged conditions, NH_4^+ -N is readily oxidised leading to a dominance of NO_3^- -N; and Mn form was changed to Mn (III) and Mn (IV) as redox potential increased to 400 mV in neutral soil.

The nitrogen dynamics of GCRPS was characterised by surprisingly low N recoveries. Only 32% of the applied fertiliser nitrogen was detectable in the soil horizon (0 – 60 cm) one month after fertilisation, which led to unexpectedly low nitrogen accumulation and nitrogen fertiliser use efficiencies of rice plants. Nitrate leaching was probably the main pathway of N losses in the field condition of GCRPS as gaseous emissions proved to be low in a parallel study. Fertiliser N split application improved nitrogen use efficiency in 2002, but NUE remained lower than paddy because of unavoidable leaching loss at the experimental site. There is evidence that nitrate itself, the dominant N form in GCRPS, had an impact on tillering and plant growth. Manganese deficiency was observed in GCRPS in 2001. In 2002, it was alleviated by Mn fertilisation. However, the tiller formation in 2002 reached only the lower limit of optimum tiller numbers after split N application and Mn fertilisation.

Hence, the effect of soil humidity (saturated, 90% water holding capacity, and 70% water holding capacity) on nutrient uptake and rice growth was conducted as a pot experiment under controlled greenhouse conditions. The soil redox-potential decreased sharply with higher soil humidity, which led to the increase of Mn accumulation in plant shoots under high humidity conditions, such as paddy and fully saturated conditions. Lowland rice grown under saturated conditions performed best among treatments, characterised by the most vigour growth (high tiller formation and high dry matter production) and optimal nutrient acquisition (N, Mn and Fe) compared to either traditional paddy control or more aerobic conditions. The reason for the growth retardants with non water logged soil remains rather obscure since plants did not show any symptom of water scarcity (C-13 discrimination values were unaffected).

The experiment demonstrated that the ground cover rice production systems have a potential to save substantial amounts of water at relatively minor yield penalties, and the acquisition of nutrients needs to be improved in the future.

Zusammenfassung

Reis ist das dominierende Grundnahrungsmittel für viele Länder in Asien, im pazifischen Raum, in Süd- und Nordamerika und auch in Afrika. China ist nicht nur der größte Reisproduzent der Welt, sondern auch eines der Länder mit der längsten Geschichte in der Kultivierung von Reis. In China kommen mehr als 90% des produzierten Reis aus dem bewässerten Sumpfreis Anbau, für den ein hoher Wasserbedarf charakteristisch ist. Die Menge an Wasser, die es bedarf, um 1 kg Korn zu produzieren, liegt zwischen 2000 – 3000 Liter und ist somit weit höher als für jedes andere Getreide. Auf Grund der Tatsache, dass mehr als 80% des Wassers, das im Sumpfreis-Anbau verbraucht wird, unproduktiv als Evaporation (16-18%) oder Versickerung und Oberflächenabfluss (50-72%) verloren geht, ist die Wasser-Nutzungseffizienz im Sumpfreis relativ niedrig. Der Wettbewerb um Wasserressourcen zwischen Sumpfreis-Anbau, Industrie und häuslichem Bedarf wird wegen der schnellen Urbanisierung, die in den letzten Dekaden in China stattgefunden hat, immer kritischer. Auch die Stickstoffnutzungseffizienz ist im Sumpfreis-Anbau niedrig, weil 50% des ausgebrachten Stickstoffs durch Ammoniak-Verflüchtigung verloren gehen können. Die überstauten Reisfelder sind besonders anfällig für Ammoniak-Verflüchtigung, weil der pH des Überstauungswassers starken Tagesschwankungen unterliegt: Tagsüber kann der pH bis auf Werte von 9 und mehr ansteigen (pK_a von $NH_4 = 9.24$), weil die photosynthetische Aktivität von Algen den Gehalt des gelösten CO_2 senkt. Vor diesem Hintergrund ist es notwendig, das traditionelle Sumpfreis-Anbausystem anzupassen, so dass durch die Vermeidung unproduktiver Wasser- und Düngerverluste mehr Reis mit weniger Wasser und geringerem Düngereinsatz produziert werden kann. In dieser Arbeit wurde das neue „Ground Cover Rice Production System“ (GCRPS) evaluiert. Mit GCRPS werden Reissorten, die typischer Weise im Sumpfreis-Anbau verwendet werden, während der gesamten Vegetationsperiode ohne Überstau-Wasser kultiviert. Stattdessen wird der Boden bis auf etwa Feldkapazität bewässert und dann entweder mit Plastikfolie oder Strohmulch abgedeckt, um

die Evaporation zu reduzieren. Es wurden ein zwei-jähriger Feldversuch (2001 und 2002) und ein Topfversuch (2003) unter kontrollierten Gewächshausbedingungen durchgeführt. Die Ziele der Versuche waren eine Analyse des Wachstums und der Ertragsbildung von Sumpfreis und eine Evaluierung sowohl der Stickstoffdynamik in Pflanze und Boden als auch der Stickstoffnutzungseffizienz in den verschiedenen Systemen.

