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***Greenhouse gas emissions (methane and nitrous oxide) and water
use in a water-saving Ground Cover Rice Production System
(GCRPS) in North China, Beijing***

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Dipl.-Ing. agr. Christine Kreye
aus Peine

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Dekan: Prof. Dr. F. Taube
Erster Berichterstatter: Prof. Dr. B. Sattelmacher
Zweiter Berichterstatter: Prof. Dr. R. Horn
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General introduction

Lowland rice production in China

Rice is the major staple food in Asia. In China, rice accounts for 44 % of the total grain production (Li, 2001). In 2001, 93 % of the 28.6 million ha of rice production area were used for irrigated lowland rice production (IRRI, 2003a). Most of the cultivated rice in China is indica rice. However, the demand for japonica rice, which was traditionally cultivated and consumed in China's north, has apparently been increasing, but limited water resources in the north and north-east restrict further expansion of japonica rice in this region (Hansen et al., 2002). The main rice cropping area is south-eastern China where temperature and rainfall constitute an ideal environment for rice and enable a long growth period; the area south of the Qinling Mountains and the Huaihe River makes up for more than 90 % of the total rice area, while low temperature and water shortage limit rice production in north-eastern China (IRRI, 2003b).

Usually lowland rice is grown in bunded and flooded fields. After seedling development in a nursery, rice is transplanted into the main field. Before transplanting, the wet, submerged soil is usually puddled (ploughed, harrowed and levelled). Besides e.g. the ease of transplanting and weed control, soil puddling also serves to reduce percolation losses and facilitate even distribution of irrigation water. On clayey soils the puddling process leads to the development of a poorly permeable plough layer or hard pan (De Datta, 1981; Wopereis et al., 1992). Depending on region and climate, fields may even remain submerged for the whole year (Cai, 1997). Since the early 1980s, mid-season drainage to reduce unproductive tillers has become a more and more common measure in rice production (Li, 2002).

Water requirements in lowland rice production

Water requirements in lowland rice are usually high as a permanent water layer has to be sustained, from which water constantly evaporates until canopy closure. Evapotranspiration demands range from 4 - 5 mm per day to 6 - 7 mm per day in the tropics during wet and dry season respectively (De Datta, 1981). The hydrostatic pressure of the ponded water contributes to higher percolation rates in paddy fields and may largely affect percolation rates on more permeable soils with relatively permeable plough soles or poor puddling (Bouman et al., 1994; Tuong and Bhuiyan, 1999). Typical seepage and percolation rates, which strongly depend on soil texture, can range from 1 - 5 mm per day and 25 - 30 mm per day in heavy clay soils and in sandy and sandy loam soils, respectively (Tabbal et al., 2002; Bouman and Tuong, 2001). The wide range of percolation losses already indicates that percolation can become the major cause of unproductive water loss on lighter more sandy soils. It is estimated that seepage and percolation loss can be as high as 50 - 80 % of total water input (Sharma (1989) in Bouman and Tuong, 2001). In wetlands, water requirements for land preparation may range from 150 to 200 mm (De Datta, 1981).

Water scarcity in Chinese agriculture

Agriculture in China depends strongly on irrigation, in South China about 90 % of the freshwater is used for rice production. But water for irrigation is becoming scarce, partly due to an increasing competition between agricultural and industrial water use and an increasing urbanisation. Furthermore, the population in China continues to grow. This will increase food demands and result in additional irrigation water requirements (Li, 2001; Wang, 2002b). The water shortage is pronounced in the North China Plain, where the drop in the ground water table has accelerated (Wang, 2002b). In Beijing, located at the border of the North China Plain, water supply cannot meet the demand, and water shortages have already caused severe losses in industrial and agricultural production (Hou and Hunter, 1998).

Lowland rice production in Northern China, Beijing region

Commonly in the Beijing area, North China, lowland rice is transplanted after a nursery stage to the submerged field, which is thereafter kept constantly under a shallow water layer. An exception to this is the drainage period during the tillering stage when the soil is allowed to dry so that the rice plants are forced to reduce unproductive tillers. Also about six weeks before harvest, the field is no longer irrigated. This period may be preceded by a time of alternate wetting and drying irrigation where the field is submerged and only flooded again after the soil has started to dry. This system is already suitable to save some water, provided intermediate soil drying is not too severe and cracks do not penetrate the protecting plough sole. In such a case, water consumption may even increase as percolating water can bypass the impeding plough sole (Lu et al., 2000; Bouman et al., 2001).

GCRPS

On the background of the severe water scarcity, water-saving agricultural systems are becoming increasingly important. One alternative system that has been developed in various regions and sub-types is the Ground Cover Rice Production System (GCRPS). This system uses different mulching materials, like plastic film or straw mulch, to reduce evaporation from the soil, which is no longer submerged but maintained at a very high soil water content, preferably still in the upper range of the respective soil water holding capacity. Farmers may also apply the mulching materials with the goal of increasing temperature and promoting plant development. Plant establishment can be facilitated by direct sowing. The GCRPS may be characterised as an intermediate system between other water-saving lowland rice cultivation techniques, like saturated soil culture, and intermittent irrigation (Tabbal et al., 2002) and Aerobic Rice (Wang et al., 2002a), where an adapted rice variety is cultivated on aerobic upland conditions. In the GCRPS, the soil is also aerobic, but fields are irrigated more frequently by flooding irrigation to maintain a high soil water status.

Greenhouse effect

Besides the high consumption of irrigation water, the paddy rice production system is supposed to be an important source of anthropogenic methane, a gas that contributes largely to the greenhouse effect (IPCC, 1997). Mid-season drainage, intermittent irrigation or pre-harvest drainage have been widely addressed as measures to reduce methane emissions; while this is promising to alleviate methane evolution, it may at the same time promote the formation of nitrous oxide, also an important greenhouse gas as, for example, outlined in a review by Aulakh et al. (2000). The natural warming of the atmosphere is due to the natural relatively low concentrations of the radiatively active gases, water vapour, carbon dioxide, methane and nitrous oxide (Rennenberg et al. (1995) and IPCC (1990) therein); higher concentrations of these gases would promote global warming. According to the IPCC (2001a) observations, the global surface temperature has increased by about 0.6 °C over the 20th century. Increases in methane and nitrous oxide concentrations in the atmosphere since 1750 have been calculated (IPCC, 2001a). According to this, methane increased by 151 %, of which about 50 % are anthropogenic, and nitrous oxide by 17 %, of which about one third are anthropogenic. The force of radiatively active gases is calculated relative to the force of carbon dioxide. For methane the IPCC calculated a factor of 23 and for nitrous oxide 296 at a time horizon of 100 years (IPCC, 2001b).

Methane

Methane is generated by methanogenic bacteria under anaerobic soil conditions at low redox potentials, lower than -200mV (Conrad, 1989). In the rice field, these low redox potentials are achieved by continuous submergence, which leads to a decline in redox potential after flooding to the respective levels at which methanogenesis is initiated, -150 mV to -160 mV

(Wang et al., 1993), and methanogenic micro-organisms decompose organic matter to methane and CO₂. The two major pathways of methane formation in flooded soils are a reduction of CO₂ with H₂ derived from an organic compound and the decarboxylation of acetic acid as outlined in an overview by Aulakh et al. (2000). The main source of methane in rice soils is the top-soil (Mitra et al., 2002) just below the oxic cover layer. Via diffusion, ebullition and plant transport, the gas reaches the ambient air. In rice, ebullition is important during the early stage of the cropping phase, but plant transport becomes more important at later vegetation stages, while diffusion is almost negligible (Aulakh et al., 2000). The transport through the plant is facilitated via the aerenchyma of rice leaves, nodes and panicles. Leaves are the major pathway at early development stages, but nodes become more important at later stages (Wang et al., 1997). Under aerobic soil conditions or in aerated soil compartments, e.g. the aerobic topmost soil layer in paddy fields, methane is subject to methane oxidation by methanotrophic bacteria (Aulakh et al., 2000).

Nitrous oxide

Nitrous oxide formation occurs as a by-product of nitrification and denitrification. Firestone and Davidson (1989) developed the conceptual model of the “leaky pipe” to visualise the formation of nitrogen trace gases in the process of either oxidation of ammonium to nitrate or the reduction of nitrate to di-nitrogen. In their model, the extent of e.g. nitrous oxide formation depends, on the one hand, on factors that control the rate of the overall process and, on the other hand, on factors that govern the partitioning of the involved nitrogen forms. For example, the availability of water soluble or mineralisable organic carbon is an important factor regulating denitrification rates as stated in the review by Bremner (1997). Nitrification and denitrification processes have different optimum soil moisture levels. Davidson (1993) found the optimum for nitrification at about 50 % water filled pore space (WFPS) and for denitrification at >80 % WFPS. He found that 60 % WFPS, which roughly corresponds to field capacity, was an important transition point from predominantly aerobic to mainly anaerobic processes. According to the review by Williams et al. (1992) and FAO (2001), wetting of dry soil has been reported to cause large fluxes of nitrous oxide. From flooded rice fields, however, it can be expected that nitrous oxide fluxes are low (Bronson and Singh, 1995; Freney, 1997). Nitrous oxide is released from the soil via diffusion; increasingly wet soil conditions, which reduce diffusion rates, may lead to increased denitrification rates, but they may also lead to a reduction of nitrous oxide release due to re-consumption of nitrous oxide (Firestone and Davidson, 1989; FAO, 2001).

Objectives

The field site for this study was located in the surroundings of Beijing where formerly rice was commonly grown. Nowadays, this specific area is characterised by a deep groundwater table and thus an example for rice production under rather unfavourable conditions as the deep groundwater table makes high irrigation water demand likely. At this site the water saving GCRPS was tested against the common lowland rice management with respect to its water saving potential and its impact on the formation of methane and nitrous oxide.

The impact of the GCRPS on yields, agronomic factors and nitrogen use efficiency, usually rather low in paddy rice, were studied in parallel (Tao, 2004).

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Chapter I

Gaseous emissions from a water-saving rice production system (GCRPS) in North China: 1. methane

Abstract

Rice is the major staple food in China, most of which is produced on irrigated lowland fields usually with high water requirements. Since irrigation water is becoming an increasingly scarce resource, alternative rice production systems are under investigation. One of which is the Ground Cover Rice Production System (GCRPS), where the soil is no longer flooded but kept at a high soil moisture content, preferably in the upper range of field capacity. Besides high water consumption, the traditional paddy rice production system is known for its contribution to global warming, because of the potential emissions of methane through the anaerobic soil conditions in the flooded rice field. In the GCRPS the very moist, but aerobic soil conditions are expected to reduce methane emissions significantly.

Methane fluxes were monitored throughout the rice cropping seasons 2001 and 2002 using portable closed chambers. In the paddy rice the observed methane emissions were very low, about $300 \text{ mg m}^{-2} \text{ a}^{-1}$ in 2001 and about $1000 \text{ mg m}^{-2} \text{ a}^{-1}$ in 2002. The enhanced flux in 2002 was most likely due to an organic fertiliser amendment. The overall low flux rates were probably related to the high demand of irrigation water input. The low methane emissions in paddy rice in Beijing were further reduced in the GCRPS, where methane fluxes were negligible.

Introduction

Rice is the major staple food in Asia. In China, rice accounts for 44 % of the total grain production (Li, 2001). In 2001, 93 % of the 28.6 million ha of rice production area were used for irrigated lowland rice production (IRRI, 2003). In northern China and in the Beijing area the common rice production system is a single rice crop which is grown on constantly submerged fields from transplanting until mid-season tillering when the fields are drained for about 1 week to reduce unproductive tillers and enhance yield. Thereafter, the soil is flooded again, but the continuous submergence may be changed to alternate wetting and drying irrigation depending on plant development and water resources. Several weeks prior to harvest the soil is allowed to dry. Although water resources in this system are already spared to some extent as compared to continuous flooding over the entire season, its water requirements are still high. Irrigation water is becoming increasingly scarce, partly due to an intensified competition between agricultural and industrial water needs as well as an increasing urbanisation (Li, 2001; Wang et al., 2002). To alleviate the increasing water scarcity, alternative water-saving rice production systems have been developed. One of them is the Ground Cover Rice Production System (GCRPS), where the soil is no longer submerged but kept at high soil moisture levels within the range of field capacity. Additionally, the soil is covered by mulching materials like straw mulch or plastic film.

The paddy rice production system is supposed to be an important source of anthropogenic methane, a trace gas that largely contributes to the greenhouse effect (IPCC, 1997). The GCRPS not only promises to save water but also to mitigate the emission of the greenhouse gas methane due to its aerated soil conditions, where methane formation is unlikely to occur. Methane is generated by methanogenic bacteria under anaerobic soil conditions at low redox potentials, lower than -200 mV (Conrad, 1989), although methane production is already

initiated at -150 mV to -160 mV (Wang et al., 1993). In the rice field, these low redox potentials are a result of continuous submergence. The redox potential decreases after flooding to levels at which methanogenic micro-organisms decompose organic matter to methane and CO_2 . The two major pathways of methane formation in flooded soils are reduction of CO_2 with H_2 derived from an organic compound and the decarboxylation of acetic acid as outlined in a review by Aulakh et al. (2000). The main source of methane in rice soils is the top-soil (Mitra et al., 2002a) just below the oxic cover layer. Diffusion, ebullition and transport through the plant's aerenchyma are the pathways of the gas into ambient air. In rice, ebullition is important during the early stage of the cropping phase, but plant transport becomes more important at later vegetation stages, while diffusion is almost negligible (Aulakh et al., 2000). The transport through the plant is facilitated via the aerenchyma of rice leaves, nodes and panicles. Leaves are the major pathway at early development stages, but nodes become more important at later stages (Wang et al., 1997). Under aerobic soil conditions or in aerated soil compartments, methane is subject to methane oxidation by methanotrophic bacteria (Aulakh et al., 2000).

A change from paddy rice to the GCRPS with the inherent change in soil moisture status is expected to cause a strong reduction in methane emissions. Therefore the objective of this study was to quantify methane fluxes from the two systems and to verify the assumed alleviation on methane emissions from GCRPS.

Apart from the mitigating effect of the GCRPS on methane production and emission, it may very well favour the formation of nitrous oxide, another important greenhouse gas, as the GCRPS is characterised by high soil moisture status and frequent irrigation events (FAO, 2001). Evolution of nitrous oxide from GCRPS is studied in the second chapter of this thesis.

Material and methods

A field experiment was carried out on Dongbeiwang experimental station of the China Agricultural University near Beijing. According to the Koeppen classification, the Beijing climate can be classified as Dwa¹ (Sträßer, 1998). The soil type was a Cambisol, FAO 1988, (Gong et al., 1994). The average soil texture of the upper 0.75 m consisted of 49 % sand, 37 % silt and 13 % clay. The pH_{Calcium-chloride} was about 6.7. Soil carbon and nitrogen content in the upper 0.4 m were 2.4 % and 0.12 % respectively. The ground water table was below 10 m. Data on precipitation, ambient air pressure, air temperature, global radiation, wind speed and humidity were collected at a meteorological station (Thies GmbH, Göttingen) next to the experimental site.

Field layout and treatments

The field was divided into an inundated lowland rice area and an irrigated upland area for the GCRPS treatments. The respective treatments were traditional lowland rice (Paddy) and GCRPS with two mulching materials: plastic film (Plastic) and rice straw mulch (Mulch) as well as two control treatments without mulching material: lowland rice bare soil (Bare) and aerobic rice (Aerobic). An additional treatment in 2001 was aerobic rice with plastic film mulch (Aerobic-plastic). Each treatment had three replicates, which were laid out according to a one-factorial block design. Due to the need to separate lowland and irrigated upland conditions, only the GCRPS treatments were randomly distributed.

Field set-up

In the GCRPS treatments, rice was sown in the beginning of May (15 x 25 cm, 6 plants per hill). In the Paddy plots, rice was transplanted in late May after a four- to five-week nursery period. In 2001, spacing in Paddy and GCRPS was identical; in 2002, planting density was reduced to 4 plants per hill in Paddy. Plastic film mulch was applied after plant emergence in 2001 and shortly after sowing in 2002. Straw mulch was applied after seedling establishment in the beginning of June 2001 and in late June 2002. In 2001 plain rice straw and in 2002 semi-decomposed rice straw was applied at a rate of 1.5 t ha⁻¹. The rice variety was Yue Fu (*Oryza sativa japonica*); the two Aerobic treatments were planted with the aerobic rice variety Han Dao 297.

Irrigation of Paddy and GCRPS plots

The paddy treatment was managed according to regional field practise under continuously flooded lowland conditions with a drainage period of about one week in July. About six weeks before harvest, the plots were allowed to dry. In 2002, this period was preceded by two weeks of alternating wetting and drying irrigation. For the GCRPS treatment, soil moisture was maintained in the range of field capacity. For 2001, the soil moisture threshold for irrigation during the seedling stage was aimed at a soil water tension of 10 - 15 kPa, then increased to 15 kPa - 20 kPa for the intermediate part of the vegetation period, and finally, to soil water tensions of 20 - 30 kPa for the late part of the vegetation period. For 2002, the threshold was reduced to alleviate drought stress for the plants to 10 kPa of soil water tension until mid-August and thereafter increased to 15 - 18 kPa for the vegetation stage after panicle initiation. Irrigation was scheduled by two tensiometers installed in each plot at 0.15 m depth and conducted as surface irrigation, which stopped in mid-September. Total amounts of irrigation water are given in Table 1.

¹ Meteorological station at 39°57'N, 116°19'E, 52 m above sea level; average data from 1930 to 1960

D: humid climate of regions with cold winters, mean temperature of the coldest month <-3°C, mean temperature of the warmest month >10°C; w: precipitation of the summer month with highest precipitation is at least 10 times higher than the precipitation of the winter month with least precipitation; a: mean temperature of the warmest month >22°C

Table 1. Irrigation and rain amounts during the rice cropping seasons 2001 and 2002

	2001			2002		
	Irrigation [mm]	sd	Rain [mm]	Irrigation [mm]	sd	Rain [mm]
Paddy	3751	1333	290	3044	1125	442
Plastic	1275	83	314	1593	35	445
Mulch	1192	8	314	1605	64	445
Bare	1328	28	314	1637	13	445
Aerobic	1072	57	314			
Aerobic-plastic	1028	29	314			

Soil water tension

Soil water tension was monitored by three tensiometers which were installed at a depth of 0.15 m in each plot; one tensiometer was installed within the gas sampling sub-plot. In Paddy, the maintenance of a water layer was recorded as water layer *present* or *not present* before irrigation events (Figure 1).

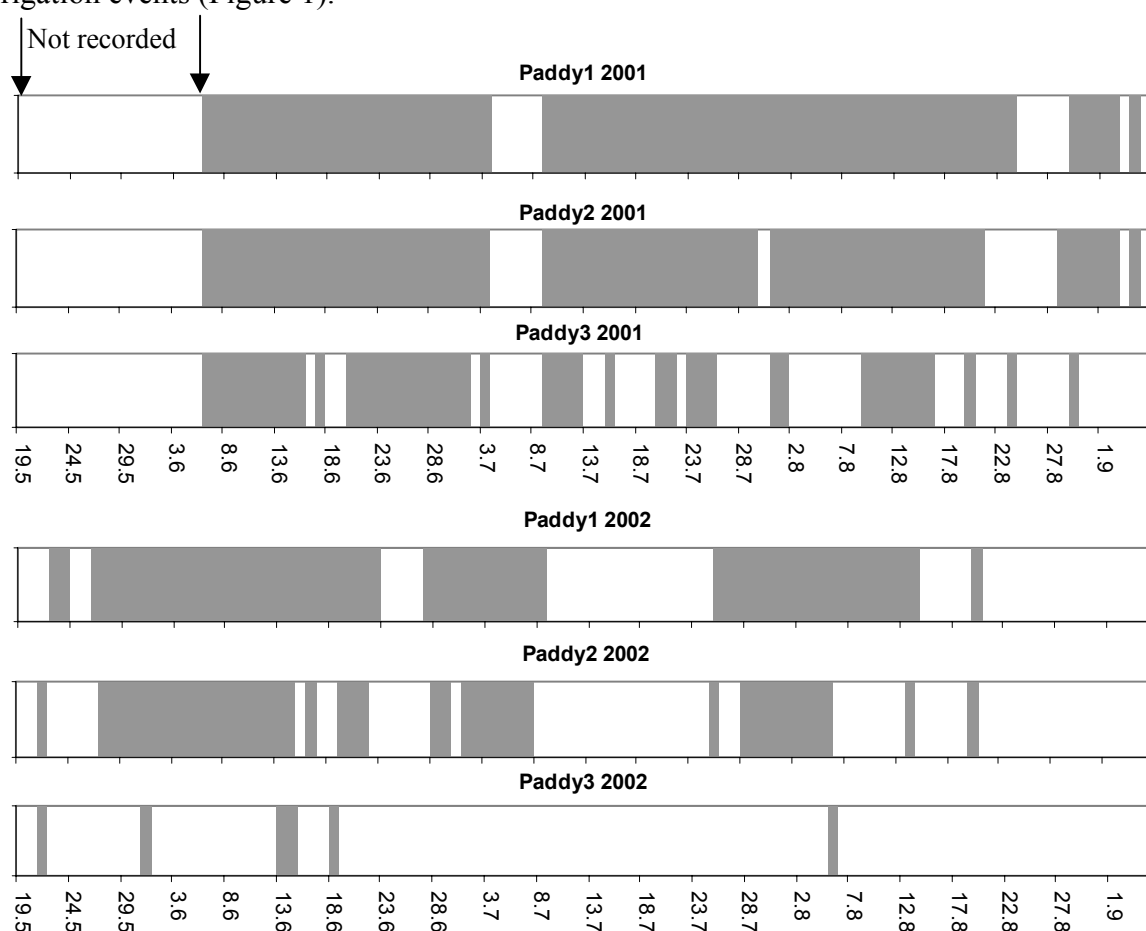


Figure 1. Presence of a water layer (grey column) for each Paddy replicate in 2001 and 2002

Fertilisation

Nitrogen fertiliser was applied as urea nitrogen (225 kg ha^{-1} and 180 kg ha^{-1} in 2001 and 2002 respectively). In Paddy, the fertiliser was applied in three splits at transplanting, tillering and heading (40/ 30/ 30). In GCRPS, the total amount was applied as basal fertiliser in 2001, in 2002 fertiliser was given in split application (30/ 40/ 30) as basal fertiliser and tillering and heading dressings. In 2002, all treatments received an organic basal fertilisation of 45 kg N ha^{-1} as rapeseed cake. The basal urea fertiliser in GCRPS was incorporated into the soil at field preparation; the later dressings were followed by irrigation on the same day to facilitate fertiliser distribution under surface mulches and incorporation into the soil.

Gas sampling

Gas sampling was facilitated by the closed-chamber technique (Hutchinson and Mosier, 1981; Denmead, 1995). Each plot was equipped with a metal frame of 0.5 m x 0.6 m and 0.2 m height at 4.5 m and 2.3 m from the plot borders. The frames were buried into the soil to 0.07 m depth. Beneath the soil surface the frame had several holes to allow for soil moisture exchange with the surrounding soil; nevertheless, irrigation was applied separately analogous to the main plot. In 2002, the frames in Paddy were equipped with an extra hole just above the soil surface to enable water exchange with the main plot. Portable sampling chambers of transparent Plexiglass were mounted onto the metal frames, the sealing between chamber and frame was facilitated by water-filled rims. Two chamber sizes (0.3 m and 0.9 m) were used in accordance with plant height. All chambers were equipped with computer fans and every second chamber held a thermometer. Ambient air pressure was measured at the meteorological station close to the site. Access to the gas-sampling sub-plot in Paddy was facilitated by small footbridges. Gas samples were collected in 1L gas bags (Guangming Chemical Engineering Research Institute, Dalian, China) via a syringe, which was injected into the chamber through a rubber septum. At each sampling event, 4 samples of 400 ml each were collected at 0 min, 10 min, 20 min and 30 min after chamber closure.

Sampling schedule during rice cropping period

The basic gas sampling schedule in 2001 followed an adapted protocol developed by Buendia et al. (1998). On selected days, gas samples were collected at 6:00, 12:00 and 18:00 h in Paddy and Plastic, and at 18:00 h from the remaining plots. Since statistical analysis (Tukey test, 0.05 probability level) did not show any differences between sampling times on one day, samples were collected at 18:00 h only in 2002. In 2002 samples were collected weekly in Paddy and GCRPS Plastic and Mulch. Around the drainage period in Paddy and for fertilisation events in GCRPS and Paddy, the sampling schedules were intensified in both years. After harvest and before the next rice crop, samples were collected on various days at 12:00 h. During these periods, emission rates were extremely low, so that emission was estimated zero, and therefore, was not considered in the calculation of annual flux.

Samples were analysed by gas chromatography within one week after collection in the laboratory of the Institute of Atmospheric Physics, Chinese Academy of Science, in Beijing. The gas chromatographic characteristics are described in detail by Wang and Wang (2003). The carrier gas N₂ was used at a flux rate of 30 cm³ min⁻¹, the column for gas separation was stainless steel measuring 2 mm x 2 m, filled with a molecular sieve of 60/80 mesh; the FID detector temperature was 200°C and the oven temperature 55°C.

Flux calculation

The flux of methane emissions (mg m⁻² h⁻¹) was calculated by the formula:

$$F=60*10^{-5}(273 (273+T)^{-1})P 1013^{-1}*\rho H(dC dt^{-1}),$$

where F is the flux [mg m⁻² h⁻¹], T the mean temperature [°C] inside the chamber during the sampling interval, P the ambient air pressure of the experimental site [hPa], ρ the methane density at 0 °C and 1013 hPa [g L⁻¹], H the height of chamber (headspace) [cm], t the time for sampling [min], C the methane concentration in volume mixing ratio [10⁻⁹], quantified with the concentration of the calibration gas, and dC dt⁻¹ the rate of increase of methane concentration in the closed chamber [10⁻⁹ min⁻¹] (Zheng et al., 2000a).

For cumulative flux calculations [mg m⁻²], fluxes for intervals between measurements were interpolated linearly and based on 18:00 h measurements. In both years after basal fertiliser application and before treatment separation (e.g. mulch applications), samples in GCRPS were collected from three plots only. During this initial period, cumulative flux calculations were based on these measurements for each GCRPS treatment to represent the initial emissions. For statistical analysis the GLM procedure of SAS (SAS, 1989) was used.

Results

Total emissions in 2001 and 2002

In GCRPS, methane emissions were extremely low, ranging from only 11 mg m⁻² a⁻¹ in GCRPS Plastic in 2001 to a methane consumption of -104 mg m⁻² a⁻¹ in GCRPS Aerobic in 2001 (Table 2). In 2001 and 2002, a slight methane consumption was predominant in GCRPS. On the contrary, low emissions in Paddy were observed in 2001, but emissions increased threefold to about 1025 mg m⁻² a⁻¹ of methane in 2002.

Table 2. Cumulative CH₄ emissions of 2001 and 2002, n = 3

	2001						2002		
	Paddy	Plastic	Mulch	Bare	Aerobic	Aerobic-plastic	Paddy	Plastic	Mulch
Mean CH ₄ [mg m ⁻² a ⁻¹]	315 _A	11 _B	-86 _B	-29	-104	-40	1025 _C	-32 _C	-1 _C
sd	127	41	104	64	86	23	781	65	167

Impact of treatment tested by Tukey test (probability level: 0.05) for each year; figures followed by the same letter are not significantly different

Within one treatment, no significant differences between the years were observed

2001

The time course of 2001 showed that methane emissions in Paddy increased after some time of flooding and reached a peak value of 0.69 mg m⁻² h⁻¹ by the second day of the drainage period, 04.07.01 – 08.07.01 (Figure 2). Then, a decline to almost zero emissions and even slight methane consumption shortly after the end of the drainage period was observed. Thereafter, emissions slightly increased again to values of about 0.2 mg m⁻² h⁻¹, but in general, fluxes remained very low. Towards the end of the vegetation period, emissions declined again, once continuous flooding ended. In GCRPS Plastic, methane emissions remained extremely low throughout the cropping period.

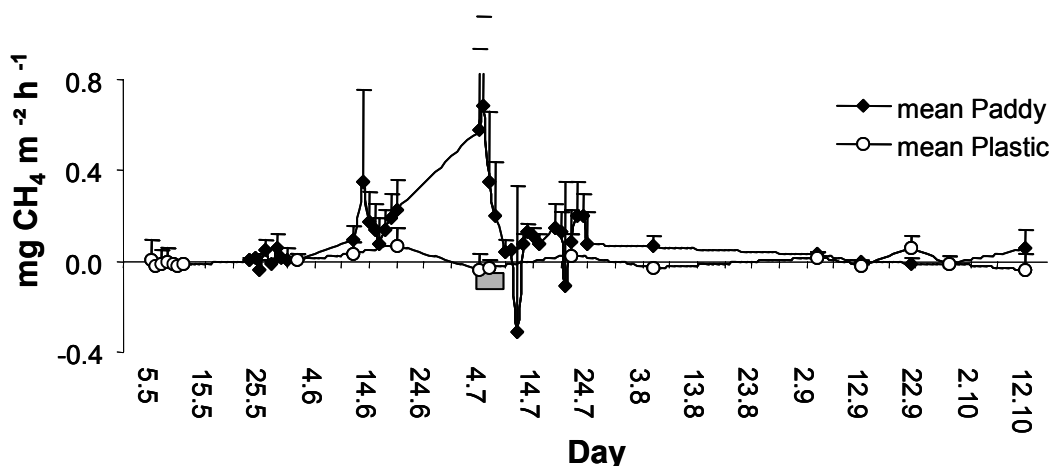


Figure 2. CH₄ emissions at 18:00 from Paddy and GCRPS Plastic in 2001

Grey box: drainage in Paddy

Measurements in Paddy started with field preparation and fertilisation

2002

The time course of methane emission in 2002 (Figure 3) was similar to 2001. Methane emissions from Paddy showed a peak ($4.3 \text{ mg m}^{-2} \text{ h}^{-1}$) at the beginning of the drainage period following a period of increasing emissions. After the drainage period, emissions remained very low. In GCRPS Plastic, almost no methane fluxes were observed in 2002.

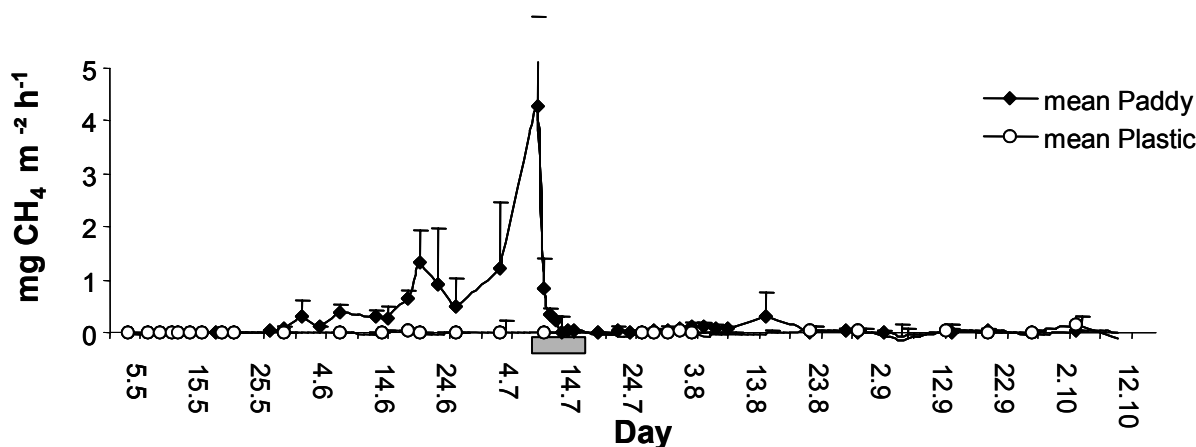


Figure 3. CH₄ emissions at 18:00 from Paddy and Plastic in 2002

Grey box: drainage in Paddy

Measurements in Paddy started the day before field preparation and fertilisation

Variation of methane fluxes among Paddy replicates

When regarding the three replicates of Paddy, data shows that the variation among plots was very high in 2001 and 2002 with a coefficient of variation of 40 % and 76 % respectively (Table 3). Both years were consistent in strikingly low fluxes in the third replicate, which coincided with an extremely poor maintenance of a water layer for this plot (Figure 1) and very high consumption of irrigation water (Table 1).

Table 3. Cumulative CH₄ flux of Paddy replicates of the vegetation phase in 2001 and 2002

	2001			2002		
	Flux [mg m ⁻²]	Mean [mg m ⁻²]	sd	Flux [mg m ⁻²]	Mean [mg m ⁻²]	sd
Rep.1	366			1886		
Rep.2	408			827		
Rep.3	170	315	127	363	1025	781

Methane fluxes during non rice-cropping periods

Over winter during the fallow period between rice crops, observed fluxes were either very low or in fact zero with the exception of 24 October 2002, when minor fluxes were recorded in GCRPS (Table 4). Thus flux per year was estimated to be the same as the cumulated emissions estimated for the respective vegetation periods of 2001 and 2002 (Table 2).

Table 4. Average CH₄ emissions rates during non-rice cropping periods at 12:00, n = 3

Day	Paddy		Plastic		Mulch	
	CH ₄ [mg m ⁻² h ⁻¹]	sd	CH ₄ [mg m ⁻² h ⁻¹]	sd	CH ₄ [mg m ⁻² h ⁻¹]	sd
26.10.01	-0.018	0.018	0.003	0.009		
10.11.01	-0.020	0.013	0.005	0.017		
10.12.01	-0.006	0.017	0.002	0.002		
07.03.02	-0.018	0.004	-0.009	0.013		
09.03.02	-0.030	0.012	-0.013	0.001		
11.03.02	0.002	0.006	-0.004	0.001		
24.10.02	-0.009	0.009	0.144	0.375	0.252	0.465
31.10.02	-0.046	0.029	-0.030	0.023	-0.020	0.015
07.11.02	-0.028	0.005	-0.037	0.014	-0.020	0.014
14.11.02	-0.020	0.008	-0.031	0.009	-0.006	0.020
21.11.02	-0.010	0.022	-0.001	0.034	-0.008	0.005
05.12.02	-0.017	0.008	-0.013	0.011	-0.014	0.001
17.12.02	-0.004	0.022	-0.011	0.017	-0.001	0.036
09.01.03	-0.031	0.015	-0.038	0.042		
11.04.03	-0.015	0.013	-0.016	0.021		

Impact of different GCRPS treatments on methane emissions

The impact of different GCRPS treatments on methane emissions was tested in the first experimental year, 2001, after the treatments were separated, e.g. mulching materials applied, and the crops established. The cumulative fluxes ranged from 22 mg m⁻² in GCRPS Plastic to -96 mg m⁻² in GCRPS Aerobic, but no significant differences among treatments were detected (Table 5). The extremely low flux rates on the representative sampling days are illustrated for GCRPS Plastic in Table 7, where the highest observed flux at 18:00 was 0.07 mg m⁻² h⁻¹. As no differences among treatments were detected, the GCRPS treatments studied in 2002 were reduced to Plastic and Mulch.

Table 5. Cumulative CH₄ emissions in GCRPS after crop establishment (1.06. - 28.09. 2001)

	Mean [mg m ⁻²]; n = 3	sd
Plastic	22.2 _A	36.3
Mulch	-41.4 _A	45.4
Bare	-16.6 _A	76.1
Aerobic	-96.1 _A	80.3
Aerobic-plastic	-42.9 _A	31.3

Impact of treatment tested by Tukey test (probability level: 0.05); figures followed by the same letter are not significantly different.

Cumulative flux for tested period, 1.06.01 until 28.09.01, calculated from 11 observations after crop establishment (table 7, except for 4.07.01 and 8.07.01).

The lack of treatment differences in GCRPS in 2001 was confirmed in the second year, 2002; again no differences were found between the GCRPS treatments Plastic and Mulch (Table 2).

Impact of daytime on methane emissions in 2001

During the first year, samples were collected at three times of day: 6:00, 12:00 and 18:00 h. Statistically, an impact of daytime on methane emission could not be verified, except for two days: one day in Paddy and one day in GCRPS Plastic (Table 6 and Table 7). Observed flux rates on the sampling days were extremely low or slightly negative in GCRPS Plastic, suggesting that no fluxes had occurred (Table 7). From Paddy, emission rates were also generally low (Table 6).

Table 6. CH₄ emission rates measured at three times of day in Paddy 2001, n =3

day	1.6	11.6	19.6	4.7	5.7	6.7	7.7	15.7	21.7	5.8	4.9	12.9	21.9	28.9	12.10
<i>Mean [mg m⁻² h⁻¹]</i>															
06:00	0.007	0.061	0.194	0.535	0.701	0.290	0.289	0.078	0.144	0.126	0.108	-0.007	0.287	0.258 _A	0.157
12:00	0.065	0.085	0.261	0.570	0.563	0.299	0.181	0.102	0.145	-0.027	0.036	0.003	0.036	-0.060 _B	0.004
18:00	0.004	0.097	0.228	0.580	0.690	0.351	0.200	0.074	0.086	0.064	0.028	-0.002	-0.008	-0.013 _B	0.056
sd															
06:00	0.090	0.025	0.044	0.363	0.657	0.222	0.286	0.047	0.067	0.142	0.145	0.008	0.281	0.119	0.324
12:00	0.082	0.043	0.174	0.422	0.432	0.227	0.215	0.012	0.086	0.015	0.070	0.040	0.055	0.069	0.056
18:00	0.033	0.059	0.129	0.412	0.552	0.309	0.234	0.043	0.144	0.047	0.014	0.011	0.027	0.011	0.082

Impact of day time tested by Tukey test (probability level: 0.05)

Table 7. CH₄ emission rates measured at three times of day in Plastic 2001, n =3

day	1.6	11.6	19.6	4.7	6.7	8.7	21.7	5.8	4.9	12.9	21.9	28.9	12.10
<i>Mean [mg m⁻² h⁻¹]</i>													
06:00	0.149	-0.023	-0.089 _B		-0.014	-0.001	0.058	-0.020	-0.024	-0.030	-0.117	0.008	-0.089
12:00	0.008	0.003	-0.007 _B	-0.002	0.002	0.005	-0.084	0.019	0.028	0.021	0.040	0.007	0.021
18:00	0.017	0.031	0.070 _A	-0.036	-0.029		0.028	-0.029	0.017	-0.020	0.057	-0.009	-0.040
sd													
06:00	0.397	0.006	0.026		0.032	0.042	0.043	0.016	0.017	0.022	0.145	0.041	0.069
12:00	0.029	0.039	0.001	0.020	0.026	0.033	0.048	0.033	0.050	0.029	0.051	0.037	0.042
18:00	0.032	0.056	0.078	0.068	0.031		0.092	0.002	0.025	0.009	0.053	0.034	0.076

Impact of daytime tested by Tukey test (probability level: 0.05)

Days with missing data were not used for statistical analysis; including 1.6.

Discussion

The observed methane emission pattern of 2001 and 2002 confirmed in general the expectation of relatively high emissions from Paddy and very low methane fluxes in the GCRPS with its aerated conditions.

In Paddy, the methane flux pattern followed a pattern commonly observed for flooded lowland rice with a mid-season drainage period in northern China. Emissions increased with the duration of the flooded period, peaked with the onset of the drainage period, declined to almost nil flux afterwards, increased again to moderate flux rates after re-flooding and ceased either towards the end of the vegetation period in 2001 or already after drainage like in 2002.

When a dry soil is flooded, some time is needed to reach sufficiently low redox potentials to start methane evolution. Wang et al. (1993) e.g. recorded a time lag of almost 14 days before methane production started in previously air-dried soil. Xu et al. (2003) found that the redox potential decreased sooner and methane emissions started earlier, the wetter the soil had been previously.

Several authors relate the seasonal methane emission pattern to the temperature regime. Wassmann et al. (2000) observed the following relationship: continuous or increasing temperatures lead to maximum emissions at the ripening stage, maximum temperatures during the middle of the cropping season lead to highest emissions during the reproductive stage, and a decreasing temperature regime promotes highest emissions during the vegetative stage. These patterns are always modified by organic manure application and drainage. That methane flux is governed by temperature is corroborated by Lu et al. (2001) and Wang et al. (2000). For Beijing, Wang et al. (2000) describe the methane emission pattern for the Beijing region as a time of increasing rates at mid-tillering stage, followed by fluctuating emission rates due to mid-season drainage, and lastly, decreasing flux rates due to a decrease in temperature and harvest drainage.

Thus, the observed emission peak at drainage can be attributed to the typical flux pattern controlled by temperature but interrupted by the drainage period. The observed peak at the beginning of mid-season drainage may be related to the soil drying and the subsequent release of entrapped methane. Denier van der Gon et al. (1996b) observed a release of entrapped methane upon soil drying one and two days after harvest once the soil surface became dry. They reason that the aeration of soil macro-pores facilitates the methane release and estimate that the entrapped methane would amount to about 10 % of the previously emitted methane through the season. Also, in a study in Southeast China Zheng et al. (1997) and Zheng et al. (2000b) observed intensive methane emissions at the beginning of the drainage period which then decreased and remained low until re-flooding. Zheng et al. (1997) report that the intensified emissions lasted for 1 to 2 days and started when the water level had dropped to 1 - 0 cm.

Sass et al. (1997) relate the seasonal methane emission pattern to plant development rather than temperature regime. The relationship of plant development and methane release is discussed in a review by Aulakh et al. (2000); the developmental stage to favour methane emissions depended strongly on the respective cultivar, whereas tiller numbers were found to be linearly correlated to methane transport capacity.

The aeration during drainage causes low emission rates. After some time of flooding, the flux rates slowly increase again (Sass et al., 1997). Zheng et al. (1997) report methane emissions at 10 days after flooding with rates close to methane flux rates before drainage.

Although methane emissions followed the reported pattern, the flux rates observed at our site were strikingly low. The seasonal methane emissions listed by the IPCC (1997) for the Beijing region are five to one hundred times higher than those observed in our study for 2002.

The low flux rates may have been caused by the high amounts of irrigation water applied daily and the related oxygen amendment to the soil through the relatively high percolation rates (12 and 20 mm in replicate one and > 30 mm in replicates two and three). This view is supported by the observation of a decreasing gradient in methane flux rates from paddy replicates one to three, while the amount of irrigation water increased in the same order. The maintenance of a water layer was extremely poor in replicate three, probably leading to quite aerated conditions. Likewise, Yagi et al. (1998) and Jain et al. (2000) attributed low flux rates to high percolation rates. Yagi et al. (1998) observed 5.7 – 13.8, 0.6 – 4.8 and 0.1 – 0.3 g m⁻² total methane fluxes with percolation rates of 0, 5 – 7.7, and 20 – 25 mm per day. They discuss that the effect of water percolation also depends on the amount of easily decomposable organic matter, as higher amounts of organic matter buffer the increased oxygen input. Also Cai et al. (1999) relate observed low methane flux rates to high percolation rates together with low organic matter content.

Another factor contributing to low methane fluxes may have been the low soil moisture between rice cropping seasons. The impact of soil moisture conditions between rice crops on methane emissions during the cropping season was studied by Xu et al. (2003) in a pot experiment. After flooding and planting of rice, they observed increasing methane production and emission with higher soil moisture contents, from air dryness to flooded, between rice cropping seasons, with the exception of the air dried soil. Also Cai et al. (1997) noted in their overview that methane emissions from paddy fields flooded throughout the year were higher than methane fluxes from fields that were allowed to dry between cropping seasons.

Min et al. (1997) observed that submerged soils under deep water layers had higher methanogenic populations than soils that were subjected to a wetting and drying pattern. Although they also showed that methanogenic populations could survive conditions of air dryness for a long time, they also measured that methane production was lower from flooded, previous upland soils than from previous paddy soils. In these upland soils the population of methanogens was reduced. These findings may also apply to our field study, since the soil was generally dry between the rice cropping periods. Additionally, the field had not been cultivated with lowland rice for several years before our first experimental year 2001, which may support the assumption of a reduced methanogenic population as compared to long-time paddy soil. Nevertheless, Min et al. (1997) did not discuss the question of substrate availability in the respective soils; in previous upland soils the carbon supply may be reduced due to aerobic decomposition during the non-flooded period.

Otherwise, the light soil texture of our experimental site may have been even favourable for methane production. Sass et al. (1997) and Sass et al. (2000) established a positive correlation between soil sand content and methane emission and a negative correlation with clay content. The organic matter may be strongly bound in the fine soil texture of clay soils and therefore not easily available to turnover (Mitra et al., 2002b). Also Denier van der Gon (1996a) found lower methane emissions from a soil with higher clay content, but this was confounded by the presence of calcium carbonate in one of the soils. Likewise, Cai et al. (1999) report lowest methane emissions from a clayey soil.

From 2001 to 2002 a threefold increase in methane emission was observed. This was most likely related to the organic manure amendment in 2002. It is generally observed that organic manure enhances methane flux (Aulakh et al., 2000; Wang et al., 2000; Wassmann et al., 2000; Denier van der Gon and Neue, 1995; Lu et al., 2001; Sass et al., 1997) since soil redox potential is lowered and carbon is provided to methanogens (Aulakh et al., 2000).

In the GCRPS, which had more aerated conditions, no major fluxes were expected during the vegetation period as well as during the non-rice cropping period when soil conditions in Paddy and in the GCRPS were dry. On the other hand, the aerated soil conditions were much

more likely to favour methane consumption through methane oxidation by methanotrophic bacteria. Xu et al. (2003) state that methane oxidation is influenced by soil moisture through diffusion by the supply of substrate and oxygen and through sustenance of the methanotrophic activity. Bender and Conrad (1995) observed that for methane oxidation, an intermediate optimum soil moisture content exists: too low soil water contents exert physiological water stress onto the methanotrophic bacteria, while too high soil moisture impedes the diffusion of the substrate methane. Boeckx et al. (1997) deduced that coarse textured soils have a higher oxidation potential than fine textured soils. In our field, we observed slight methane consumption as well as slight methane production in the GCRPS over the rice cropping phase. Between rice crops, when soil was mainly dry in Paddy as well as in the GCRPS, methane fluxes were negligible. Also, Henckel and Conrad (1998) did not observe methane oxidation at atmospheric methane concentrations in a laboratory experiment on aerated slurried soil. At methane concentrations below 10 ppmv they even recorded a slight methane emission.

No diurnal methane flux pattern was observed from our field measurements. Generally a diurnal time course is reported for methane emissions, which is held largely due to soil temperature variations by Sass et al. (1997) and Buendia et al. (1998). Buendia et al. (1998) observed for Beijing a diel pattern of two peaks at 12:00 to 14:00 h and 24:00 to 1:00 h from planting to flowering and for the later part of the season three peaks at 2:00 h, 8:00 to 10:00 h and at 20:00 h. Nevertheless, in our field study, measurements at 6:00, 12:00 and 18:00 h in 2001, did not show a diel emission pattern.

Conclusion

With respect to the emission of the greenhouse gas methane, the new GCRPS is a clear improvement. Although the observed methane emissions were very low at the experimental site, they followed the commonly observed flux pattern of lowland rice with mid-season drainage in northern China. The low flux rates observed in traditional Paddy were probably related to the high water input. The low methane emissions could be further reduced by the aerated GCRPS. In 2002, the organic fertiliser amendment to Paddy resulted in an increase in methane emissions, while emission rates remained unaffected in the GCRPS.

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Chapter II

Gaseous emissions from a water-saving rice production system (GCRPS) in North China: 2. nitrous oxide

Abstract

Rice is the major staple food in China, most of which is produced on irrigated lowland fields usually with high water requirements. Since irrigation water is becoming an increasingly scarce resource, alternative rice production systems are under investigation. One of which is the Ground Cover Rice Production System (GCRPS), where the soil is no longer flooded but kept at a high soil moisture content, preferably in the upper range of field capacity. Besides high water consumption, the traditional paddy is known for its contribution to global warming, because of the potential emissions of methane. While the anaerobic soil conditions in the flooded rice field lead to the formation of methane, the very moist soil conditions in the GCRPS may lead to the formation of the second important greenhouse gas nitrous oxide.

Nitrous oxide fluxes were monitored throughout the rice cropping seasons 2001 and 2002 using portable closed chambers. The major difference in nitrous oxide emissions from paddy rice and the GCRPS were found in the clearly changed temporal pattern of nitrous oxide fluxes. Nitrous oxide fluxes in GCRPS were stable in the two years and followed mainly fertilisation events. In paddy rice, nitrous oxide flux was low throughout the year, but in 2002 large emissions occurred during the drainage period. In 2002, cumulative flux was with almost $400 \text{ mg m}^{-2} \text{ a}^{-1}$ of similar height as fluxes in the GCRPS of about 500 to $600 \text{ mg m}^{-2} \text{ a}^{-1}$. The flux pattern of nitrous oxide from paddy rice, as observed in 2002, was consistent with generally observed flux patterns from lowland rice with a drainage period. The GCRPS did not significantly enhance nitrous oxide emissions.