Im Feldversuch wurde die Menge an Bewässerungswasser im GCRPS signifikant reduziert (45%– 70% der Menge im Sumpfreis), und die Wassernutzungseffizienz wurde entsprechend verbessert. Jedoch waren Pflanzenwachstum und Ertrag limitiert. Die Pflanzen im GCRPS waren kleiner, entwickelten weniger Rispen und hatten im Vergleich zum Sumpfreis einen geringeren BFI. Unter den guten Bedingungen des Jahr 2002 war der Ertrag in GCRPS_{Plastik} um 10% niedriger als im Sumpfreis. Dies stand in engem Zusammenhang mit der Blattflächenindexdauer ($R^2 = 0.84$), worin sich die klare Sourcelimitierung des Systems zeigt. Von den Ertragskomponenten, hatte die Anzahl der produktiven Bestockungstriebe den stärksten Einfluss auf den Ertrag ($R^2 = 0.73$), während die Kornzahl pro Rispe und das Tausendkorngewicht fast unbeeinflusst blieben. Die reduzierte Bildung von Bestockungstrieben im GCRPS ging mit Ernährungsstörungen einher, z.B. Stickstoffmangel und Manganmangel in 2001 im Feld. Mit geringer Bodenfeuchtigkeit ist mehr Sauerstoff für die Nitrifikation vorhanden, so dass die dominierende N-Form von NH_4^+ im Sumpfreis zu NO_3^- im GCRPS wechselte; auch die Mn-Form wechselte mit dem Anstieg des Redox -Potenzials auf 400mV in neutralem Boden zu Mn (III) und Mn (IV). Die Stickstoffdynamik von GCRPS war durch erstaunlich niedrige Wiederfindungsraten charakterisiert. Nur 32% des ausgebrachten Düngerstickstoffs konnten in der Bodenschicht von 0-60cm einen Monat nach der Düngung wiedergefunden werden, was zu einer unerwartet niedrigen Stickstoff-Anreicherung und Stickstoffnutzungseffizienz der Reispflanzen führte. Nitratauswaschung war wahrscheinlich der Hauptverlustpfad von Stickstoff im GCRPS, da sich gasförmige Verluste in einer Parallelstudie als gering erwiesen hatten. Die Ausbringung des Stickstoffs in

drei Gaben verbesserte die Stickstoffdüngereffizienz im Jahr 2002, aber die NUE blieb wegen der unvermeidbaren Auswaschungsverluste am Versuchsstandort niedriger als im Sumpfreis. Es gibt Hinweise darauf, dass Nitrat selbst, die dominierende N-Form im GCRPS, einen Einfluss auf Bestockung und Pflanzenwachstum hatte, möglicherweise durch Auswirkungen auf das Gleichgewicht der Phytohormone und die Kohlenhydrat-Produktion. Mn-Mangel wurde im GCRPS in 2001 beobachtet. 2002 wurde dies durch Mn-Düngung gelindert. Jedoch erreichte die Ausbildung von Bestockungstrieben nach Aufteilung der Stickstoffgaben und der Mn- Düngung nur die untere Grenze der optimalen Anzahl an Bestockungstrieben.

Daher wurde eine weitere Untersuchung zum Effekt der Bodenfeuchtigkeit auf die Aufnahme von Pflanzennährstoffen und Reisswachstum im GCRPS mit Plastikfolienabdeckung unter kontrollierten Gewächshausbedingungen als Topfversuch durchgeführt. Unterschiedliche Bodenfeuchtigkeiten, z.B. Wassersättigung, 90% Feldkapazität und 70% Feldkapazität wurden mit den Verhältnissen im Sumpfreis verglichen. Da es im Topfversuch zu keiner Auswaschung kam, war die Stickstoffanreicherung im GCRPS verbessert. Es wurden keine Symptome von Wasserstress beobachtet, z.B. nahm das Boden Redox- Potenzial mit steigender Bodenfeuchtigkeit stark ab, was zu einer verstärkten Mn-Aufnahme in den Pflanzenspross bei hohen Bodenfeuchten wie im Sumpfreis oder bei Wassersättigung führte. Sumpfreis, der unter gesättigten Bedingungen angebaut wurde, zeigte von allen Behandlungen die beste Leistung, charakterisiert durch das kräftigste Wachstum (hohe Bestockung und hohe Trockenmasseproduktion) und optimale Nährstoffaufnahme (N, Mn und Fe).