Introduction

Rice is the major staple food in Asia. In China, rice accounts for 44 % of the total grain production, and about 90 % of the available freshwater is used for rice cultivation in south China (Li et al., 2001). At the same time irrigation water is becoming scarce in China, e.g. due to an increasing competition between agricultural and industrial water use and an increasing urbanisation (Li, 2001; Wang et al., 2002). Thus, alternative water-saving rice production systems to the traditional lowland rice production are becoming more and more important.

An alternative system that has been developed in various regions and sub-types is the Ground Cover Rice Production System (GCRPS). This system uses different mulching materials like plastic film or straw mulch to reduce evaporation from the soil which is no longer submerged but maintained at a very high soil water content, preferably still in the upper range of the respective soil water holding capacity. Farmers may also apply the mulching materials with the purpose of increasing soil temperature and promoting plant development (e.g. in the province of Hubei). Plant establishment can be facilitated by direct sowing.

Commonly in north China, the high yielding lowland rice is transplanted at an early vegetation stage to the submerged field, which is thereafter kept constantly under a shallow water layer. An exception to this is the drainage period during the tillering stage when the soil is allowed to dry, so that the rice plants are forced to reduce unproductive tillers. Also, about six weeks before harvest, the field is no longer irrigated. This period may be preceded by a

time of alternate wetting and drying irrigation, when the field is submerged and only flooded again after the soil has started to dry.

The field site for this study was located in the surroundings of Beijing, where formerly rice was commonly grown. Nowadays, this specific area is characterised by a deep groundwater table and thus an example for rice production under rather unfavourable conditions as the deep groundwater table makes high irrigation water demand likely. At this site the water-saving GCRPS was tested in comparison to the common lowland rice management.

The potential of the GCRPS system not only lies in the promise to save water, but also in the reduction of emissions of methane, which is an important greenhouse gas. The natural warming of the atmosphere is due to the natural relatively low concentrations of the radiatively active gases water vapour, carbon dioxide, methane and nitrous oxide (Rennenberg et al., 1995 and IPCC (1990) therein); higher concentrations of these gases promote global warming. According to IPCC (IPCC, 2001a) observations, the global surface temperature has increased by about 0.6 °C over the 20th century. Increases in methane and nitrous oxide concentrations in the atmosphere since 1750 have been calculated (IPCC, 2001a). According to this, methane increased by 151 %, of which about 50 % are anthropogenic, and nitrous oxide by 17 %, of which about one third are anthropogenic. The force of radiatively active gases is calculated relative to the force of carbon dioxide. For methane, the IPCC calculated a factor of 23 and for nitrous oxide 296 at a time horizon of 100 years (IPCC, 2001b).

The traditional lowland rice production system is well known for its high potential of methane evolution, which is caused by the anaerobic conditions in the submerged soil (Aulakh et al., 2000). Thus the new GCRPS, where soils are no longer submerged, can be seen as a chance to alleviate the emission of methane. This new system, however, is characterised by high soil moisture conditions and frequent irrigation events. These conditions may very well lead to the evolution of the even more powerful green house gas nitrous oxide.

Nitrous oxide formation occurs as a by-product of nitrification and denitrification. Firestone and Davidson (1989) developed the conceptual model of the “leaky pipe” to visualise the formation of nitrogen trace gases in the process of either oxidation of ammonium to nitrate or the reduction of nitrate to di-nitrogen. In their model, the extent of e.g. nitrous oxide formation depends, on the one hand, on factors that control the rate of the overall process and, on the other hand, on factors that govern the partitioning of the involved nitrogen forms. For example the availability of water soluble or mineralizable organic carbon is an important factor regulating denitrification rates as stated in the review by Bremner (1997). Nitrification and denitrification processes have different optimum soil moisture levels. Davidson (1993) found the optimum for nitrification at about 50 % water filled pore space (WFPS) and for denitrification at >80 % WFPS. 60 % WFPS, which roughly corresponds to field capacity, was found to be an important transition point from predominantly aerobic to mainly anaerobic processes. According to a review by Williams et al. (1992) and to FAO (2001), wetting of dry soil may cause large fluxes of nitrous oxide. From flooded rice fields, however, it can be expected that nitrous oxide fluxes are low (Bronson and Singh, 1995; Freney, 1997). Nitrous oxide is released from the soil via diffusion; therefore, increasingly wet soil conditions, which reduce diffusion rates, may lead to increased denitrification rates but they may also lead to a reduction of nitrous oxide release due to re-consumption of nitrous oxide (Firestone and Davidson, 1989; FAO, 2001).

The objective of this study was to determine the impact of GCRPS, with the inherent changes to the soil moisture regime, on nitrous oxide emissions, following the hypothesis that emission increases under GCRPS management.

Material and methods

A field experiment was carried out on an experimental station, Dongbeiwang, from the China Agricultural University near Beijing. According to the Koeppen classification, the Beijing climate can be classified as Dwa² (Sträßer, 1998). The soil type was a Cambisol, FAO 1988 (Gong et al., 1994). The average soil texture of the upper 0.75 m consisted of 49 % sand, 37 % silt and 13 % clay. The pH_{Calcium-chloride} was about 6.7. Soil carbon and nitrogen content in the upper 0.4 m were 2.4 % and 0.12 % respectively. The ground water table was below 10 m. From a meteorological station (Thies GmbH, Göttingen) next to the experimental site data on precipitation, ambient air pressure, air temperature, global radiation, wind speed and humidity were collected.

Field layout and treatments

The field was divided into an inundated lowland rice area and an irrigated upland area for the GCRPS treatments. The respective treatments were traditional lowland rice (Paddy) and GCRPS with two mulching materials: plastic film (Plastic) and rice straw mulch (Mulch) as well as two control treatments without mulching material: lowland rice bare soil (Bare) and aerobic rice (Aerobic). An additional treatment in 2001 was aerobic rice with plastic film mulch (Aerobic-plastic). Each treatment had three replicates which were laid out according to a one-factorial block design. Due to the need to separate lowland and irrigated upland conditions, only the GCRPS treatments were randomly distributed.

Field set-up

The GCRPS treatments were sown in the beginning of May (15 x 25 cm, 6 plants per hill). In the Paddy plots, rice was transplanted in late May after a four- to five-week nursery period. In 2001, spacing in Paddy and GCRPS were identical, in 2002 planting density was reduced to 4 plants per hill in Paddy. Plastic film mulch was applied after plant emergence in 2001 and shortly after sowing in 2002. Straw mulch was applied after seedling establishment in the beginning of June 2001 and in late June 2002. In 2001 plain rice straw and in 2002 semi-decomposed rice straw was applied at a rate of 1.5 t ha⁻¹. The rice variety was Yue Fu (*Oryza sativa japonica*); the two Aerobic treatments were planted with the aerobic rice variety Han Dao 297.

Irrigation of Paddy and GCRPS plots

The paddy treatment was managed according to regional field practise under continuously flooded lowland conditions with a drainage period of about one week in July. About six weeks before harvest, the plots were allowed to dry. In 2002, this period was preceded by two weeks of alternate wetting and drying irrigation. For the GCRPS treatment, soil moisture was maintained in the range of field capacity. For 2001, the soil moisture threshold for irrigation during the seedling stage was aimed at a soil water tension of 10 - 15 kPa, then increased to 15 kPa - 20 kPa for the intermediate part of the vegetation period, and finally, to 20 - 30 kPa for the late part of the vegetation period. For 2002, the threshold was reduced to alleviate drought stress for the plants to 10 kPa of soil water tension until mid-August and thereafter increased to 15 - 18 kPa for the vegetation stage after panicle initiation. Irrigation was scheduled by two tensiometers installed into each plot at 0.15 m depth and conducted as surface irrigation, which stopped in mid-September. Total amounts of irrigation water are given in Table 1.

² Meteorological station at 39°57'N, 116°19'E, 52 m above sea level; average data from 1930 to 1960

D: humid climate of regions with cold winters, mean temperature of the coldest month <-3°C, mean temperature of the warmest month >10°C; w: precipitation of the summer month with highest precipitation is at least 10 times higher than the precipitation of the winter month with least precipitation; a: mean temperature of the warmest month >22°C

Table 1. Irrigation and rain amounts during the rice cropping seasons 2001 and 2002

	2001			2002		
	Irrigation [mm]	sd	Rain [mm]	Irrigation [mm]	sd	Rain [mm]
Paddy	3751	1333	290	3044	1125	442
Plastic	1275	83	314	1593	35	445
Mulch	1192	8	314	1605	64	445
Bare	1328	28	314	1637	13	445
Aerobic	1072	57	314			
Aerobic-plastic	1028	29	314			

Soil water tension

Soil water tension was monitored by three tensiometers which were installed at a depth of 0.15 m in each plot; one tensiometer was installed within the gas sampling sub-plot. In Paddy, the maintenance of a water layer was recorded as water layer *present* or *not present* before irrigation events.

Fertilisation

Nitrogen fertiliser was applied as urea nitrogen (225 kg ha⁻¹ and 180 kg ha⁻¹ in 2001 and 2002 respectively). In Paddy, the fertiliser was applied as split application at transplanting, tillering and heading (40/ 30/ 30). In GCRPS, the total amount was applied as basal fertiliser in 2001; in 2002, fertiliser was given in split application (30/ 40/ 30) as basal fertiliser and tillering and heading dressings. In 2002, all treatments were amended with an organic basal fertilisation of 45 kg N ha⁻¹ as rapeseed cake. The basal urea fertiliser in GCRPS was incorporated into the soil at field preparation; the later dressings were followed by irrigation on the same day to facilitate fertiliser distribution under surface mulches and incorporation into the soil.

Gas sampling

Gas sampling was facilitated by the closed-chamber technique (Hutchinson and Mosier, 1981, Denmead, 1995). Each plot was equipped with a metal frame of 0.5 m x 0.6 m and 0.2 m height at 4.5 m and 2.3 m from the plot borders. The frames were buried into the soil to a depth of 0.07 m. Beneath the soil surface the frame had several holes to allow for soil moisture exchange with the surrounding soil. Nevertheless, irrigation was applied separately analogous to the main plot. In 2002, the frames in Paddy were equipped with an extra hole just above the soil surface to enable water exchange with the main plot. Portable sampling chambers of transparent Plexiglass were mounted onto the metal frames, the sealing between chamber and frame was facilitated by water-filled rims. Two chamber sizes (0.3 m and 0.9 m) were used in accordance with plant height. All chambers were equipped with computer fans and every second chamber held a thermometer. Ambient air pressure was measured at the meteorological station close to the site. Access to the gas-sampling sub-plot in Paddy was facilitated by small footbridges. Gas samples were collected in 1L gas bags (Guangming Chemical Engineering Research Institute, Dalian, China) using a syringe, which was injected into the chamber through a rubber septum. At each sampling event, 4 samples of 400 ml each were collected at 0 min, 10 min, 20 min and 30 min after chamber closure.

Time schedule during rice cropping period

The basic gas sampling schedule in 2001 followed an adapted protocol developed by Buendia et al. (1998) for simultaneously measured methane. On selected days, gas samples were collected at 6:00, 12:00 and 18:00 h in Paddy and Plastic, and at 18:00 h from the remaining plots. Since statistical analysis (Tukey test, 0.05 probability level) did not show any differences between sampling times on one day (Table A2 and Table A3), samples were

collected at 18:00 h only in 2002. In 2002, samples were collected weekly in Paddy and GCRPS Plastic and Mulch. Around the drainage period in Paddy and for fertilisation events in GCRPS and Paddy, the sampling schedules were intensified in both years. After harvest and before the next rice crop, samples were collected on various days at 12:00 h. During these periods emission rates were extremely low (Table A1), so that emission was estimated zero and, therefore, was not considered in the calculation of annual flux.

Samples were analysed by gas chromatography within one week after collection in the laboratory of the Institute of Atmospheric Physics, Chinese Academy of Science, in Beijing. The gas chromatographic characteristics are described in detail by Wang and Wang (2000). The carrier gas was N₂ at a flux rate of 25 cm³ min⁻¹, the column for gas separation was Stainless steel measuring 2 mm x 1 m (column 1) and 2 mm x 3 m (column 2) packed with Porapak Q of 80/100 mesh; the ECD detector temperature was 330°C and the oven temperature 55°C.

Flux calculation

The flux of nitrous oxide emissions (mg m⁻²h⁻¹) was calculated by the formula:

$$F=60*10^{-5}(273 (273+T)^{-1})P 1013^{-1}*\rho H(dC dt^{-1}),$$

where F is the flux [mg m⁻²h⁻¹], T the mean temperature [°C] inside the chamber during the sampling interval, P the ambient air pressure of the experimental site [hPa], ρ the nitrous oxide density at 0 °C and 1013 hPa [g L⁻¹], H the height of chamber (headspace), t the time for sampling [min], C the nitrous oxide concentration in volume mixing ratio [10⁻⁹], quantified with the concentration of the calibration gas, and dC dt⁻¹ the rate of increase of nitrous oxide concentration in the closed chamber [10⁻⁹ min⁻¹] (Zheng et al., 2000a).

For cumulative flux calculations [mg m⁻²], fluxes for intervals between measurements were interpolated linearly and based on 18:00 h measurements. In both years after basal fertiliser application and before treatment separation (e.g. mulch applications), samples in GCRPS were collected from three plots only. During this initial period, cumulative flux calculations were based on these measurements for all treatments to represent the initial emissions. For statistical analysis the GLM procedure of SAS (SAS, 1989) was used.

Results

Total emissions in 2001 and 2002

Cumulative nitrous oxide emissions from GCRPS treatments in both years were almost identical, in spite of large differences in nitrogen fertilisation and organic manure amendment. Fluxes in the GCRPS treatments Plastic, Mulch, Bare and Aerobic rice averaged $553 \text{ mg m}^{-2} \text{ a}^{-1}$ in 2001 and $533 \text{ mg m}^{-2} \text{ a}^{-1}$ nitrous oxide in 2002 in the GCRPS treatments Plastic and Mulch (Table 2). Contrasting were the emissions in Paddy: the value of $33 \text{ mg m}^{-2} \text{ a}^{-1}$ in 2001 is extremely low as compared to GCRPS of the same year. In the following year, flux was twelve-fold higher, $396 \text{ mg m}^{-2} \text{ a}^{-1}$ nitrous oxide. However, this difference was not significant (Tukey test, 0.05 probability level).

Table 2. Cumulative N_2O emissions of the vegetation periods 2001 and 2002, n = 3

	2001						2002		
	Paddy	Plastic	Mulch	Bare	Aerobic	Aerobic-plastic	Paddy	Plastic	Mulch
Mean N_2O [$\text{mg m}^{-2} \text{ a}^{-1}$]	33 _B	589 _A	508 _A	548	539	579	396 _A	594 _A	471 _A
sd	98	115	105	61	72	61	221	110	87

Impact of treatment tested by Tukey test (probability level: 0.05) for each year; figures followed by the same letter are not significantly different.

Within each treatment, no significant differences between years were observed.

2001

In 2001 nitrous oxide emissions in Paddy were very low, in fact around zero for the entire vegetation period. In GCRPS Plastic, major nitrous oxide emissions occurred only during the four weeks following the basal fertilisation in early May (Figure 1). This rather short period accounted for 88 % of the total nitrous oxide flux and is responsible for the differences between Paddy and GCRPS Plastic. Since only during the first week nitrous oxide flux was measured daily, but calculated from linear interpolation for the remaining three weeks, the absolute emission is afflicted with a certain uncertainty.

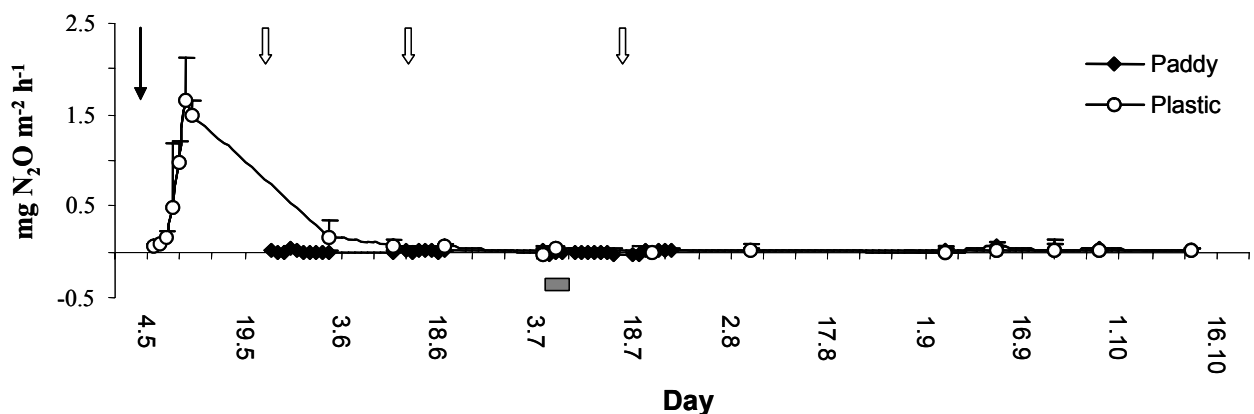


Figure 1. N_2O emissions at 18:00 h from Paddy and GCRPS Plastic in 2001

Black arrow: fertilisation in GCRPS; open arrow: fertilisation in Paddy; grey box: drainage in Paddy; measurements in Paddy started with field preparation and fertilisation

The importance of irrigation and water availability for nitrous oxide emissions is underlined by Table 3 and Figure 1: only after irrigation, emissions in Plastic increased, almost doubled from 0.077 to 0.146 mg m^{-2} .

Table 3. Average N₂O emission rates from GCRPS after fertilisation (4.05.01) and initial irrigation (7.05.01), n=3

Day	5.5.01	6.5.01	7.5.01 ¹⁾	8.5.01	9.5.01	10.5.01	11.5.01
Mean N ₂ O [mg m ⁻² h ⁻¹]	0.063	0.077	0.146	0.475	0.987	1.646	1.496
sd	0.032	0.035	0.090	0.713	0.235	0.469	0.149

1) first irrigation to dry soil: 120 mm

Impact of different GCRPS treatments on nitrous oxide emissions in 2001

The impact of the different GCRPS treatments on nitrous oxide emissions was tested in the first experimental year, 2001, after crop establishment and application of mulching materials, e.g. plastic film and straw mulch. The cumulative fluxes were generally low as they excluded the emission peak after fertilisation and ranged from 27 mg m⁻² nitrous oxide in GCRPS Mulch to 84 mg m⁻² in GCRPS Aerobic-plastic. Plastic film covered treatments tended to show higher emissions, but the differences among treatments were not significant (Table 4).

Table 4. Cumulative N₂O emissions in GCRPS after crop establishment (1.06. - 28.09. 2001)

	Mean [mg N ₂ O m ⁻²]; n = 3	sd
Plastic	74 _A	84
Mulch	27 _A	105
Bare	62 _A	37
Aerobic	48 _A	15
Aerobic-plastic	84 _A	44

Treatment differences tested by Tukey test (probability level: 0.05); figures followed by the same letter are not significantly different.

Cumulative flux for tested period, 1.06. until 28.09.01, calculated from 11 observations after crop establishment (Table A2 and Table A3, except for 4.07.01 and 8.07.01, for Paddy and GCRPS Plastic respectively)

2002

The management pattern in 2002 had changed with respect to amount of N-fertiliser and timing as well as water management. After each of the three fertiliser applications, nitrous oxide emission peaks were observed in GCRPS Plastic (Figure 2). Strikingly, Paddy also showed significant emissions which were mainly related to the drainage period and revealed a high variation among Paddy replicates. In particular, the second replicate, which had become dry in the morning before irrigation after a period of continuous inundation, showed substantial nitrous oxide emissions (6.08.02). Cumulative nitrous oxide emissions in Paddy and GCRPS Plastic were not significantly different (Table 2), but periods of major emissions from Paddy and GCRPS were provoked by different events. In GCRPS Plastic, 64 % of total nitrous oxide were emitted within two weeks after each of the three fertiliser applications, whereas in Paddy these periods showed only 21 % of the total emission. In Paddy, major emissions occurred during the drainage period, when 36 % of the total nitrous oxide were released.

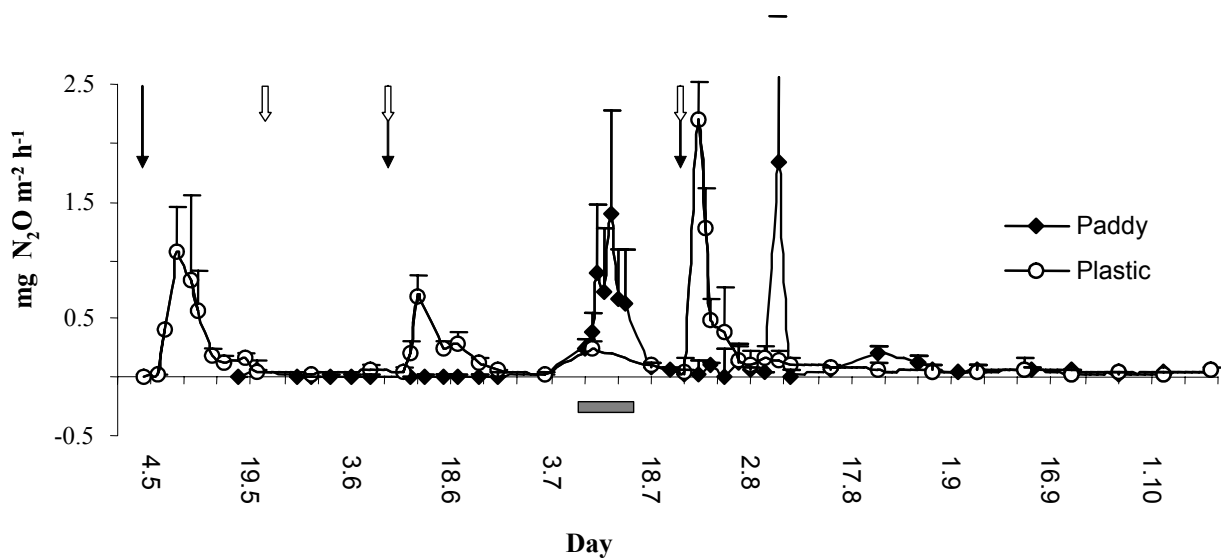


Figure 2. N₂O emissions at 18:00 from Paddy and Plastic in 2002

Black arrows: fertilisation in GCRPS; open arrow: fertilisation in Paddy; grey box: drainage in Paddy measurements in Paddy started the day before field preparation

Nitrous oxide emissions in Paddy during drainage periods in 2001 and 2002

The difference in cumulative nitrous oxide fluxes in Paddy (Table 2) between the years 2001 and 2002 was mainly due to the different nitrous oxide fluxes during the respective drainage periods (Figure 1 and Figure 2). While in 2001, during the drainage period, nitrous oxide flux was negligible in Paddy (Figure 1), large emissions occurred during this period in 2002 (Figure 2). When, for the time of the drainage period, nitrous oxide emissions are plotted against soil water tension (Figure 3) no relation between soil water tension and the amount of emitted nitrous oxide could be detected for 2001, but for 2002 a roughly fitting optimum curve for the replicates one and two was found.

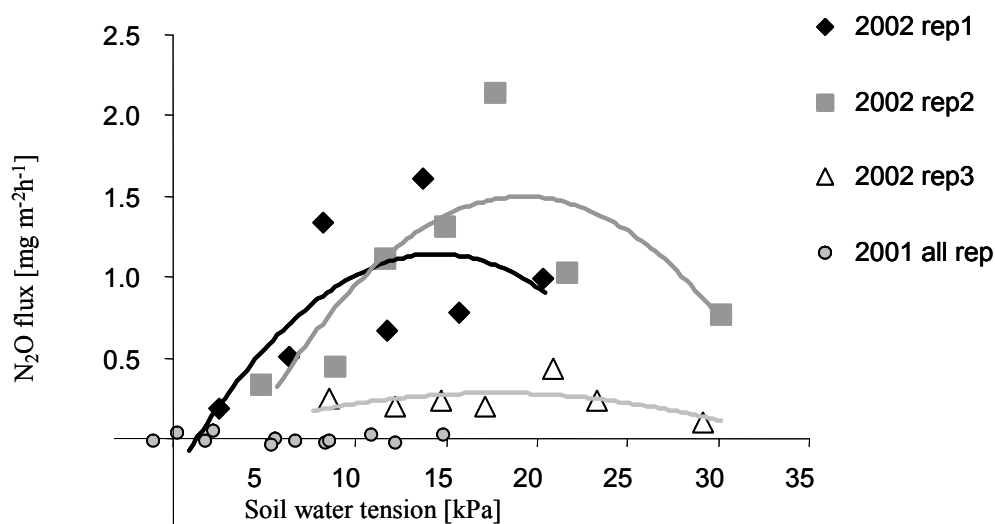


Figure 3. N₂O flux from Paddy replicates and soil water tension in 2001 and 2002 during the drainage period in 2001 and 2002

For 2001, no relationship between soil water tension and nitrous oxide flux was expected as fluxes were almost zero. Nevertheless, the tendency of higher soil water tensions in 2002 could partly explain the differences between both years, especially as a relation between

nitrous oxide flux and soil water tension could be observed for two replicates of this year. Also the application of rapeseed cake and thus easily accessible carbon for micro-organisms may have contributed to higher emissions in 2002.

One reason for the low emissions in replicate three may be seen in its high water permeability: maintenance of a continuous water layer was extremely poor (Figure 4), probably resulting in rather aerated conditions, which contrasted those in replicates one and two.

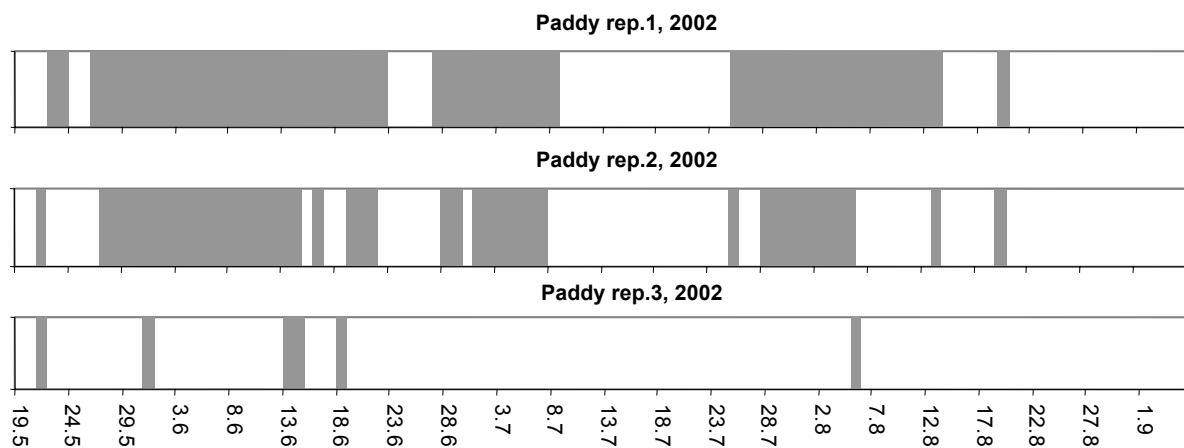


Figure 4. Presence of a water layer before irrigation (grey column) in Paddy replicates in 2002

Impact of GCRPS on global warming resulting from methane and nitrous oxide emissions

The combined impact of methane and nitrous oxide from GCRPS Plastic on global warming as compared to Paddy was estimated for 2001 and 2002 (Table 5). CO₂ equivalents were calculated according to the respective Global Warming Potential (GWP) of nitrous oxide, factor 296, and methane, factor 23, at a time horizon of 100 years (IPCC, 2001b). Methane emissions from the respective treatments were measured simultaneously with nitrous oxide emissions and are presented in chapter1 of this thesis. For GCRPS Plastic, the conversion of cumulative methane and nitrous oxide fluxes to CO₂ equivalents resulted in almost identical CO₂ equivalents for 2001 and 2002, at roughly 175 g CO₂ m⁻². For Paddy, a large change was observed: from 17 g m⁻² to 141 g CO₂ m⁻². This rise was mainly due to greatly increased nitrous oxide emissions, by a factor of about 12, in 2002 during the drainage period. Additionally, a threefold increase in methane emissions was observed, in 2002. In comparing the CO₂ equivalents of Paddy and GCRPS Plastic, the CO₂ equivalents of GCRPS Plastic were about 10 times higher than the CO₂ equivalents of Paddy in 2001, but in 2002 the CO₂ equivalents were within a similar range in Paddy and GCRPS Plastic: 141 and 175 g CO₂ m⁻² respectively.

Table 5. Cumulative GWP in Paddy and GCRPS Plastic for CH₄ and N₂O in 2001 and 2002

CO ₂ equivalents ¹⁾	2001		2002	
	Mean [g CO ₂ m ⁻²]	sd	Mean [g CO ₂ m ⁻²]	sd
Paddy Methane	7.2		23.6	
Paddy Nitrous oxide	9.8		117.1	
Paddy Total	17.0	27.1	140.7	73.0
Plastic Methane	0.2		-0.7	
Plastic Nitrous oxide	174.2		175.9	
Plastic Total	174.5	34.9	175.2	34.1

1) GWP relative to CO₂: factor for CH₄: 23; factor for N₂O: 296; time horizon: 100 years (IPCC, 2001b). Calculations refer to the estimated cumulative fluxes of nitrous oxide (Table 2) and methane (chapter1 of this thesis, Table 2).

Discussion

Nitrous oxide fluxes from GCRPS remained stable during both experimental years, while the magnitude of flux varied in Paddy, showing very low emissions in 2001, but similar fluxes as GCRPS in 2002. Thus, the overall evaluation was highly affected by the pronounced variation in Paddy over the two years.

Nitrous oxide fluxes in Paddy

In both experimental years, nitrous oxide emissions were very low during the flooded period. In contrast, the two drainage periods were very different; major amounts of nitrous oxide were released in 2002 during the drainage period, while emissions remained very low in 2001. In 2002, the drainage period lasted not only longer, but also led to slightly lower soil water potentials. Peaks in nitrous oxide fluxes during drainage periods and low or very low nitrous oxide fluxes from submerged soils are in agreement with several studies (Zheng et al., 2000a; Zheng et al., 2000b; Xu et al., 1997; Zheng et al., 1999; Cai et al., 2001; Cai et al., 1999; Bronson et al., 1997a). Also, low nitrous oxide fluxes were measured after fertilisation events in rainfed rice on the Philippines (Abao et al., 2000).

The inhibition of nitrous oxide flux under anaerobic or flooded conditions was reported by several authors. Under saturated or increasingly wet conditions, nitrous oxide release may be reduced by a slowed diffusion rate of nitrous oxide from the wet phase to air. This slow-down may lead then to re-consumption and further reduction to di-nitrogen (Firestone and Davidson, 1989). Likewise Henckel and Conrad (1998) assume that nitrous oxide was further reduced in the denitrification process, when they observed a decrease of previously accumulated nitrous oxide under anoxic conditions in a laboratory experiment.

In our study, denitrification may have been additionally limited by a shortage in the first substrate, nitrate. Potentially, nitrate could be produced within the rhizosphere and the aerobic topmost soil layer. In our study, nitrate concentrations in Paddy ranged from 0.09 to 2.62 mg NO₃-N kg⁻¹ during the irrigated period in 2002 and from 0.00 to 1.59 mg NO₃-N kg⁻¹ throughout the vegetation period in 2001 within 0 to 0.2 m (Tao, 2004). Thus, in addition to impeded release and re-consumption of nitrous oxide, substrate availability was probably a limiting factor for denitrification.

High nitrous oxide fluxes during drainage periods were frequently observed. A relation between changes in soil water content and intensified nitrous oxide fluxes was seen by Zheng et al. (2000a), who established an empirical function of nitrous oxide flux depending on soil moisture. Here maximum emissions were found with paddy soil at 110 % soil water holding capacity or 99 % water filled pore space. Therefore, they concluded that soil in an established anaerobic rice field differs from aerobic systems in the way that optimum soil moisture for nitrous oxide emission is higher than at 74 % water filled pore space as found by Davidson (1993) for grassland. The reason for higher nitrous oxide flux during periods of drainage is seen in a more suitable oxygen availability for nitrification and denitrification and nitrous oxide as an intermediate product (Zheng et al. (1996) and (1997) in Zheng et al., 2000a).

Differences in soil moisture could be one explanation for the different gas fluxes during the drainage period in 2001 and 2002. Soil moisture tended to be higher in 2001 than in 2002. The relation between soil moisture and nitrous oxide flux, which could be established in 2002 (Figure 3), is in accordance with this assumption. Nevertheless, soil moisture decreased to similar soil water tensions in 2001 as 2002, when strong increases in gas flux were observed; however, in 2001 fluxes remained extremely low. Also, the third field replicate of Paddy was

inconsistent with the other two replicates in 2002. Although gas fluxes increased about ten-fold as compared to the previous year, nitrous oxide flux from the third plot was not correlated to soil moisture.

Although the observation of 2002 of increased nitrous oxide flux during the drainage period due to more aerated soil conditions, is consistent with observations from literature, soil aeration cannot satisfactorily explain the differences between the drainage period of the two years.

Application of organic fertiliser may have been an additional factor contributing to higher nitrous oxide production during the drainage period in 2002. Organic carbon may be an important factor to enhance nitrous oxide emissions when organic manure is applied to paddy fields (Xing and Zhu, 1997). Contrasting to this are the observations on straw amendment by Bronson et al. (1997a), who report a decline in nitrous oxide emissions from flooded fields after organic amendment with large amounts of labile carbon as straw. Avalakki et al. (1995) observed in a pot experiment an intensified denitrification in straw amended saturated soils but only very low nitrous oxide flux. The key to these contrasting observations may be seen in the wide carbon to nitrogen ratio of straw. McKenney et al. (1993) could relate, with one exception, the total amount of nitrous oxide released in an anaerobic incubation to the C:N ratio of the respective green manure; fluxes were higher at closer C:N ratios. Organic matter often has a retarding effect on nitrification, but when organic manure is added, extra ammonium is produced stimulating the nitrifying bacteria as stated in an overview by Li (1997). Substrate availability is also discussed by Henckel and Conrad (1998), who conclude from a laboratory experiment that the evolution of nitrous oxide is due to nitrification when strictly anaerobic soil is aerated. They suggest that only later, after the production of nitrate, denitrification contributes to the evolution of nitrous oxide. Likewise, in our study, nitrous oxide evolution may be mainly due to nitrification at the onset of drainage. The substrate for nitrification, ammonium, could have been provided by the microbial turnover of the organic manure, rapeseed cake, with its close C:N ratio. Ammonium concentrations, measured under flooded soil within the upper 0.2 m before the drainage period, were slightly increased in 2002: 0.47 to 3.22 mg kg⁻¹ NH₄-N in 2001 and 4.31 to 22.54 mg kg⁻¹ NH₄-N in 2002 (Tao, 2004). This way the increased substrate availability may have contributed to the increased evolution of nitrous oxide in 2002. The time of nitrogen fertiliser application probably did not have an impact since fertiliser was applied about three weeks before drainage started in both years. Nevertheless, whether an increased ammonium availability or the easily available carbon of the rapeseed cake manure had a promoting effect on nitrous oxide evolution in 2002 remains speculative.

One obvious factor responsible for the different nitrous oxide emissions of the drainage periods 2001 and 2002 could have been soil temperature, which influences rates of nitrification and denitrification. During the drainage periods in 2001 and 2002 air temperature was similar throughout the first four days around the time of gas sampling (28°C – 33°C). In 2001, the drainage period was terminated on the fifth day while it lasted for nine days in 2002. But already during these first four days, fluxes were ten to one hundred times higher in 2002. A complete set of soil temperatures could not be obtained, but soil temperatures were in a narrow range of 23°C and 28°C. Within a temperature range of 21°C to 35°C, Xu et al. (1997) did not find a correlation between variations in soil temperature and variations in nitrous oxide flux in their field study. Changes in temperature above a threshold of about 15 °C have less impact on biochemical processes than below this threshold (Ingraham, (1962) in Williams et al., 1992). Although from our data a temperature effect cannot be excluded, it would be safe to say that temperature was not a limiting factor. Altogether, there was no clear indication of a temperature effect during the drainage period in Paddy.

The exact reason for the change in the emission pattern between both experimental years in Paddy remains uncertain. Nevertheless, the emission pattern in Paddy, as observed in 2002, is consistent with usually observed flux patterns from lowland rice with a drainage period.

Stable nitrous oxide flux from GCRPS

Cumulative nitrous oxide emissions from GCRPS remained stable in both years, although the fertiliser application changed from single basal to split application with a reduction in mineral fertiliser and the addition of organic fertiliser. Nevertheless, the total amount of N applied remained similar. In 2001, nitrous oxide fluxes followed mainly fertilisation in combination with irrigation, and fertilisation events in 2002.

Substantial nitrous oxide emissions can be observed after significant soil wetting. After strong rainfalls (>20 mm) to aerobic soil conditions, intensified nitrous oxide fluxes were observed (Abao et al., 2000; Bronson et al., 1997b). Zheng et al. (2000a) calculated that 79 % of emission from fertilised wheat fields was caused by rainfall, with peak emissions usually observed on the second day after rain or irrigation and thereafter, a gradual decline. In our study, we applied the initial nitrogen fertiliser to dry soil at field preparation. Especially in 2001, we observed the triggering effect of the first irrigation, after which nitrous oxide emissions started to peak (Table 3). According to the review by Williams et al. (1992) the initial wetting of very dry soil yields strongest nitrous oxide emissions, whereas subsequent wettings promote fluxes only to a lesser extent.

The impact of rain can be attributed to several factors: wetting results in an increase in carbon and nitrogen availability as well as a change in oxygen availability, which may result in a transient period of high nitrification and denitrification (Firestone and Davidson, 1989). Likewise, Groffman and Tiedje (1988) observed that denitrification dynamics of wetted soil were closely correlated to pulses of carbon and nitrogen mineralisation. They assume that the intensified mineralisation was caused by the death of microbial biomass through drying and re-wetting, but they ascribe the promotion in denitrification in their experiment to reduced oxygen levels from respiration rather than to an increased substrate availability. The microbial populations related to nitrification and denitrification are able to react rapidly to soil wetting (Davidson, 1992).

With respect to soil humidity it should be stated, that the conditions for nitrous oxide evolution in GCRPS remained almost the same in the two years; irrigation was frequent and soil moisture was high, though slightly increased in 2002, when soil water tension was approximately 5 kPa lower than in 2001.

In 2002, the dominating role of the nitrogen fertiliser application became evident when the fertiliser was applied to moist soil under frequent irrigation; emissions peaked shortly after fertiliser application and returned to baseline fluxes after two to three weeks (Figures 1 and 2). The impact of fertiliser application is, for example, illustrated in the reviews by Mosier (1998) and Bouwman (1996): nitrous oxide emissions typically increase after fertilisation for a short period of about 6 or 4 weeks; thereafter, fluxes are reduced to fluctuation around a low baseline. In our study, the cumulative rate of nitrogen lost as nitrous oxide in both years, e.g. about 590 mg N₂O m⁻² (375 mg N₂O-N m⁻²) in GCRPS Plastic, accounted for approximately 1.7 % of applied nitrogen in both years, which is slightly higher than the general loss of applied nitrogen as nitrous oxide (1.25 %) for nationwide nitrous oxide flux balances (IPCC, 1997). This 1.25 % IPCC estimate is discussed in Boeckx and van Cleemput (2001). They conclude that actual direct nitrous oxide emissions could differ substantially from the calculated value depending on land use, soil type, fertiliser type, fertiliser application, irrigation and crop residues. Bouwman (1996) concluded in his review

that the ratio of 1.25 % may be a satisfactory estimate with regard to the order of magnitude of fertiliser-induced nitrous oxide flux per annum for global estimates. He outlines that, due to various interactions in nitrous oxide generation this ratio may not be adequate for specific local conditions, fertiliser types and crops.

In our study, nitrous oxide emissions were obviously dominated by nitrogen fertilisation. Soil moisture, the most sensitive factor regulating nitrous oxide flux (Zheng et al., 2000a), was probably not a limiting factor, as soil moisture content remained in a stable range, within field capacity. Additionally, to facilitate fertiliser distribution under surface mulches and incorporation into the soil, irrigation was applied directly after fertilisation. Therefore, nitrous oxide emissions followed mainly events of fertilisation. The total amount of applied nitrogen remained similar in both years, 225 kg ha⁻¹ urea N in 2001 and 180 kg ha⁻¹ urea N plus about 45 kg ha⁻¹ organic N in 2002. Thus, under similar environmental conditions and crop management, it is safe to assume that the amount of nitrous oxide emissions remains stable, within a small range, over the years in GCRPS.

Conclusion

The major difference in nitrous oxide emissions in Paddy and the GCRPS can be seen in the clearly changed temporal pattern of nitrous oxide fluxes in Paddy. Nitrous oxide fluxes in the GCRPS were stable and followed fertilisation in the two years, while in Paddy, a strong change with high nitrous oxide emissions during the drainage period of 2002 was observed. The cumulative fluxes in Paddy and in the GCRPS were then in a similar range in 2002. The emission pattern in Paddy, as observed in 2002, is consistent with generally observed flux patterns from lowland rice with a drainage period. Thus, from the environmental point of view, a change in management from Paddy to GCRPS had no significant negative effect on nitrous oxide emissions.

Global warming

Cumulative fluxes of both global warming relevant trace gases, methane and nitrous oxide, from the water-saving GCRPS and Paddy, expressed as CO₂ equivalents, were in a similar range in 2002. In the GCRPS, cumulative CO₂ equivalent fluxes were almost identical in the two years, while in Paddy, a large increase was observed from 2001 to 2002, as nitrous oxide flux was surprisingly low in 2001. Since the flux pattern in Paddy of 2002 is consistent with observations from other studies and the cumulative CO₂ equivalent flux was in a similar range as the flux in the GCRPS, we assume that GCRPS, under the field and management conditions of our study, has no negative impact on global warming.

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Chapter III

Water use in a water-saving rice production system (GCRPS) in North China

Abstract

Rice is the major staple food in China, most of which is produced on irrigated lowland fields usually with high water requirements. A major part of the applied water may be lost unproductively by evaporation, percolation and seepage and run-off. The high water consumption also leads to low water use efficiencies. Since irrigation water is becoming an increasingly scarce resource, alternative rice production systems are under investigation. One of these is the Ground Cover Rice Production System (GCRPS), where the soil is no longer flooded but kept at high soil moisture contents, preferably in the upper range of field capacity. The Beijing experimental site was characterised by a light soil texture throughout all soil layers and a low groundwater table (>10 m). For the rice cropping season in the years 2001 and 2002, a water balance was set up for the common paddy rice and two GCRPS treatments: GCRPS with plastic film mulch and GCRPS without mulch. Comparisons were made with respect to evapotranspiration (ET), evaporation, soil water tensions, deep percolation and water use efficiency (WUE) as g biomass produced per L water input.

A complete water balance was derived by the application of the eco-physiological crop model *Oryza2000* in combination with the soil-water balance model *PADDY*. The modelling results were checked by limited field observations on ET in paddy rice, evaporation from bare soil and soil water tensions in the top-soil and at a depth of 0.5 to 0.6 m. The model application appeared to be successful for the paddy rice, but applicability to the GCRPS was limited.

Nevertheless, the GCRPS led to a reduction in irrigation water of approximately 67 % and 47 % on average in 2001 and 2002, respectively, as compared to the paddy rice. Still, the proportion of percolation water loss remained high, with 60 and 80 % of the total water input. These losses were a result of the high soil moisture status requiring frequent irrigation and a flooding irrigation technique, by which water was applied in rather high amounts. The high consumption of irrigation water also led to only small increases in WUE in GCRPS with plastic film mulch while in GCRPS without mulch the water saving effect was offset by the high yield reductions.

Introduction

Rice is the major staple food in Asia. In China, rice accounts for 44 % of the total grain production (Li, 2001). In 2001, 93 % of the 28.6 million ha of rice production area were used for irrigated lowland rice production (IRRI, 2003). Usually lowland rice is grown in banded and flooded fields, into which it is transplanted after a nursery period. Before transplanting, the wet, submerged soil is usually puddled: ploughed, harrowed and levelled. Besides the ease of e.g. transplanting and weed control, soil puddling also serves to reduce percolation losses and facilitate even distribution of irrigation water. On clayey soils, the puddling process leads to the development of a poorly permeable plough layer or hard pan (De Datta, 1981; Wopereis et al., 1992). Depending on region and climate, fields may even remain submerged for the whole year (Cai, 1997).

Irrigation water is becoming scarce in China, partly due to an increasing competition between agricultural and industrial water use and an increasing urbanisation (Li, 2001; Wang, 2002).

But water requirements in lowland rice production are usually high as a permanent water layer has to be sustained, from which water constantly evaporates, until canopy closure. Evapotranspiration (ET) demands range from 4 - 5 mm per day to 6 - 7 mm per day in the tropics during wet and dry season, respectively (De Datta, 1981). The hydrostatic pressure of the ponded water contributes to higher percolation rates in paddy fields and may largely affect percolation rates on more permeable soils with relatively permeable plough soles or poor puddling (Bouman et al., 1994; Tuong and Bhuiyan, 1999). Typical seepage and percolation rates, which depend strongly on soil texture, can range from 1 - 5 mm per day and 25 - 30 mm per day in heavy clay soils and sandy loam soils, respectively (Tabbal et al., 2002; Bouman and Tuong, 2001). The wide range of percolation losses already indicates that percolation could become the major cause for unproductive water loss on lighter more sandy soils. It is estimated that seepage and percolation loss can be as high as 50 - 80 % of total water input (Sharma (1989) in Bouman and Tuong, 2001). In wetlands, water requirements for land preparation may range from 150 - 200 mm (De Datta, 1981).

Commonly in the Beijing area, North China, lowland rice is transplanted after a nursery stage to the submerged field, which is thereafter constantly kept under a shallow water layer. An exception to this is the drainage period during the tillering stage when the soil is allowed to dry so that the rice plants are forced to reduce unproductive tillers. Also, about six weeks before harvest, the field is no longer irrigated. This period may be preceded by a time of alternate wetting and drying irrigation when the field is submerged and only flooded again after the soil has started to dry.

One alternative rice production system, which has been developed in various regions and sub-types, is the Ground Cover Rice Production System (GCRPS). This system uses different mulching materials like plastic film or straw mulch to reduce evaporation from the soil which is no longer submerged but maintained at a very high soil water content, preferably still in the upper range of the respective soil water holding capacity. Farmers may also apply the mulching materials with the purpose of increasing temperature and promoting plant development. Plant establishment can be facilitated by direct sowing.

The field site for this study was located in the surroundings of Beijing where formerly rice was commonly grown. Nowadays, this specific area is characterised by a low groundwater table, and therefore, is an example for rice production under rather unfavourable conditions as the deep groundwater table makes high irrigation water demands likely. At this site, the water saving GCRPS was tested against the common lowland rice management with respect to its water saving potential in the situation of no mulch application and plastic film mulch application, which can be assumed a very effective mulching material. To determine the single components of a water balance (irrigation, precipitation, ET, seepage and percolation) a combined approach of limited field observations with a model application, Oryza2000 (Bouman et al., 2001), was used.

According to Bouman et al. (2001), Oryza2000 is an eco-physiological crop model, which can simulate rice development in three situations: no limitations in water or nutrients (potential production), water-limited production and nitrogen-limited production. The water balance within Oryza2000 is simulated e.g. by PADDY, a one-dimensional, universal multiple layer soil-water-balance model working on a daily time step basis. PADDY is suitable for puddled and non-puddled soils of irrigated and rainfed environments as well as for soils with impeded drainage (Wopereis et al., 1996a).

The major impact of the GCRPS on the water balance components can be expected in reduced percolation rates, as explained above, and the evaporation rate. From a free water surface, as

present in paddy rice at early vegetation stages, evaporation is at a maximum (potential evaporation) and is only limited by the atmospheric demand. When no water layer is present, but mulching material is applied, evaporation is reduced, but without mulch, the evaporation rate is likely to be modified, also. Evaporation from wet soil occurs at constant rates over time, which are mainly governed by the supply of energy to the surface (stage-one evaporation); when the soil dries it enters stage-two evaporation, which is characterised by falling evaporation rates over time and is regulated by the soil hydraulic properties (Ritchie, 1972).