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Table A1 Effect of different rice production systems on leaf size (16 July 2002), length of uppermost internode (final harvest), and plant height (final harvest) of rice¹⁾

	Leaf size ²⁾ (cm ²)	Length of uppermost internode (cm)	Plant height (cm)
Paddy control	21.1 A	40.2 A	129.1 A
GCRPS _{Plastic}	14.5 BC	30.0 B	108.5 BC
GCRPS _{Straw}	12.2 CD	31.4 B	95.0 CD
GCRPS _{Bare}	11.1 D	29.1 B	91.0 D
Aerobic rice	15.3 B	32.0 B	113.5 AB

¹⁾ Identical letters in the same column indicate no statistical difference, p=0.05, n=3

²⁾ Average leaf size= average leaf length × average leaf width × 0.75

Table A2 Fertilizer N residue in the soil after final harvest (¹⁵N-isotope method; n=3)

	% of applied urea- ¹⁵ N	
	2001	2002
Paddy control	0.77 ± 0.26	0.95 ± 0.25
GCRPS _{Plastic}	0.66 ± 0.11	0.64 ± 0.09
GCRPS _{Straw}	0.74 ± 0.04	0.56 ± 0.02
GCRPS _{Bare}	0.52 ± 0.11	-----
Aerobic rice	0.61 ± 0.29	0.76 ± 0.20
Mean	0.64	0.67

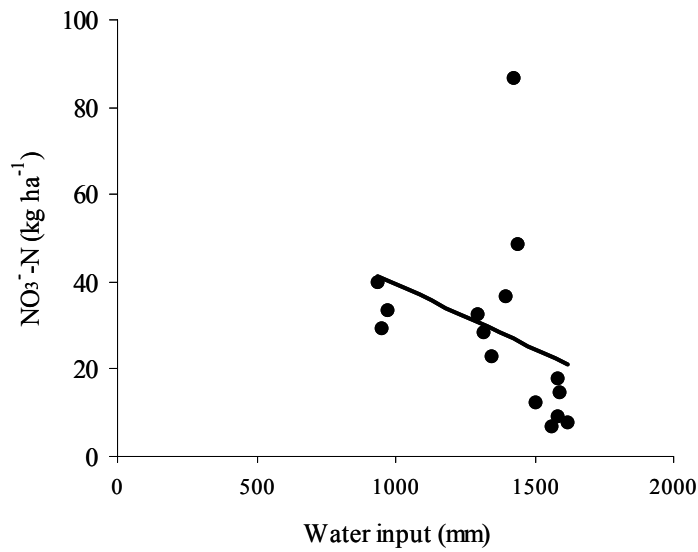


Figure A1 Correlation between water input (irrigation+rain, from sowing to PI) and soil nitrate-N content at PI stage in the rooting depth (0-60 cm) of GCRPS plots ($y = -0.0297x + 69.2$; $R^2 = 0.12$, not significant; $n = 15$)

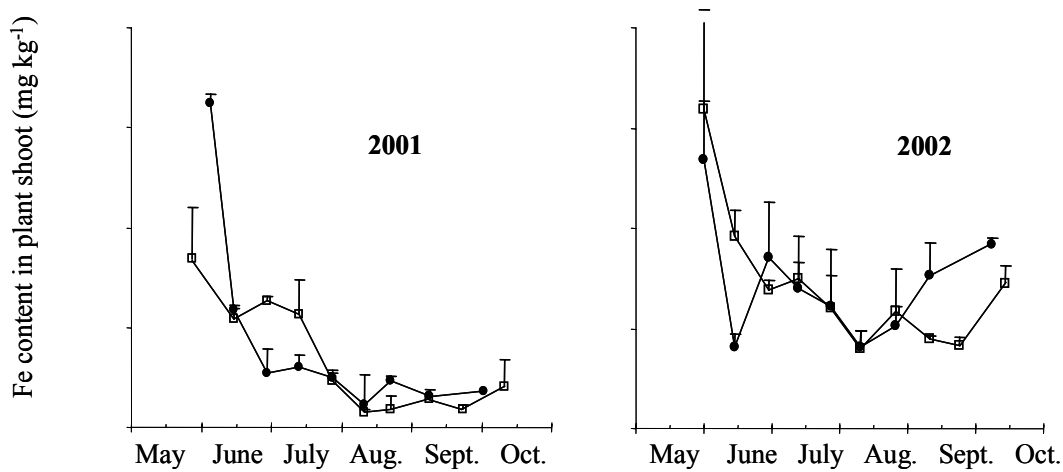


Figure A2 Fe content in shoots of lowland rice grown under submerged conditions (Paddy control) or with plastic film soil cover under different soil humidity regimes (field experiment). Error bars indicate 1 standard deviation —●— Paddy control —□— GCRPS, 90%WHC