The model was expected to give insight into the single water balance components. To verify the applicability of the model, not only data for the model parameterisation were collected, but also observations on the field water balance were made. Here, the focus was on deep percolation below the root zone, supposedly the major loss factor, ET in paddy rice and bare soil evaporation in the GCRPS. For comparison of ET rates in paddy rice and evaporation rates in the GCRPS, the FAO approach (FAO, 1998) was applied, where a reference ET, which is calculated from weather data only, is related to a crop-coefficient.

The objective of the study was to compare observations on soil water potentials, ET in paddy rice and evaporation from bare soil with simulation results as well as to evaluate a water balance for paddy rice and the GCRPS with and without plastic film mulch application.

Material and Methods

Location

The experiment was carried out in the years 2001 and 2002. The site was located north-west of Beijing at 39.95 °N and 116.3 °E at 55 m above sea level. Average annual temperature and precipitation for the Beijing area are 11.8 °C and 619 mm, respectively. Months with the highest rainfalls are from June to September. According to the Koeppen classification, the Beijing climate can be classified as Dwa³ (Sträßer, 1998). The ground water table at the experimental site was low (>10 m); soil texture of the upper soil layers to a depth of about 0.75 m was on average 49 % sand, 37 % silt and 13 % clay. The soil type was classified as Cambisol, FAO 1988, (Gong et al., 1994). Data on precipitation, ambient air pressure, air temperature, global radiation, wind speed and humidity were collected at a meteorological station close to the experimental site.

Field layout and treatments

The field was divided into an inundated lowland rice area for the paddy treatments and an irrigated upland area for the GCRPS treatments, which were surrounded by respective protection zones (Figure 1). Irrigated upland and lowland areas were separated by an isolation area of one row of paddy and one row of GCRPS plots each. Between both areas strong plastic film was buried to a depth of 0.6 m. The experiment was comprised of 6 treatments of three replications each. These were laid out according to a one-factorial block design. Due to the need to separate lowland and irrigated upland conditions, only the GCRPS treatments were randomly distributed; and the three paddy replicates were laid out in parallel. The individual plot size was 72 m² (12 m x 6 m). Plots were separated by dams, which were protected by plastic film to a depth of 0.6 m in the paddy area and 0.2 m in the GCRPS area. The treatments, in which observations on water balance were carried out, were traditional lowland rice (Paddy), GCRPS with the mulching material plastic film (Plastic) and GCRPS without mulching material (Bare).

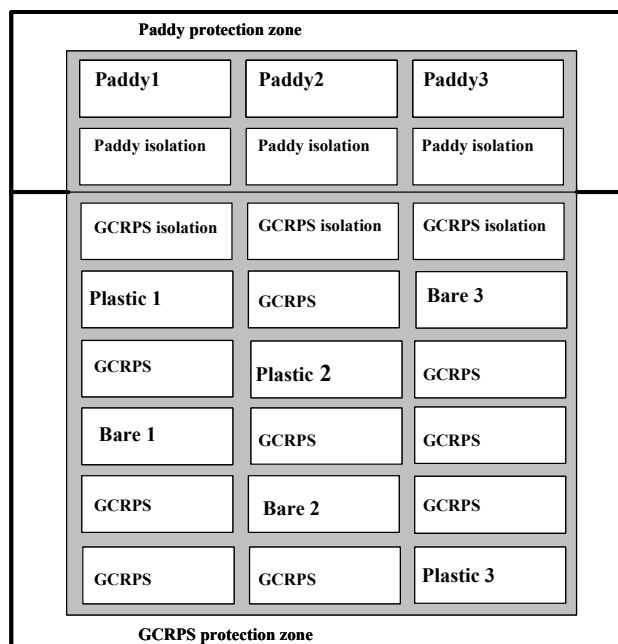


Figure 1. Sketch of the main field experiment

³ Meteorological station at 39°57'N, 116°19'E, 52 m above sea level; average data from 1930 to 1960

D: humid climate of regions with cold winters, mean temperature of the coldest month <-3°C, mean temperature of the warmest month >10°C; w: precipitation of the summer month with highest precipitation is at least 10 times higher than the precipitation of the winter month with least precipitation; a: mean temperature of the warmest month >22°C

Field Management

Field set-up

For both major treatments, Paddy and GCRPS, the traditional lowland rice variety Yue Fu (*Oryza sativa japonica*) was used. The GCRPS treatments were sown in the beginning of May at a spacing of 0.15 x 0.25 m. Planting density was aimed at 6 plants per hill. In the Paddy plots, rice was transplanted in late May after a four- or five-week nursery period. The spacing was the same as in GCRPS, in 2002 planting density was reduced to 4 plants per hill. Plastic film mulch was applied after plant emergence in 2001 and shortly after sowing in 2002.

Irrigation of Paddy and GCRPS

The paddy treatment was managed according to regional field practise under continuously flooded lowland conditions with a drainage period of about one week in July (04.07.01 to 08.07.01 and 08.07.02 to 16.07.02) to reduce unproductive tillers. About six weeks before harvest, the plots were allowed to dry. In 2002, this period was preceded by about two weeks of alternate wetting and drying irrigation. To maintain a water layer, plots were irrigated twice per day in 2001 before drainage and shortly after drainage; this frequency was then reduced to daily irrigation. In 2002, irrigation water was applied daily.

For the GCRPS treatment, soil moisture was maintained in the range of field capacity. For 2001, the soil moisture threshold for irrigation during the seedling stage was aimed at a soil water tension of 10 - 15 kPa, then increased to 15 kPa - 20 kPa for the intermediate part of the vegetation period, and finally, to 20 - 30 kPa for the late part of the vegetation period. For 2002, the threshold was reduced to alleviate drought stress for the plants to soil water tensions of 10 kPa until mid-August and thereafter, increased to 15 - 18 kPa for the vegetation stage after panicle initiation. Irrigation was conducted as surface irrigation and scheduled by two tensiometers installed into each plot at a depth of 0.15 m. After sowing and fertilisation, the plots were irrigated with 120 - 170 mm to ensure thorough soil wetting. Typical irrigation depths for irrigation events during the vegetation period were 40 - 60 mm. Irrigation started following a delay period of about 10 days after sowing and stopped in mid-September. Irrigation depth was measured by a water meter installed at the water tube outlets in each plot. Total amounts of irrigation water are listed in Table 1.

Table 1. Irrigation and rain amounts during the rice cropping seasons 2001 and 2002

	2001		2002			
	Irrigation [mm]	sd	Rain [mm]	Irrigation [mm]	sd	Rain [mm]
Paddy	3751	1333	290	3044	1125	442
Plastic	1275	83	314	1593	35	445
Bare	1328	28	314	1637	13	445

In Paddy, the maintenance of a water layer was recorded as water layer *present* or *not present*.

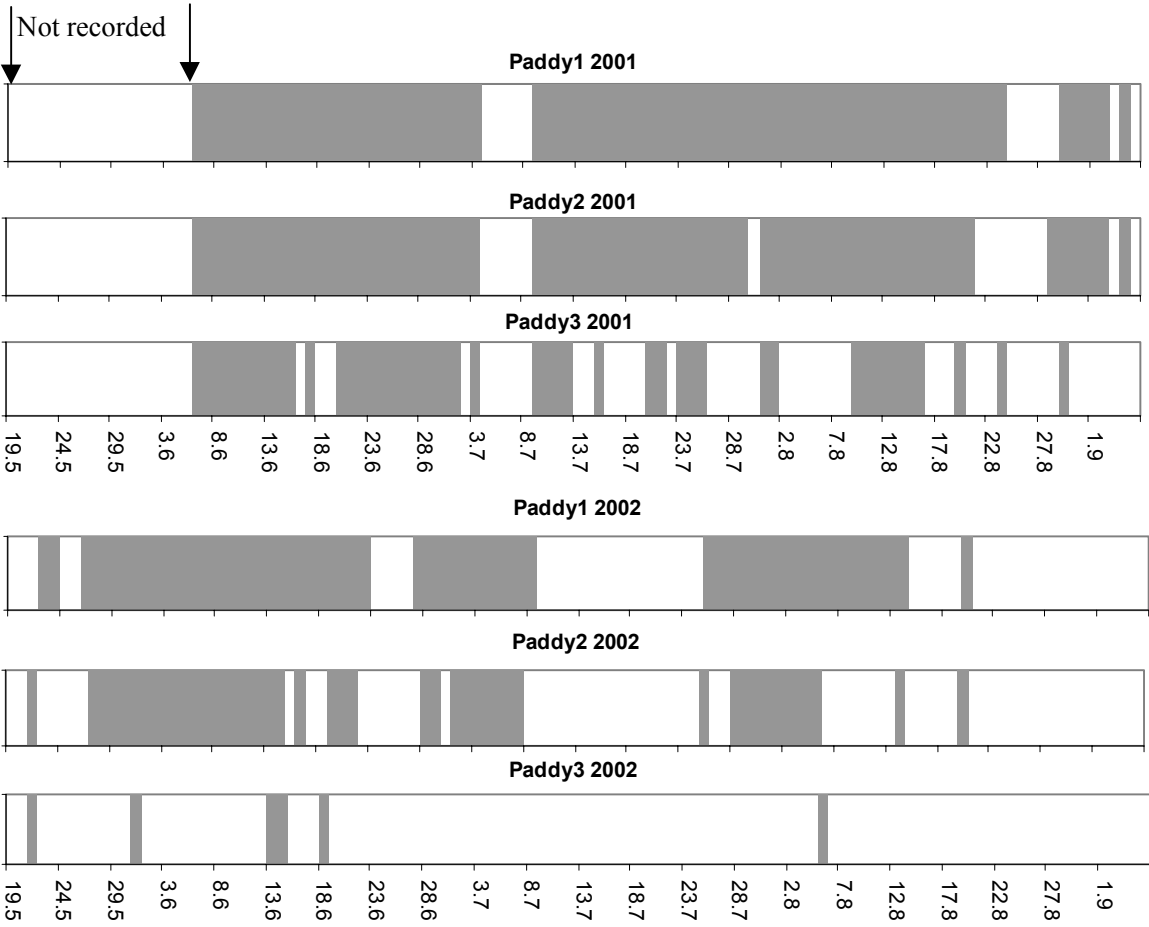


Figure 2. Presence of a water layer (grey column) for each Paddy replicate in 2001 and 2002

Figure 2 and Table 1 clearly illustrate the high diversity among the Paddy replicates: replicate three showed a very poor water layer maintenance and replicate two still required about 1300 mm (>50 %) and about 1500 mm (>80 %) more irrigation water than replicate one in 2001 and 2002, respectively. Thus, conditions in replicate one were closest to those of a “true” paddy, and therefore, replicate one was selected as reference to be compared to GCRPS Plastic and Bare in detail.

Calculation of water balance

Soil water tensions

Soil water tensions were surveyed in Paddy and GCRPS Plastic and Bare. Soil water tensions in the upper soil layer were measured by two tensiometers at a depth of 0.15 m and a third tensiometer, installed at the same depth into a sub-plot in 2001. In 2002, only two tensiometers were used. The main root zone was assumed to comprise the soil depth up to 0.6 m. At the bottom of this zone, three sets of tensiometers were installed, each at the depths of 0.5 m and 0.6 m. The treatment comparison for soil water tensions was based on the comparison of mean soil water tension at 0.15 m and the mean of the average soil water tension at a depth of 0.5 m to 0.6 m.

Initial and final soil water content

Initial and final soil water contents were measured by a mobile TDR (Easy Test Ltd., Lublin, Poland) before field preparation and after rice harvest. Measurement interval depths were 0.1 m to a total depth of 1 m. In 2001, the measurements were carried out in 7 plots before sowing (sampling: 03.05.01) and at two replications per plot in Paddy and GCRPS Bare and Plastic after harvest (sampling: 16.10.01). In 2002, measurements were taken from 0-0.1, 0.1-0.2, 0.3-0.4, 0.5-0.6 and 0.8-0.9 m in 10 plots at two replications per plot before sowing (sampling: 23.04.02) and at three replications per plot in Paddy and GCRPS Plastic and Bare after harvest (sampling: 10.10.02 and 15.10.02). The average soil water content was calculated for each soil layer as well as the main rooting zone (0 – 0.6 m) at each sampling day as the average for the whole field as well as for the treatments Paddy and GCRPS Bare and Plastic after harvest. For the lowest soil layer, soil water contents of the preceding layer were assumed, as the lowest layer was below sampling depth.

Percolation

For the water balance percolation was calculated as the difference between water inputs (irrigation and rain) and the water outputs (evaporation, transpiration, and the change in soil water storage). Plot bunds were high enough to exclude run-off. Seepage was prevented by the plastic film protection of the bunds in Paddy. The percolation in the field below the root zone was calculated by the hydraulic gradient between the tensiometers at 0.5 m and 0.6 m and the respective unsaturated hydraulic conductivity according to the Darcy equation.

Reference Evapotranspiration (ET_o)

The reference evapotranspiration was calculated from meteorological data according to the adapted FAO Penman – Monteith equation (FAO, 1998), which relates the original Penman-Monteith ET to the theoretical ET demand of a well watered standard grass-crop of defined height. The reference surface was defined as: “A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹ and an albedo of 0.23” (FAO, 1998). This way the reference ET_o becomes independent of specific plant parameters and can be related to field ET measurements by an empirical coefficient. For different crops and different crop-growth stages different coefficients need to be applied.

FAO Penman-Monteith equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

ET_o: reference evapotranspiration [mm d⁻¹]; R_n: net radiation at the crop surface [MJm⁻²d⁻¹]; G: soil heat flux density [MJm⁻²d⁻¹]; T: mean daily air temperature at 2 m height [°C]; u₂: wind speed at 2 m height [m s⁻¹]; e_s: saturation vapour pressure [kPa]; e_a: actual vapour pressure [kPa]; e_s - e_a: saturation vapour pressure deficit [kPa]; Δ: slope vapour pressure curve [kPa °C⁻¹]; γ: psychrometric constant [kPa °C⁻¹].

Evapotranspiration in Paddy

Measurements to determine ET from Paddy were conducted in the paddy isolation area. For this purpose, a metal box (0.9 x 1.0 m) with a closed bottom was installed at about 4 m and 1.5 m from the dam in one corner close to the paddy main plots in each isolation plot. The boxes were 0.3 m high and buried at 0.15 m deep into the soil. The boxes were filled with soil, and rice was planted according to the planting density of the main plots. All boxes were filled with water to about 0.1 m under the rim. The water layer height was measured at regular time intervals without irrigation. Measurement intervals were several hours to several days (up to 7 days). For water height measurements two methods were employed.

Bottle method:

A bottle (1 L volume, 101 mm in diameter) with a valve at the bottom was placed into the box, allowed to fill with water to the same level as outside and weighed afterwards. The

difference in water level in mm height was calculated from the weight differences between two measurements. Weight measurements at one measurement time were repeated at least twice and facilitated by a balance with an accuracy of 0.1 g. The method was changed because of its high labour intensity.

Ruler method:

A ruler (Nanjing Research Institute of Water Resources and Hydrology Automation, MWR) was inserted into a base at the box wall and could be scrolled slowly down to the water level. The contact with the water surface was indicated by an acoustic signal. The water height was read in mm with an accuracy of 1mm.

Water height measurements, which were corrected for rain, yielded the ET of the respective time intervals. To obtain data for time periods, when no measurements were taken, observed ET rates were related to the reference ETo. The reference ETo was calculated following the FAO approach (FAO, 1998) on an hourly time basis for the observation intervals. The cumulative hourly ETo was compared to the respective observation intervals, after both sets of data were calculated as daily rates for the comparison of different time intervals.

Evaporation from bare soil

Evaporation measurements from bare soil were facilitated by micro-lysimeters (Boast and Robertson, 1982). White PVC tubes of 7 cm inner diameter and 8 cm height were used. The cylinders were evenly inserted into the soil to collect a soil column of about 7 cm. The cylinders were sealed by rubber stoppers and grease, weighed and installed in the field at defined locations in prepared holes, at the same height as the surrounding soil. The cylinders were additionally protected by small plastic bags, which were trimmed to the same height as the cylinder. Evaporation water loss was calculated on the basis of weight difference and cylinder diameter. For weighing, a balance with an accuracy of 0.1 g was used. Evaporation water losses were calculated on a daily time basis. For comparison, the reference ETo was calculated as cumulative hourly ETo for the respective measurement intervals and then transferred to daily evaporation rates.

Evaporation and soil water tension

To determine at which soil water tension stage-two evaporation would start, two sub-plots were set up. One sub-plot was ploughed, the second one remained in its original state of well settled soil. Both plots were thoroughly wetted by flooding irrigation. Into both plots a set of 6 tensiometers was installed at a depth of 0.15 m. Four cylinders to hold continuously saturated soil samples and four cylinders to hold successively drying soil samples were installed in alternating order into both plots at defined locations. No individual location was assigned to a certain cylinder.

The experiment was conducted for five days in mid-May in 2002. Sampling intervals varied from about 2 h to overnight intervals. Cylinders to hold saturated soil samples were saturated at the onset of the experiment and thereafter, were always re-filled with water to their original weight or slightly more at weighing intervals. The cylinders to hold successively drying soil samples were filled with undisturbed soil samples, as described above, every morning during the experiment, with one exception when sampling was delayed by 0.5 days. At weighing times, the soil water tension was also recorded from the tensiometers. For comparison, the mean soil water tension, read at initial and final weighing times, was used. At one weighing time, water loss of saturated and drying soil samples, as well as soil water tensions, were compared. The experiment was terminated when it was no longer possible to insert the PVC cylinders into the soil, which occurred at a soil water tension of 21.8 kPa in the ploughed sub-plot and 13.5 kPa in the unploughed sub-plot. Data from the ploughed sub-plot and the unploughed sub-plot were presented as one set, which also included data of a third experiment, conducted in early September. For the experiment in September, three replicates

of drying and saturated soil were placed in one row, each in the unploughed sub-plot, while soil was collected from the ploughed sub-plot in which soil water tensions were measured also.

Evaporation from bare soil under a rice crop

To obtain evaporation rates from bare soil under the rice crop, a cylinder was installed into each replicate of GCRPS Bare at a defined location between rows and filled with an undisturbed soil sample of the surrounding soil. The duration of measurement intervals ranged between ca. 2 h and 8 h. Two observation intervals could be conducted during one day, on which the soil of the cylinder holding the successively drying soil was not exchanged. To verify that a stage two evaporation stage had not been reached already in the field, a second cylinder with a saturated sample was also installed. At the second observation interval, a third cylinder with a fresh soil sample of the surrounding plot could be installed to verify that the soil of the first cylinder was not already drier than the surrounding soil of the plot.

In 2001, only one set of soil cylinders with drying soil was installed.

Application of the crop and water model Oryza2000

To obtain a complete water balance, the rice crop model Oryza2000 (Bouman, et al. (2001) version 2.1) was applied with a water balance. To simulate rice crop growth several parameters are required by the model. The main intersection between the crop model and the water model of Oryza2000 is the development of leaf area to meet evapotranspiration requirements. As yield modelling was not in the focus of this study, the LAI forcing option of the crop model was used. By this option the observed LAI data (Tables A4 and A5) were applied to all calculations and also to ET. Otherwise, the crop parameterisation for IR72 (Bouman et al., 2001) was applied; phenological development rates were adapted for Paddy in 2001 and 2002 and also applied to the GCRPS treatments of the respective years (Table A6). Roots deplete the soil of water, but root development was not monitored and therefore, could not be critically compared to simulated root development. For simulation of potential evaporation and transpiration, the Penman equations were used as the basis for calculations. The option to generally increase atmospheric demand was kept at a value of 1. Irrigation was input as rain one day prior to actual application, as soil water tensions were usually recorded after irrigation. For simulation of the water balance, the soil-water balance model PADDY of Oryza2000 was applied. Parameters for the soil-water balance were derived for the experimental field as explained below.

Soil parameters

Soil profile – soil layers

Three soil profiles were established to determine number and thickness of soil horizons, which will be further referred to as soil layers according to the terminology of the model. The first soil profile was established under a wheat crop (“Wheat”) close to the experimental field in 2001. Two more soil profiles were established in 2002 after rice harvest in Paddy replicate 1 (“Paddy1”) and replicate 3 (“Paddy3”). A strong gradient in water permeability had been observed with increasing rates of water loss from “Paddy1” to “Paddy3” (Table 1 and Figure 2).

Saturated hydraulic conductivity

Saturated hydraulic conductivity was measured in-situ at the profile “Wheat” using a disc-permeameter (Department of Soil Science and Water Management, China Agricultural University) of 0.2 m diameter.

Furthermore, the saturated hydraulic conductivity was measured in the laboratory from 100 cm³ soil cylinders. These soil samples were obtained from the soil profiles “Paddy1” and “Paddy3” as well as the Paddy isolation area for the puddled soil layer at the onset of the drainage period. The saturated hydraulic conductivity was determined at four to five replicates according to the falling water head method, a non-stationary method, according to Hartge (Hartge and Horn, 1992).

Water retention characteristics

“Wheat” Profile

The water retention characteristic of the soil profile “Wheat” was obtained in the laboratory of the Department of Soil Science and Water Management (China Agricultural University). Samples were collected in 100 cm³ soil cylinders at five replicates of each soil layer. First, the soil water content of soil water tensions from 10 kPa to 1500 kPa was obtained by the pressure plate method. Secondly, for tensions below 10 kPa until saturation the water content was determined using the “water pole method”, in which the height of the water column defines the respective tensions. As a third step, the bulk density was determined by the weight of oven dry soil.

“Paddy1” Profile

The water retention characteristic of the soil profile “Paddy1” was obtained in the laboratory of the Institute of Plant Nutrition and Soil Science (Kiel University). Samples were collected in 100 cm³ soil cylinders of each soil layer at three to four replicates, including samples from the puddled layer of the paddy isolation area taken at the beginning of the drainage period. The soil water content at respective soil water tensions was determined by the pressure plate method. Water content at saturation was estimated identical to pore volume. The pore volume was calculated as

$$PV = 1 - dB \cdot dF^{-1};$$

PV: pore volume, dB: soil bulk density, dF: soil mass density, 2.65 g cm⁻³ assumed.

The bulk density was determined on the basis of soil weight at pF 7.

Top-soil, 0 to 0.06 m, at field capacity

Soil samples were collected at 4 replicates using cylinders of 10 cm x 6 cm size of the GCRPS top soil. After saturation, the respective water losses were determined at soil water tensions of 3 kPa, 6 kPa and 15 kPa by weighing. The respective tensions were applied by a hanging water column in a sand bed (3 kPa and 6 kPa) and pressure plates (15 kPa).

Van Genuchten parameterisation, RETC model

The pF curves were established using the Van Genuchten parameters and the formula:

$$\theta = (1/(1+(\alpha\psi)^n))^{(1-1/n)}(\theta_s - \theta_r) + \theta_r$$

with θ : water content; θ_s : water content at saturation; θ_r : residual water content; α : Van Genuchten parameter; n: Van Genuchten parameter; ψ : matric potential

The parameters were derived from the RETC model (US Salinity Laboratory, 1999).

Unsaturated hydraulic conductivity

The Unsaturated hydraulic conductivity was measured in the laboratory by a method for small differences in water content and short time steps according to Becher (Becher, 1970) and was calculated by the Darcy equation. Samples were collected from the soil profile “Wheat” in 2001 in cylinders of 6 cm height and 10 cm diameter at 4 replicates at 0.5 m - 0.6 m deep.

The relationship between unsaturated hydraulic conductivity and matric potential was expressed by the Van Genuchten formula (Mualem, 1976):

$$K_u = K_s(1 - (\alpha\psi)^n)^{(n-1)}(1 + (\alpha\psi)^n)^{(1/n-1)^2} / (1 + (\alpha\psi)^n)^{((1-1/n)/2)}$$

with α : Van Genuchten parameter; n: Van Genuchten parameter; ψ : matric potential; K_s : saturated hydraulic conductivity; K_u : unsaturated hydraulic conductivity

The parameters were derived from the RETC model (US Salinity Laboratory, 1999). According to Mualem (1976) the parameter l was always set to 0.5.

Seepage and percolation rate in Paddy

The seepage and percolation rates for the Paddy replicate one were derived from water height measurements. Measurements were facilitated as described above for ET in Paddy and additionally corrected for irrigation water input and the reference ETo multiplied with a crop coefficient derived for the field (compare “Reference Evapotranspiration (ETo)”) to account for all water inputs and water outputs except for seepage and percolation. The seepage and percolation rate was then calculated as the difference in water height as mm per day. Before the drainage period, three measurement intervals with continuous water layer and water height observations as well as one interval after the drainage period were identified. The measurement intervals lasted from three days to ten days. The mean seepage and percolation rate before drainage was calculated as the weighed mean (by length of time interval).

Plant parameters

Field measurements for plant parameters were conducted at bi-weekly intervals.

LAI

During the early development stage, the LAI was determined by the copy method: the leaves of five tillers were cut and copied by an ordinary copy machine. The leaf area was calculated by the weight of the copied leaves and the reference paper. In 2001, the disc method was applied to the older plants, of which the leaves were also divided into lower and upper leaves. From these leaves small discs (100 pieces) of known diameter (6 mm) were cut. Leaf area was calculated on the basis of the disc dry weight and disc area. In 2002, the leaves of five older tillers were scanned, from which leaf area was calculated by a computer software (Yu and Lin, 2003). Of all the leaves, only the green leaf area was measured; dead leaves or yellow parts of otherwise green leaves were discarded. Leaves that had to be transferred to the laboratory were transported as a whole plant with roots in an ice-box to avoid leaf shrinkage.

Roots

Roots were sampled for root length up to 0.8 m deep from Paddy and GCRPS Bare at flowering using a root auger of 8 cm diameter and 10 cm height. The soil of each sampling interval of 0.2 m was compressed to the auger height at sample collection. Samples were collected between two hills within one row at five replicates in a diagonal line across the plot. The samples were washed using a sieve of 0.5 mm diameter and counted on a disk of 15 cm x 10 cm size with a 1 cm² grit. The finest roots were discarded. The root samples of the first layer of GCRPS Bare were counted in sub-samples after dilution. Root length density was calculated according to the intersection method with: Root length = 0.786* number of intersections with grit (Tennant (1975) in Böhm, 1979).

Calculation of water use efficiency (WUE)

The WUE was calculated as dry weight grain yield per total water input, irrigation and rain, as g L⁻¹.

Results and discussion

Evapotranspiration

Evapotranspiration in Paddy (2002)

Daily evapotranspiration rates for flooded conditions in Paddy could be related to the reference ETo (Figure 3). ET rates among replicates varied highly, indicating that the specific conditions of each replication box had a strong impact on individual ET rates. The relation of the measured ET to the reference ETo changed in early July, when canopy closure was within one week of being completed. The variation among replicates became stronger after canopy closure underlining the sensitivity of the plant component in the system of the planted metal boxes to microclimatic influences.

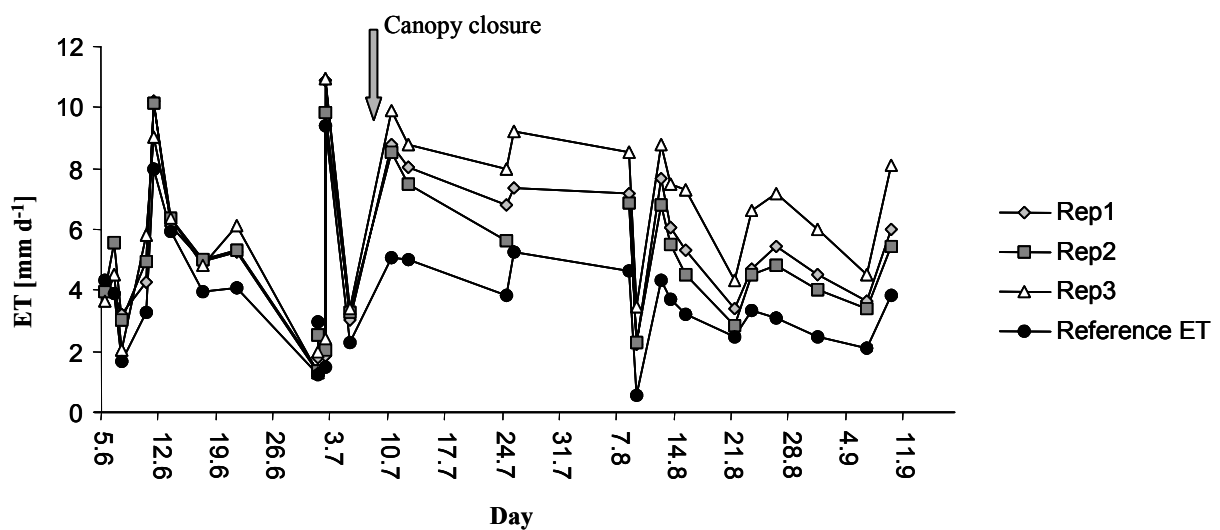


Figure 3. ET of three replicates and reference ETo for the rice vegetation period in 2002

For both vegetation stages, before and after canopy closure, a correlation between measured ET_{field} and reference ETo was established (Figure 4). During the initial vegetation stage, before canopy closure, ET_{field} and reference ETo were almost identical, but after canopy closure, during the mid-season stage, the ratio increased to 1.42.

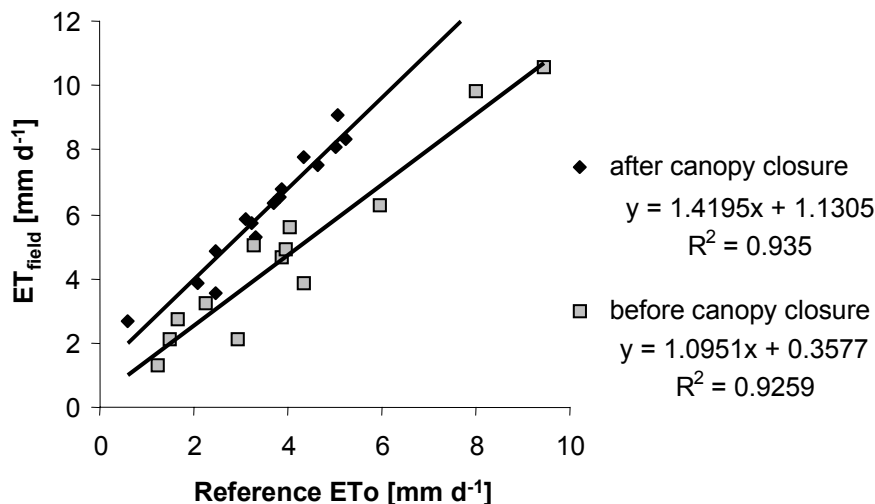


Figure 4. Correlation of average ET_{field} ($n = 3$) and calculated reference ETo before and after canopy closure

The observation of two distinct stages (Figure 3) in the relation of measured ET_{field} and reference ET_0 agrees with the FAO concept of an initial phase, a crop development period (in this case very short), a mid-season stage (after canopy closure) and a late season stage, which was omitted in our study (FAO, 1998). The rather high intercept with the Y-axis (Figure 4) may be attributed to conditions specific for the box situation, like the possibility of increased water temperature. Although the boxes were initially buried to a depth of 0.15 m into the soil, the box system was elevated as compared to the main plot. Thus, less heat exchange with surrounding soil and water may have taken place. Furthermore, plants were slightly elevated as well and thus, were more exposed to e.g. drying by wind. Since these factors are not likely to be predominant in the Paddy field environment, the intercept was ignored for further calculations. The observed regression coefficient of 1.42 is rather high as compared to the crop coefficient of 1.2, supplied by FAO (FAO, 1998) for the mid-season stage, sub-humid climate and moderate wind speed. In our field, the daily minimum relative humidity from July to mid-September was on average 48 % and wind speed averaged 1 m s^{-1} , implying sub-humid conditions and moderate wind speed. But the high regression coefficient of our field may be related again to an “oasis effect” of the rather small, isolated paddy area in an otherwise irrigated, but not submerged area. Supportive to this assumption may be the fact, that the difference between reference ET_0 and observed ET rates was highest in the third replicate (Figure 3). This plot was located closest to the field border and susceptible to a very poor maintenance of ponded water (Figure 2).

Evapotranspiration simulated by Oryza2000

Simulated ET from Paddy is high and almost identical to potential ET throughout the season as at low LAIs, water evaporates from the free water surface (Figure 5). Maximum ET rates in GCRPS Bare and Plastic are identical to Paddy, but they are interrupted by extremely low rates. This behaviour is due to the irrigation frequency and the simulation of evaporation which will be discussed later. With increasing LAI, the share of evaporation in ET becomes smaller and more even rates are simulated. On day 211 (30.07.02) in GCRPS Bare and day 173 (22.06.02) in GCRPS Plastic, simulated potential evaporation and simulated actual transpiration are about equal. At the corresponding times, a LAI of about 1 in GCRPS Bare and of 0.4 to 2.4 in GCRPS Plastic was established in the field in 2002.

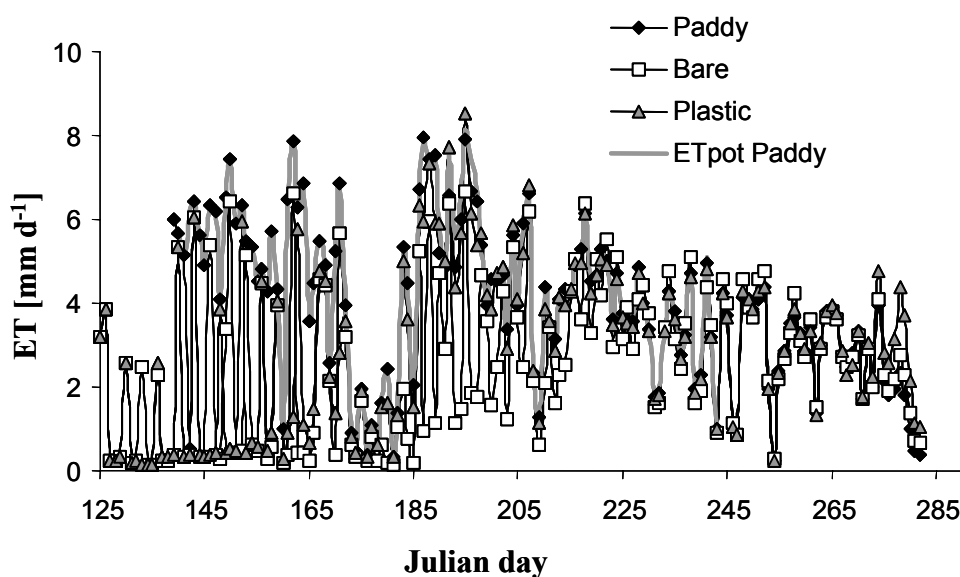
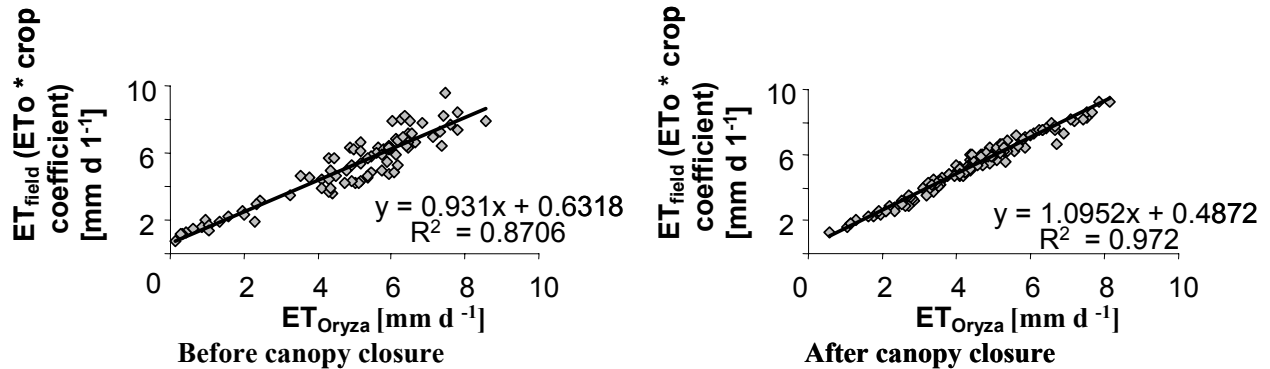


Figure 5. Simulation of daily ET rates with forced LAI for Paddy, GCRPS Bare and Plastic by Oryza2000 for 2002

A close correlation could be established between ET_{field} (ET_o * crop coefficient of 1.10 and 1.42 respectively) and $ET_{Oryza2000}$ at potential settings, no water limitation, (Figure 6). Before and after canopy closure, regression coefficients are close to 1, indicating that rates, which were calculated from ET_{field} and $Oryza$, were almost identical; values from ET_{field} tended to be lower before canopy closure, but higher after canopy closure.



$Oryza2000$ simulation at potential production settings and forced LAI from transplanting to canopy closure and from canopy closure to the day of the last irrigation event (5.09.01 and 31.08.02)
Canopy closure observed in 2002 and estimated for 2001

Figure 6. Correlation of ET_{field} (ET_o *crop coefficient) and ET as simulated by $Oryza_{2000}$ before and after canopy closure until irrigation stopped for 2001 and 2002

The close correlation of $ET_{Oryza2000}$ with a forced LAI and ET_{field} is not surprising since the ET simulation in the model also refers to the Penman equation (Bouman et al., 2001). Nevertheless, the simulation of ET appears to be reliable for Paddy (Figure 5), where the situation of no water limitation is met during the larger part of the vegetation period, while in GCRPS, especially during the initial vegetation stage, a considerable amount of water may be lost by evaporation from bare soil. Up to a minimum threshold of a LAI value of 2.5, evaporation rates depend on soil surface wetness (Ritchie, 1983). Yoshida (1981) states that transpiration reaches a plateau in rice at a LAI of 3.5 to 4, which explains the identical ET rates for Paddy and GCRPS at the later vegetation stages; at these LAI values, transpiration should account for about 90 % of ET (Kato et al. (1965) in Yoshida, 1981).

Evaporation from bare soil

Soil water tension and evaporation stage

The soil remained in stage-one evaporation until a soil water tension of 13 to 14 kPa at a depth of 0.15 m was reached, as only at this point the evaporation rates from drying and saturated soil samples started to separate (Figure 7). The lower atmospheric demands characterised by the reference ET_o were met up to soil water tensions of about 21 kPa. Very similar correlations with regression coefficients of about 1.3, between the reference ET_o and evaporation rates from saturated as well as from drying soil samples, could be established up to a soil water tension of 14 kPa (Figure 8).

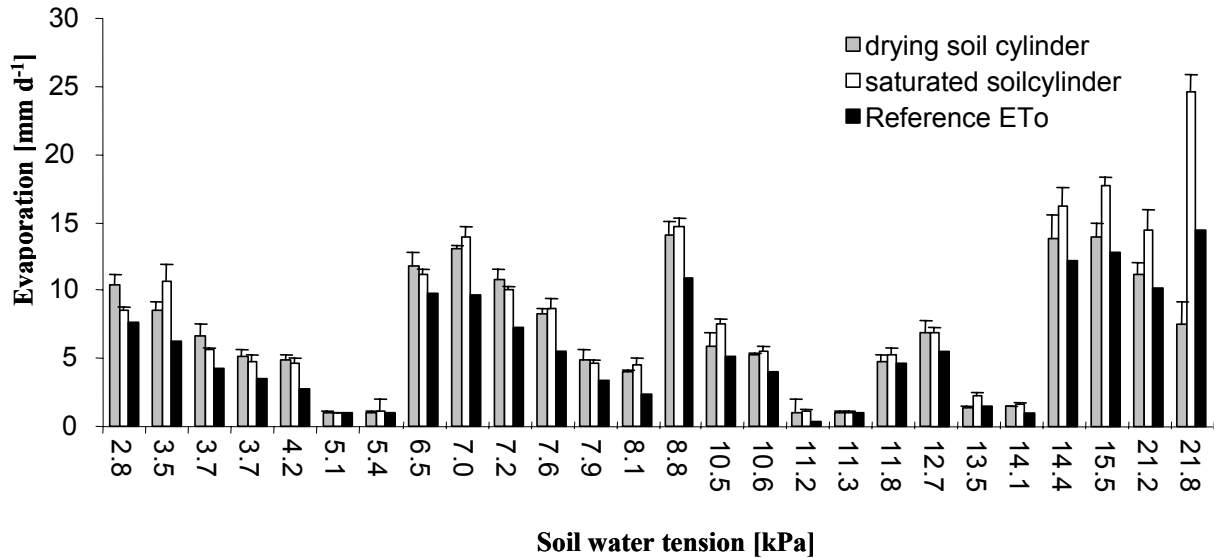


Figure 7. Evaporation rates of bare soil from drying and saturated soil samples and reference ETo, n=4 and 3

Sources of error were probably the relatively short measurement intervals as well as time delays caused by the weighing and re-installing of the respective cylinder group. Moreover, the sample depth and surface were small and thus, the samples were more susceptible to disturbances and not truly representing the undisturbed soil conditions. Boesten and Stroonsnijder (1986) cite a ratio of 0.9 for evaporation from a free water surface to potential evaporation, determined by meteorological parameters. FAO (1998) suggest a factor of 1.15 to calculate stage-one evaporation of bare soil from reference ETo. The value 1.15 is supposed to represent the low albedo of wet soil and the possibility of heat storage in previously dry soil.

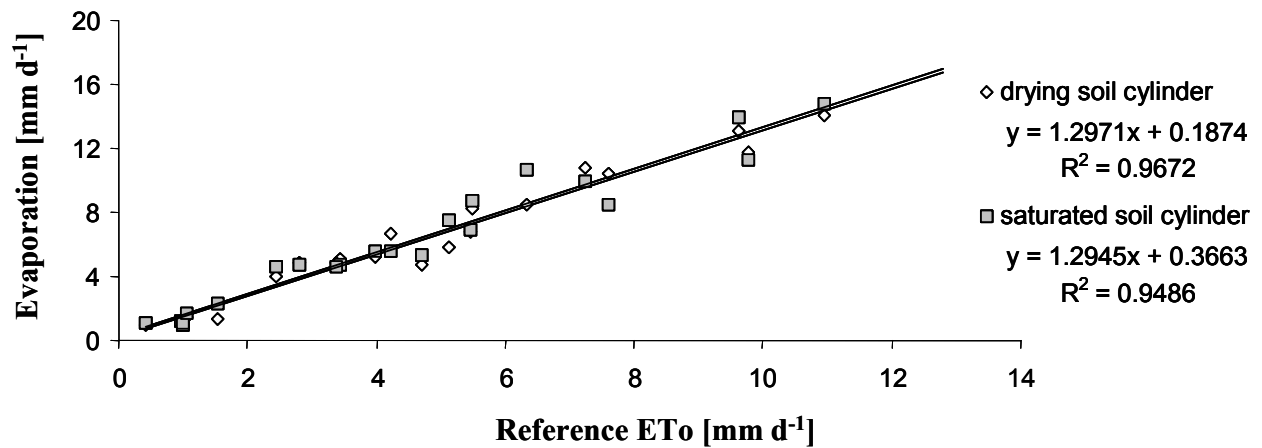


Figure 8. Correlation between reference ETo and average evaporation from saturated and drying soil samples up to a field soil water tension of 14 kPa at a depth of 0.15 m, n = 4 and 3

Our field observations were supported by the behaviour of the water retention characteristic at field capacity of the top-soil layer. Water losses of each desiccation step from saturation to soil water tensions of 3, 6 and 15 kPa were on average 6.7, 6.7 and 5.9 % of cylinder volume, respectively. The cumulative water loss at 15 kPa was about 19.3 % of cylinder volume. This volume would equal 52 g of water loss by evaporation from the drying soil cylinder in the field, calculated for a soil depth of 7 cm. To compare this amount from laboratory measurements with field observations, a time interval of the main experiment was selected: May 13th, mid-day when sampling started, to May 17th in the morning when 14 to 15 kPa of

soil water tension was reached at a depth of 0.15 m in both experimental sub-plots. The initial soil water tension was about 3 kPa. The cumulative ET was calculated as the sum of the hourly E_{To} * 1.3 (the regression coefficient in Figure 8) and yielded 51.6 g of water per cylinder surface area. The similarity between calculated theoretical water loss by stage-one evaporation (51.6 g) and the rate calculated from laboratory measurements (52 g) shows that measured water losses from the evaporation cylinders in the experimental sub-plots were in a feasible range and that apparently soil water tensions in the top soil were similar to those at a depth of 0.15 m. Thus stage-one evaporation can be assumed to occur up to soil water tensions of 13 kPa to 15 kPa.

Evaporation from GCRPS Bare

Evaporation measurements were undertaken at various days. From 20 June 2002 on, at LAI values between 0.07 and 0.12, the relation of evaporation, measured from saturated soil samples, and the reference E_{To} shifted, indicating the increasing shading effect of the developing leaf canopy. Figure 9 illustrates these decreasing evaporation rates with increasing LAI in GCRPS Bare.

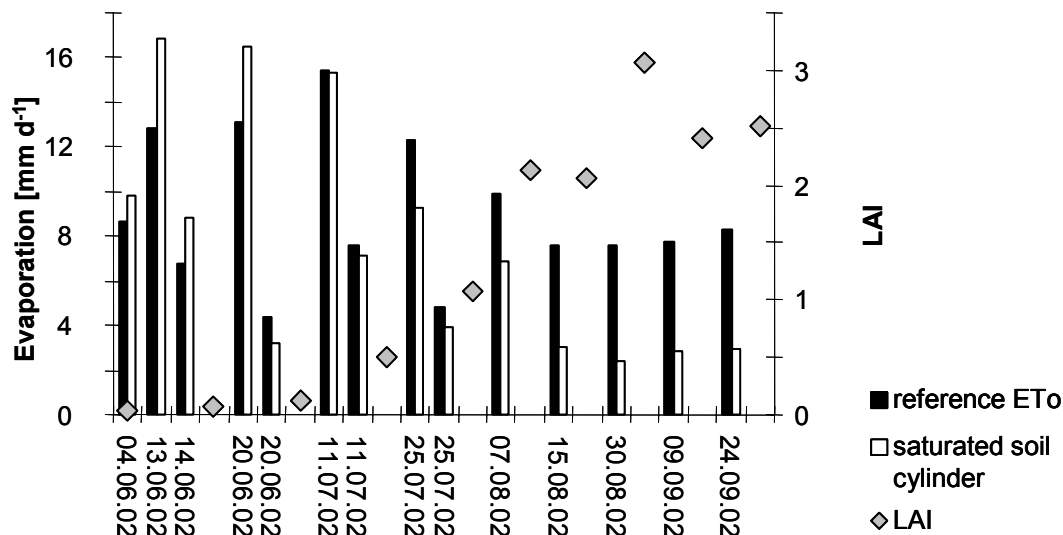
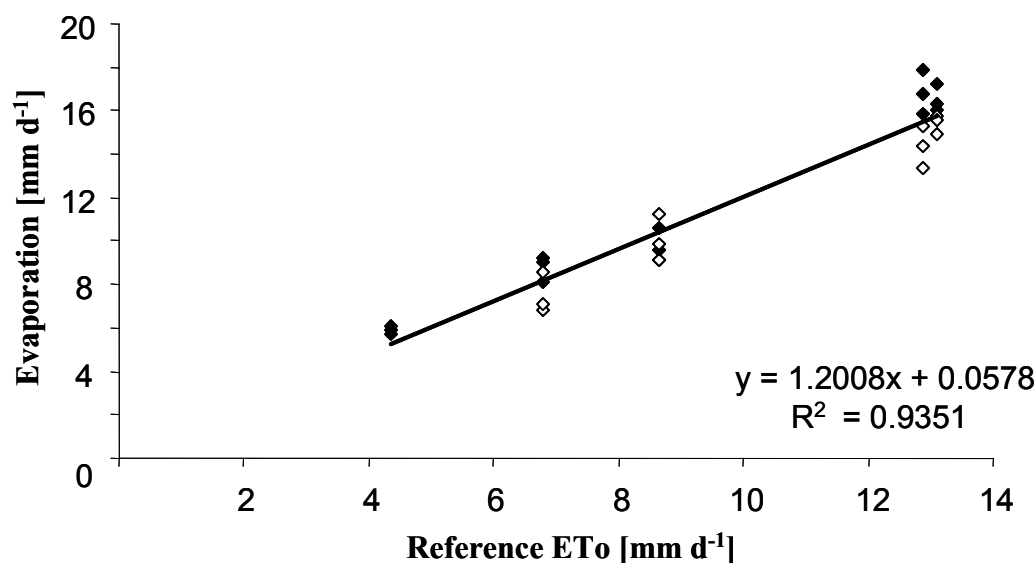


Figure 9. Mean evaporation from saturated soil cylinders under canopy development in GCRPS Bare and reference E_{To} in 2002, $n=3$; time scale refers to fixed days

From the evaporation rates of saturated and drying soil samples and the reference E_{To} , a good correlation could be established (Figure 10) up to LAI values of 0.07 to 0.12 (Figure 9). On all days of observation the soil water tension at a depth of 0.15 m remained below 14 kPa, and although evaporation rates from drying soil cylinders tended to be lower than from saturated soil cylinders, rates from both cylinder types were considered as one group. The obtained regression coefficient of 1.2 is lower by about 0.1 than the ratio of the relationship of bare soil evaporation to reference E_{To} (1.3), observed in the previous experiment (Figure 8).



Filled symbol: saturated soil cylinder; open symbol: drying soil cylinder

Figure 10. Correlation between ETo and evaporation rates from field soil samples under a developing plant canopy, until LAI 0.07 to 0.12, n=3

On 20 June 2002 two data sets of the second observation interval were excluded due to their high diversity, and only the second set of freshly sampled drying cylinders was included into the calculation.

After canopy closure almost 40 % of the daily reference ETo still evaporated from the soil surface in the two years (Table 2) in GCRPS Bare. This rather high rate may be attributed to the sparse canopy closure in GCRPS Bare, maximum LAIs were 3.8 and 3 in 2001 and 2002, respectively, whereas in GCRPS Plastic, maximum LAIs were 7.8 and 8.4. The standard deviations were generally very high which may be due to field variability, different shading effects and sampling errors, e.g. time lags at cylinder installation and weighing.

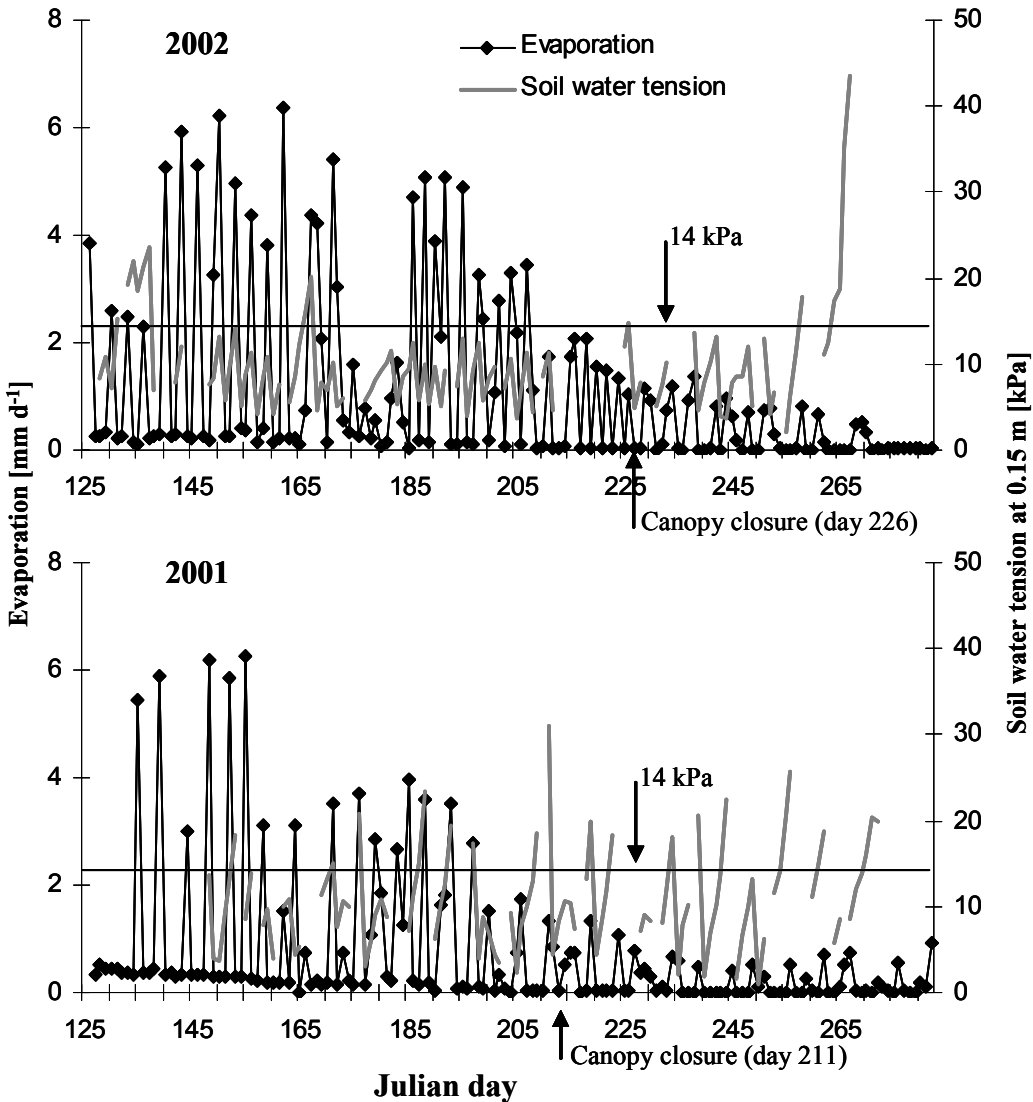
Table 2. Correlation of reference ETo and evaporation from saturated and drying soil cylinders after canopy closure in GCRPS Bare, n=3

	Day	Reference ETo	mean Evaporation		coefficient
		[mm d ⁻¹]	soil cylinder	sd [%]	ETo * ET _{soil cylinder} ⁻¹
2002	15.08	7.59	2.99	37	0.39
	30.08	7.55	2.43	27	0.32
	30.08	7.55	2.77*	31	0.37
	09.09	7.78	2.85	19	0.37
	24.09	8.31	2.99	36	0.35
2001	15.08	3.20	1.24*	23	0.39
	6.09	3.07	1.14*	8	0.37
	18.09	3.37	1.28*	10	0.38
average					0.37
sd					0.02

*drying soil cylinder
sd: standard deviation

Evaporation from GCRPS Bare, simulated by Oryza2000

When comparing the observed evaporation rates at soil water tensions below 14 kPa (Figure 8 and 10) and the evaporation rates simulated by Oryza2000, an underestimation of these rates by the model becomes obvious (Figure 11). The evaporation rates simulated by the model are characterised by an extreme up and down; rates are high after the application of irrigation or after precipitation, indicated in Figure 11 by low soil water tensions (see note), but the day after irrigation the evaporation rates are already extremely low. Evaporation is especially high before canopy closure. During this time soil water tensions were mostly below 14 kPa in both years and even almost throughout the whole vegetation phase in 2002. Thus, for GCRPS Bare the simulated actual evaporation should be substituted by the potential evaporation rate for the calculation of evapotranspiration in the water balance.

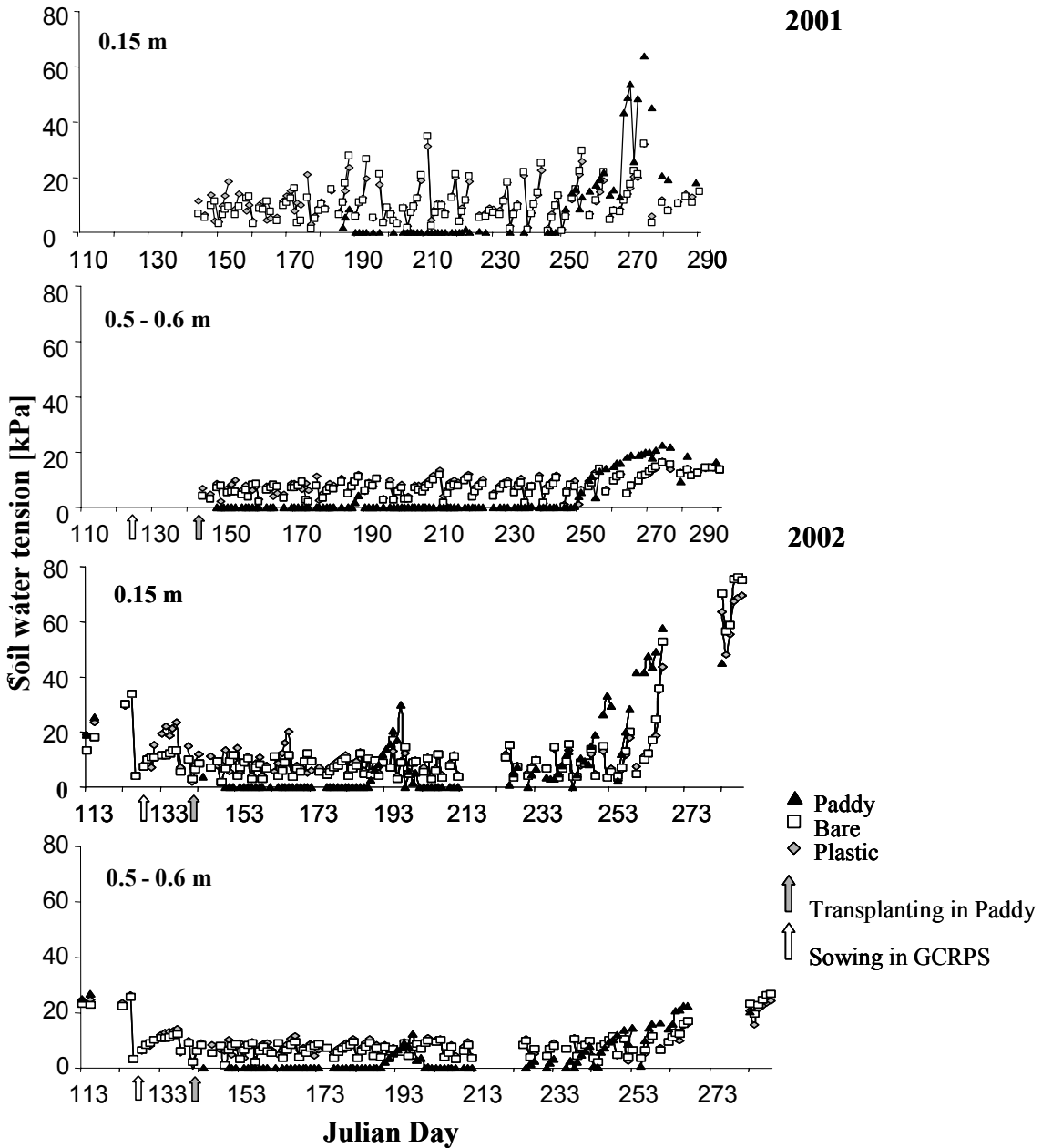


In this figure maximum soil water tensions and maximum evaporation rates coincide due to the input mode of rain and irrigation water to the model (compare the materials and methods section). Canopy closure estimated for 2001

Figure 11. Evaporation rates simulated by Oryza2000, for GCRPS Bare, 2001 and 2002, and observed soil water tensions at a depth of 0.15 m

Soil water tensions and percolation

Observed soil water tensions



Paddy: drainage: 04.07.01-08.07.01, 08.07.02-16.07.02; irrigation stop: 05.09.01, 30.08.02; AWD: 14.08.02
 GCRPS: irrigation stop: 20.09.01, 16.09.02

Paddy: negative soil water tensions, indicating an overlying water layer, were set to 0

2001: tensiometers were installed late, therefore no observation from the initial vegetation stages

Figure 12. Soil water tensions at 0.15 m and 0.5 - 0.6 m deep in Paddy and GCRPS Bare and Plastic in 2001 and 2002

The general level of soil water tensions was lower in 2002 than in 2001 as the irrigation threshold had been lowered (Figure 12). The soil in Paddy was usually saturated except for drainage periods and towards the end of the vegetation phase when the soil was allowed to dry. Soil water tensions in GCRPS Bare and Plastic were almost identical in both depths and in the two years. Only during the initial stage of 2002 could the water preserving impact of the plastic film cover be observed in smaller soil water tensions in GCRPS Plastic, on average almost 8 kPa for the time interval from day 131 to day 137 (Figure 12). Also, water inputs to

both GCRPS treatments were very similar with a difference of only 53 mm in 2001 and 44 mm in 2002.

Soil characteristics

Soil Profiles

The three soil profiles showed a similar distribution of soil layers; however, in the “Wheat” profile, the last clayey layer was not observed (Table 3). The third layer in “Wheat” was observed as a sub-layer of the second layer and was specially sampled to describe the soil characteristics in the layer of the two tensiometers at 0.5 and 0.6 m deep. The soil profile “Paddy3” under replicate three, which had extremely high irrigation requirements, showed a softer and more permeable fifth layer than the other two profiles, whereas the clayey sixth layer was more distinct. An impact of soil puddling in the “Paddy” profiles could not be detected after harvest when the profiles were described. Although in “Paddy3” a plough layer was observed at a depth of 0.2 to 0.25 m, this layer was too deep to be a result from puddling, which was not likely to be effective to more than 0.15 m (Wopereis et al., 1992). No poorly permeable hard pan, as is often typical for rice soils, was observed. This is not surprising as the soil had been used only for two years for paddy rice, and the soil texture was rather light. According to De Datta (1981), only rice soils with a clay content of more than 20 % are prone to puddling. Saturated hydraulic conductivities either measured in the field (“Wheat”) or in the laboratory (“Paddy1” and “Paddy3”) were very high.

Table 3. Soil profiles near and at the experimental field

Layer	"Paddy 1"							"Paddy 3"							"Wheat"								
	depth [m]	bulk density[g/cm ³]	texture	structure	consistency	roots	sat. hyd. cond. [cm/d]	sat. water content [Vo%]	depth [m]	bulk density[g/cm ³]	texture	structure	consistency	roots	sat. hyd. cond. [cm/d]	sat. water content [Vo%]	depth [cm]	bulk density[g/cm ³]	structure	consistency	roots	sat. hyd. cond. [cm/d]	sat. water content [Vo%]
1a	0-0.15	1.39					193	0.47															
1	0-0.27		light loam	puddled earthworm holes, crumbly	soft	+++			0-0.27		light loam	earthworm holes, crumbly	soft	+++			0-0.30	1.32	soft		+++	97	0.42
2	0.27-0.57	1.62	middle to light loam	earthworm holes, crumbly	little tight	+	210	0.39	0.27-0.55		light loam - middle loam	earthworm holes, crumbly	soft with tighter sublayer, 20 - 25 plow layer	+			0.30-0.49	1.46	compact		+	69	0.45
3																	0.49-0.60	1.44	slightly compacted		+	97 *	0.47
4	0.57-1.00	1.48	fine sand	polyhedral; partly CaCO ₃ nodules	soft		266	0.44	0.55-1.00		fine sand	polyhedral	soft				0.60-0.95	1.41	soft			166	0.46
5	1.00-1.30	1.63	coarse sand - tighter than "Paddy3"	polyhedral	very tight		37	0.39	1.00-1.26	1.58	coarse sand; CaCO ₃ nodules	no structure	soft		82	0.40	0.95 -	1.6	block-structure			29	0.46
6	1.30-		mixture of clay and sand	partly CaCO ₃ nodules; partly platy structure	tight				1.25- 1.36		clay, CaCO ₃ nodules	platy structure	tight										

* fitting of saturated hydraulic conductivity:37

Paddy1 : profile description after harvest of rice crop in 2002

Paddy3 : profile description after harvest of rice crop in 2002

Layer1a in Paddy1 characteristics of the puddled soil layer, samples were obtained during the drainage period when the water had drained

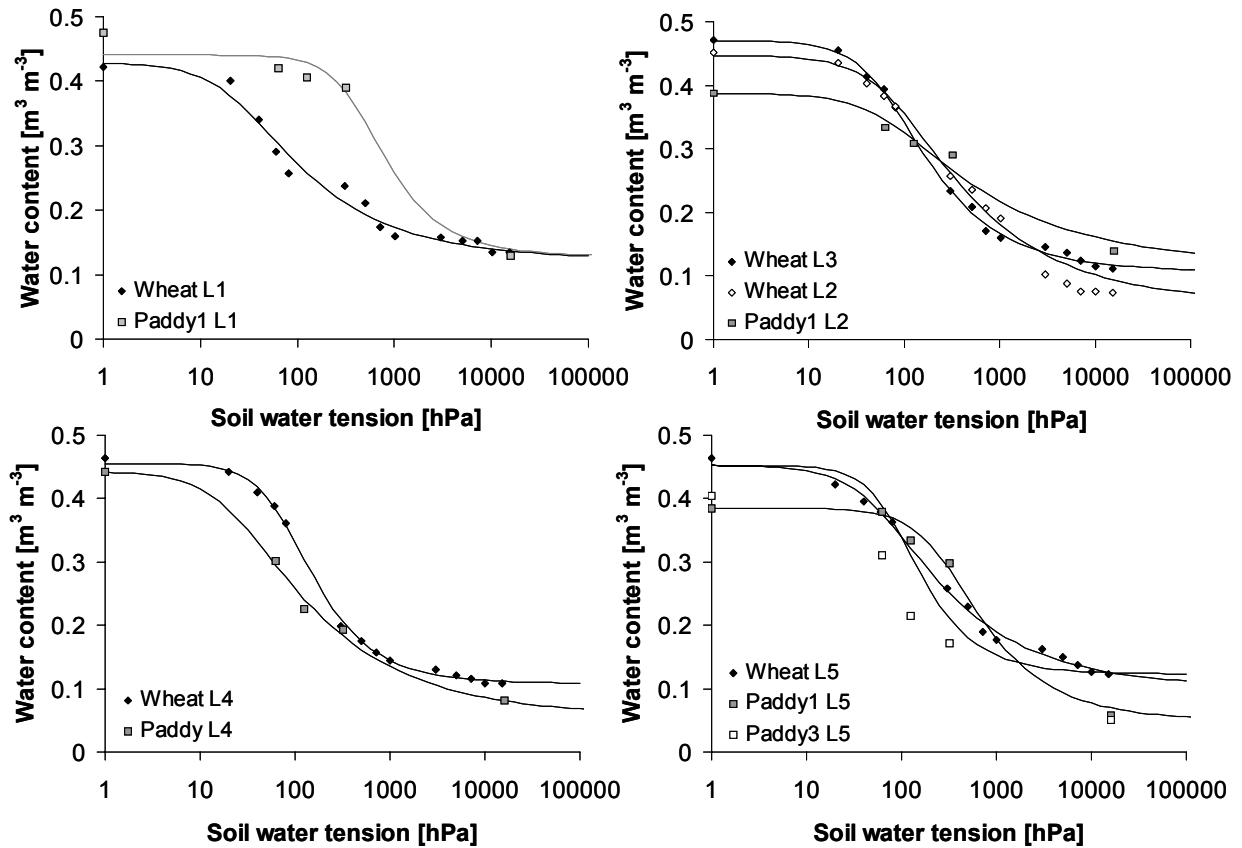
Layer1 in Paddy1 and 3 characteristics of the top soil as observed after harvest, remains of a puddled layer were not detectable

Wheat : profile description in spring of 2001 under wheat crop

Soil water retention characteristics

The water retention characteristics from the "Paddy1" and the "Wheat" profile exhibit some differences and underline field heterogeneity (Figure 13). Striking is the difference in the puddled and non-puddled top soil of the soil profiles "Paddy1" and "Wheat". The puddled soil maintains a high water content up to pF 2.7, when soil water already has been strongly depleted in layer1 of the "Wheat" profile. The differences between "Paddy1" and "Wheat" in layer2 are mainly due to the saturated water content of "Paddy1", which is based on calculation and thus, may not be reliable. In the range of field capacity, soil water contents in layer4 are about 10 % lower in "Paddy1" than in "Wheat", while in the last layer, the main difference can again be found in the different soil water contents at saturation.

To describe the water retention characteristics van Genuchten parameters were fitted by the RETC model (US Salinity Laboratory, 1999), but in case of unsatisfactory modelling results, the parameters were manually adapted to fit the data of the observed values in the range of field capacity, which was important for this study.



Saturated water content is shown at 1 hPa in the diagram; L = layer

Figure 13. Water retention characteristics of the soil profiles “Wheat” and “Paddy1”

Unsaturated hydraulic conductivity

The observed hydraulic conductivities of the four replicates of layer3 (“Wheat” Profile) were extremely variable and data close to saturation could not be obtained (Figure 14). Therefore, to derive a fitted hydraulic conductivity characteristic, the fitted van Genuchten parameters of the water retention characteristic from the respective soil layer of the “Wheat” profile were applied. The saturated hydraulic conductivity was fitted to the replicates two and three since replicates four and one do not indicate any reasonable saturated conductivity; the measured data do not show a tendency to intercept the y-axis. As the saturated conductivity is usually very susceptible to the actual field conditions of a specific spot, e.g. macro-pores, and the in-situ measured saturated conductivity, which resulted from a single observation, was very high, 97 cm d⁻¹ (Table 3), the saturated conductivity was fitted on the basis of replicates two and three and the observed saturated water content (Table 3).

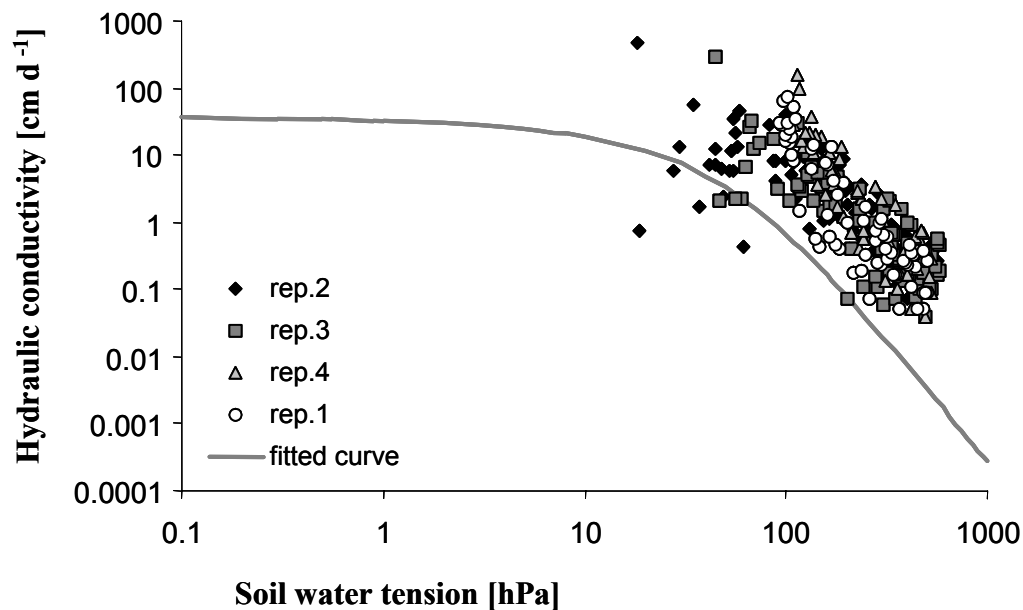


Figure 14. Unsaturated hydraulic conductivity characteristic of the “Wheat” Profile in 0.5 to 0.6 m depth

Field percolation

GCRPS

Percolation rates out of the rooted soil zone were calculated by the hydraulic gradient and fitted hydraulic conductivity (Figure 14). The daily percolation rates calculated in this way were extremely high on the day of water input or the day after (Table 4, for selected intervals of observation). This resulted in a very high total water loss by percolation, 146 % and 117 %, respectively, of the total water input leaving nothing for evapotranspiration requirements. One critical point, apart from field variability and a high uncertainty of the precise parameters for the hydraulic conductivity characteristic, may be the fact that soil water tensions were recorded usually in the afternoon, also after irrigation, when soil water tensions were very low. But soil drying was probably faster during the initial period after irrigation than during the following days. Mean soil water tension several hours after irrigation reached values of 3.8 kPa on average, already of 6.6 kPa on the day after irrigation and 9.1 kPa on the day before irrigation in GCRPS Plastic in 2002. The hydraulic conductivity decreased from 5.4 cm d^{-1} by a factor of 2.8 to the value of 1.9 cm d^{-1} and 0.8 cm d^{-1} , respectively. Therefore, it can be assumed that the calculated daily amount of percolation was overestimated on the days of major water inputs. Hence, especially since irrigation was frequent, it was not possible to derive the share of percolation from daily soil water tension observations.

Table 4. Percolation rates in GCRPS Bare, 12.06.01 to 02.07.01 and Plastic 24.06.02 to 11.07.02

GCRPS Bare						GCRPS Plastic					
water input	hydr. Grad.	mean tension	ku	percol	sd	water input	hydr. Grad.	mean tension	ku	percol	sd
[mm]		[hPa]	[cm d ⁻¹]	[mm d ⁻¹]		[mm]		[hPa]	[cm d ⁻¹]	[mm d ⁻¹]	
49	0.7	85.26	1.006	6.67	14.2	1	1.19	71.54	1.549	18.46	9.7
5	0.9	38.52	5.219	49.26	63.9	76	1.09	<i>54.6</i>	2.794	30.46	11.6
16	0.5	51.49	3.138	15.89	17.5	1	0.99	37.68	5.403	53.42	51.7
30	0.71	48.9	3.461	24.51	35.1	1	0.62	57.38	2.526	15.56	5.3
	0.9	46.32	3.823	34.80	51.1		0.64	69.34	1.666	10.64	21.4
	0.79	66.6	1.827	14.48	25.9	1	0.48	77.13	1.293	6.22	3.1
	0.7	86.89	0.958	6.46	11.9		0.38	82.95	1.079	4.09	0.7
	0.6	88.40	0.916	5.87	9.0	1	0.40	94.01	0.778	3.13	1.4
3	1.5	80.38	1.168	18.09	60.4	45	0.63	36.66	5.635	35.36	16.4
49	0.8	67.19	1.791	14.69	20.3	2	0.60	62.06	2.138	12.93	5.4
1	0.7	85.49	0.999	6.85	11.4		0.51	75.95	1.343	6.91	3.9
	0.4	62.76	2.086	7.52	16.6		0.39	90.79	0.854	3.33	2.0
	0.28	88.1	0.923	2.60	7.0	47	0.56	42.08	4.520	25.30	7.7
	0.2	113.48	0.461	0.94	3.3		0.42	73.24	1.465	6.22	6.8
55	0.7	24.33	9.582	67.87	85.0	43	0.42	41.52	4.623	19.62	7.3
1	0.4	49.41	3.395	12.24	31.4		0.57	75.10	1.380	7.88	5.3
3	0.6	73.42	1.456	8.84	16.4	41	0.54	35.53	5.905	31.72	5.5
11	0.6	87.56	0.939	5.91	11.0	2	0.68	67.99	1.744	11.92	7.6
	0.9	78.47	1.239	10.86	17.7						
	0.70	92.4	0.815	5.72	10.7						
	0.5	106.36	0.555	2.93	5.4						
total	221			323.02		260				303	
% percolation of water input				146						117	

Figures in italics are mean values of the previous and the following day, no measured data were available
sd: standard deviation

ku: unsaturated hydraulic conductivity

Paddy

During times of submergence for the replicate Paddy1, a seepage and percolation rate of 12 mm before drainage and 20 mm after drainage was observed in 2002. Two sampling intervals, one interval of one day and one interval of only one hour, were excluded as the respective rates exhibited a high deviation from the other rates. The seepage and percolation rate after drainage was then calculated from only one measurement interval of ten days. The seepage and percolation rates were obtained using the crop coefficients 1.1 and 1.42 (Figure 4) in the calculation of actual ET for the respective crop development stages. An additional “intermediate” crop coefficient of 1.2 had been assumed as one observation interval lay within the crop development period (compare “Evapotranspiration in Paddy”). Changing all crop coefficients to 1 would only result in a change for the period after drainage with a rate of 22 mm per day. Nevertheless, this illustrates that the correct calculation of the seepage and percolation rate depends, of course, on a good estimate of ET.

Well puddled soils with a poorly permeable plough sole should exhibit seepage and percolation rates of 0.2 to 0.5 cm d⁻¹ (Bouman et al., 1994). This shows that puddling on the rather light soil over two years had only limited effect; also, within the soil profile (Table 3) no hard pan had formed. The measured saturated hydraulic conductivity of soil cylinders from the topmost puddled soil layer (0-6 cm) showed a wide range of conductivities from 0.7 cm d⁻¹ to 465.3 cm d⁻¹. These samples were of course not likely to include a possible hard pan, as their depth was limited to the upper 6 cm. Tuong et al. (1994) found that only 1 % of non-puddled soil in a puddled field increased field percolation losses fivefold. The two different seepage and percolation rates before and after drainage, the latter being the higher rate, suggest the need to re-fill the soil profile. The observed clayey layer at about 1.3 m can be taken as evidence that seepage and percolation in our field were either limited by this deep soil layer or even a deeper layer, which was neither located nor characterised. Supportive to

this assumption is that, as shown above, the seepage and percolation rates in replicates two and three were much higher, as irrigation water inputs increased, but periods of submergence were shorter than in replicate one. An other explanation for the increased seepage and percolation rate after drainage is the possibility that cracks, which developed during soil drying, penetrated the puddled layer and led to a bypass flow after re-flooding (Lu et al., 2000).

Soil water tensions simulated by Oryza2000

Soil Parameters for the PADDY model

Parameterisation (Table 5 and Table 6) was carried out on the basis of field data for Paddy1 and GCRPS Bare for 2002. Soil puddling was defined for the top soil as puddled for Paddy and non-puddled for GCRPS. Soil layers were defined from the soil profiles (Table 3). Mainly five soil layers, to a depth of about 1.3 m, were recorded. For model application three, rather thick layers (1, 4 and 5) were split into sub-layers with mainly the same properties. In Paddy, where the soil was puddled prior to transplanting, the first layer was split into an artificial puddled layer of three sub-layers. Although puddling was only effective to about 0.15 m, the first layer was kept at 0.3 m deep. The first two sub-layers were set to a very high saturated conductivity. This way the lower 0.1 m of the first layer would resemble the unobserved plough layer of a puddled soil. No “slow” soil layer was observed from soil samples of the profile “Paddy1” (Table 3). Therefore, the saturated hydraulic conductivity of the last soil layer was set to 1.2 cm per day to fit the observation of the seepage and percolation rate and the observation of a thin clayey sixth soil layer at around 1.3 m, especially in the profile “Paddy3” (Table 3). However, the seepage and percolation rate before drainage was set to 14 mm d⁻¹ and 20 mm d⁻¹ after drainage as observed in the field. The observed seepage and percolation rate before drainage was 12 mm d⁻¹, but at simulation with 12 mm d⁻¹ the soil profile remained too wet. Apart from the first layer, the soil characteristics of the “Wheat” profile were applied to Paddy and GCRPS as for the water retention characteristic more data were available and saturated hydraulic conductivities from in-situ measurements appeared to be more reliable. No interpolation of soil layers for soil water tensions and soil water contents was carried out. The ground water table was set to deep ground water.

Table 5. Parameters for the soil water balance model PADDY as applied to the Paddy treatment

	Sat. conductivity [cm d ⁻¹]	Sat. water content** [m ³ m ⁻³]	Ini. Water content*** [m ³ m ⁻³]		Van Genuchten parameter		
			2001	2002	VGA	VGN	VGR
			Layer 1a	1000	0.44	0.16	0.22
Layer 1b	1000	0.44	0.16	0.22	0.0028	1.95734	0.1293
Layer 1c	97	0.44	0.16	0.22	0.0028	1.95734	0.1293
Layer 2	69	0.45	0.24	0.25	0.01238	1.456	0.0588
Layer 3	37*	0.47	0.20	0.24	0.0152	1.66396	0.1073
Layer 4a	166	0.46	0.17	0.18	0.0127	1.88607	0.1082
Layer 4b	166	0.46	0.17	0.18	0.0127	1.88607	0.1082
Layer 5a	29	0.45	0.18	0.18	0.01757	1.48223	0.10221
Layer 5b	29	0.45	0.18	0.18	0.01757	1.48223	0.10221
Layer 5c	1.2	0.45	0.18	0.18	0.01757	1.48223	0.10221

Layer1: puddled layer (puddling to about 0.15 m); pF parameter of puddled soil (profile “Paddy1”, Figure 13); conductivity of profile “Wheat” (Table 3) in layer1c; Layer 5: saturated hydraulic conductivity set to 12 mm d⁻¹, in accordance with observed seepage and percolation rate before drainage

*derived from saturated hydraulic conductivity fitting; **as parameterised for van Genuchten formulation of water retention characteristic; ***Initial soil water content at simulation start

VGA, VGN, VGL, VGR: Van Genuchten parameter; α , n, l and residual water content; VGL for all layers at 0.5

Fixed percolation rate: before drainage: 14mm; after drainage: 20mm

Maximum root length: 0.6 m; root length at transplanting estimated at 0.18 m

Table 6. Parameters for the soil water balance model PADDY as applied to GCRPS Bare and Plastic

	Sat. conductivity [cm d ⁻¹]	Sat Water content** [m ³ m ⁻³]	Ini. Water content*** [m ³ m ⁻³]		Van Genuchten parameter		
			2001	2002	VGA	VGN	VGR
			Layer 1a	97	0.43	0.16	0.22
Layer 1b	97	0.43	0.16	0.22	0.04077	1.48763	0.12363
Layer 1c	97	0.43	0.16	0.22	0.04077	1.48763	0.12363
Layer 2	69	0.45	0.24	0.25	0.01238	1.456	0.0588
Layer 3	37*	0.47	0.20	0.24	0.0152	1.66396	0.1073
Layer 4a	166	0.46	0.17	0.18	0.0127	1.88607	0.1082
Layer 4b	166	0.46	0.17	0.18	0.0127	1.88607	0.1082
Layer 5a	29	0.45	0.18	0.18	0.01757	1.48223	0.10221
Layer 5b	29	0.45	0.18	0.18	0.01757	1.48223	0.10221
Layer 5c	1.2	0.45	0.18	0.18	0.01757	1.48223	0.10221

*derived from saturated hydraulic conductivity fitting

**as parameterised for van Genuchten formulation of water retention characteristic

***initial water content at simulation start

VGA, VGN, VGL, VGR: van Genuchten parameter; α , n, l and residual water content

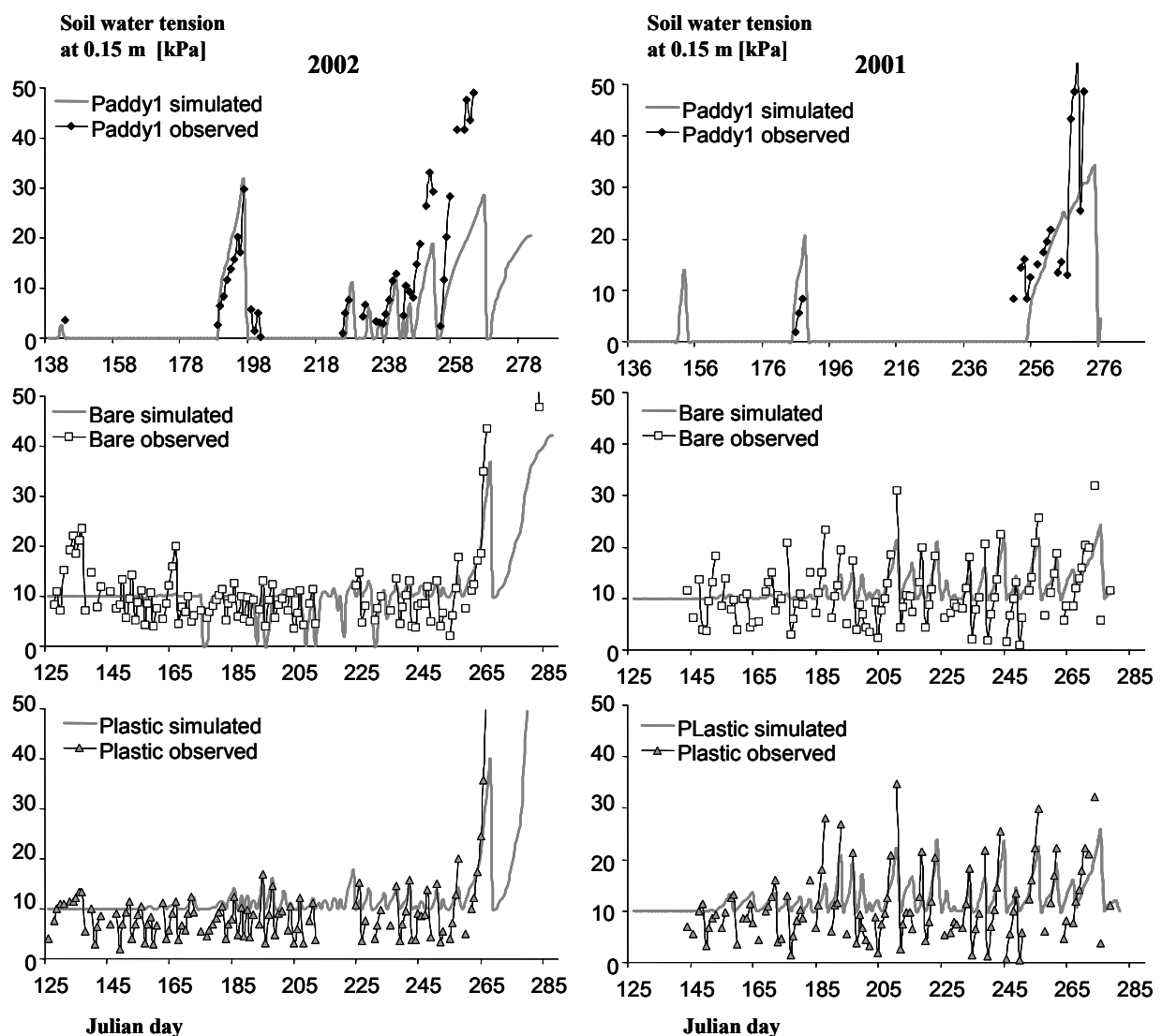
VGL for all layers at 0.5

Fixed percolation rate, arbitrarily high: 300 mm d⁻¹

Maximum root length: 0.4 m

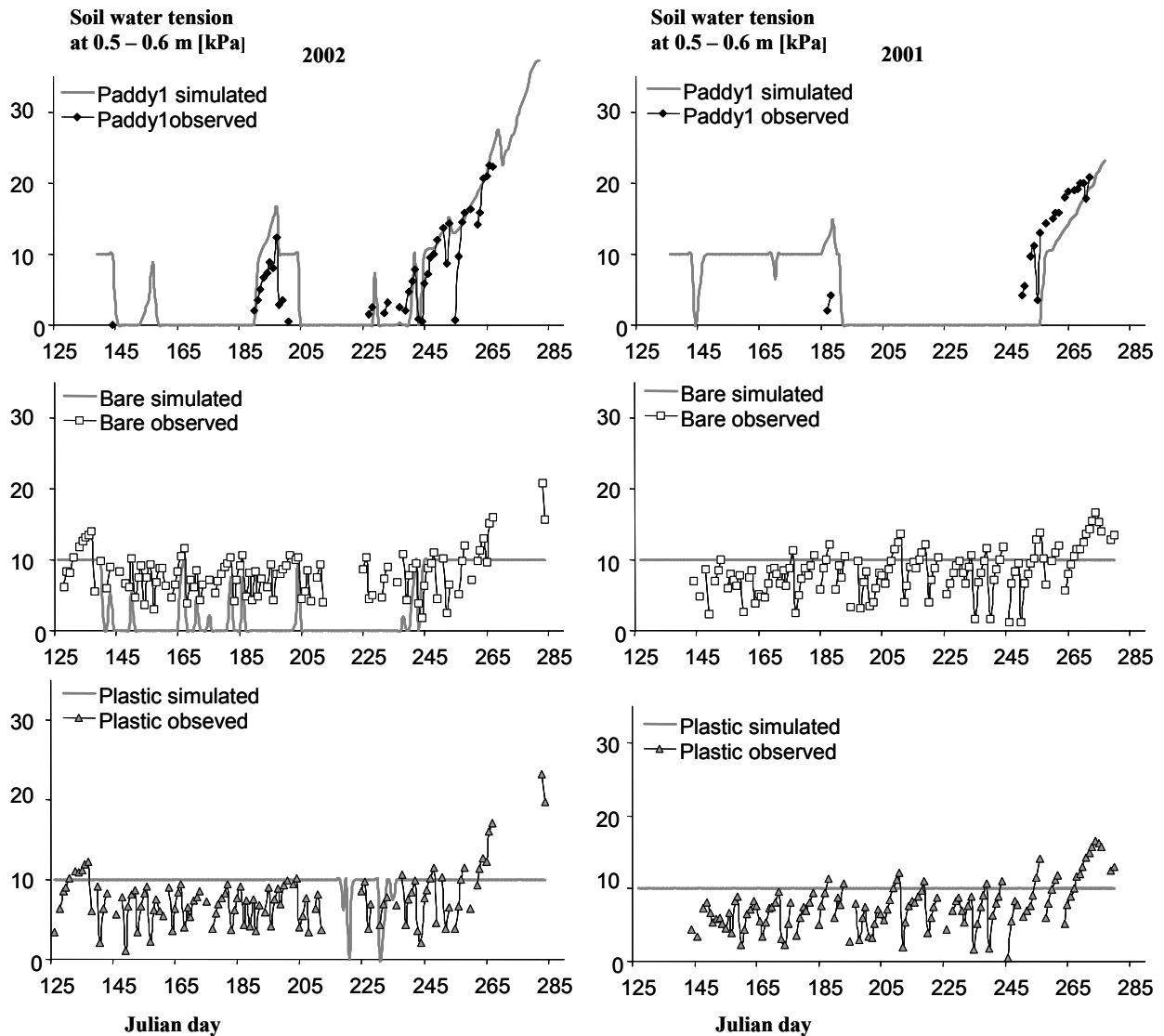
Simulated soil water tensions

In Paddy, simulated soil water tensions for the upper soil layer fit quite well with the observed tensions during larger parts of the vegetation period in 2002; for 2001, data were limited. For the late stage of the vegetation phase, simulated soil water tensions are strongly underestimated in the two years (Figure 15). For GCRPS simulated tensions are more problematic; although the inhibiting soil layer was also included in the GCRPS simulation, the simulated soil water tensions do not sufficiently repeat the observed fluctuation below 10 kPa. Only in GCRPS Bare of 2002 is this fluctuation indicated. Fluctuations in soil water tensions at levels higher than 10 kPa are in better agreement. During the initial vegetation phase, when evaporation is probably underestimated by the model, the soil water is not depleted by the simulation and soil water tensions remain too low. This effect is less pronounced for GCRPS Plastic as evaporation can be assumed to have been reduced by the plastic film mulch.



Only data after start of irrigation are presented

Figure 15. Observed and simulated, *Oryza2000*, soil water tensions at 0.15 m deep in 2001 and 2002



Only data after start of irrigation are presented

Figure 16. Observed and simulated, *Oryza2000*, soil water tensions at 0.5 to 0.6 m deep in 2001 and 2002

In Paddy, simulated and observed soil water tensions for the lower soil layer are in relatively good agreement (Figure 16). Before drainage in 2001, the simulated tension is too high; recorded tensions were at saturation (Figure 12). For GCRPS in 2002, the simulated tensions show a fluctuation below 10 kPa, but not in the same range as the observed tensions; this effect is less pronounced under GCRPS Plastic and not existent at all in 2001. For both years simulated soil water tensions never increase above a soil water tension of 10 kPa. Within the model, 10 kPa of soil water tension are defined as field capacity; therefore, the soil is not drained to lower soil water tensions, and due to the limitation of roots up to 0.4 m in depth, the soil layer of 0.5 to 0.6 m is not depleted of water by the plant. In Paddy and GCRPS, more than 90 % of the roots were located in the soil depth up to 0.6 m and 0.4 m, respectively (Figure 17). A rooting depth of 0.8 m is unusual for Paddy rice, where normally roots are limited to 0.4 m and where about 90 % of the root system is located in the upper 0.2 m in lowland soils (Sharma et al., 1994). On the other hand, it was surprising that rice in GCRPS limited its root growth mainly to 0.4 m depth. Sharma et al. (1994) observed an increase of soil mechanical impedance with the decline of moisture content and a decrease of root length density as a power function of soil mechanical impedance. The Paddy treatment had a relatively light soil texture with no plough sole inhibiting root growth, and daily irrigation

provided probably additional oxygen to the root system. Mishra et al. (1997) observed maximum rooting depths of 0.55 m and 0.65 m in a field experiment on more permeable soils.

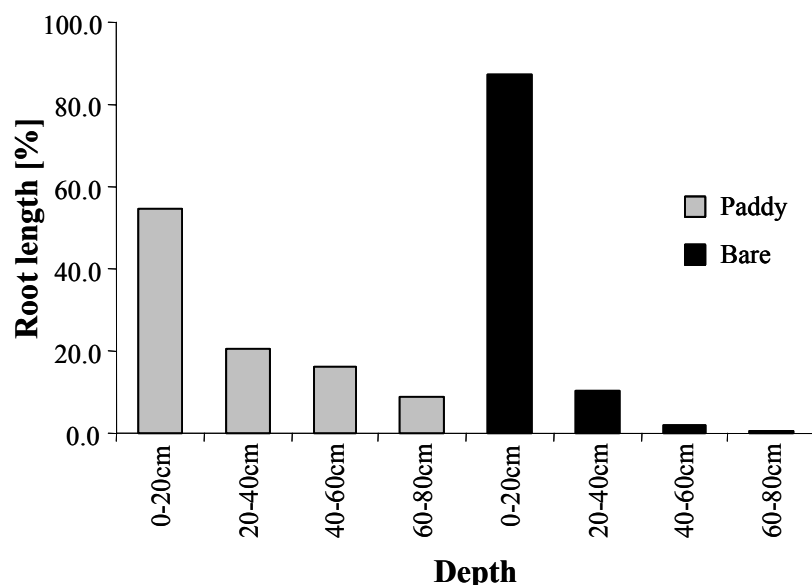


Figure 17. Distribution of roots in GCRPS Bare and Paddy in different soil depths as share of total root length at flowering in 2001, n = 5

Balance

Soil water storage

Initial and final soil water storage of the main root zone, 0 - 0.6 m, was determined in the two years (Table 7). Differences in soil water storage were almost negligible in both years, although for GCRPS Plastic, an increase in soil water content of 63 mm was observed in 2001. As simulated soil water tensions were not reliable (Figure 15 and Figure 16), the simulated soil water contents were not used for water balance calculations, but instead, the observed values (Table 7) were applied.

Table 7. Changes in soil water storage of the main rooting depth, 0 to 0.6 m, before and after the rice cropping periods of 2001 and 2002

Soil water content	2001				2002			
	Vol %	sd	Δ [%]	Δ [mm]	Vol %	sd	Δ [%]	Δ [mm]
Initial (mean)^{a)}	19.6	3.9			23.4	3.3		
Final (mean)^{b)}	28.1	10.7	8.4	50.5	24.0	3.8	0.6	3.6
Paddy	27.6	12.2	8.0	47.9	26.1	3.1	2.7	16.3
Bare	26.6	2.6	7.0	42.0	23.0	4.1	-0.3	-1.9
Plastic	30.1	14.3	10.5	63.1	23.2	3.2	-0.2	-1.1

^{a)} 3.05.01; 23.04.02; ^{b)} 16.10.01; 10.10.02 and 15.10.02

TDR measurements with an accuracy of about 4 Vol %; sd: standard deviation

Water balance and deep percolation

The water balance showed for Paddy a stable share of percolation in 2001 and 2002 (Table 8). For GCRPS, the proportion of percolation increased as the irrigation threshold was lowered from 2001 to 2002. As previously illustrated, the GCRPS Bare simulated actual evaporation tended to be underestimated (Figure 11); therefore, for the water balance, the potential

evaporation data were applied to calculate ET. The actual evaporation was only 32 % and 44 % of the potential evaporation in 2001 and 2002, respectively. For GCRPS Plastic, the actual evaporation was applied to calculate ET as a reduction in evaporation, due to the plastic film cover, was desired. The simulated actual evaporation was 30 % and 36 % of the simulated potential evaporation in 2001 and 2002, respectively. In Paddy1 of 2002, the actual simulated ET accounted for 95 % of the simulated potential ET and 96 % in 2001, indicating that evaporation could not have been significantly underestimated here.

Table 8. Water balance: total water input, cumulative simulated ET, cumulative simulated percolation (Oryza2000) and calculated percolation water loss for 2001 and 2002

	Total input		ET _{sim}		Percol. _{sim}		Δ *		Percol.		Percol. share of input**	
	[mm]		[mm]		[mm]		[mm]		[mm]		[%]	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Paddy1	2724	2248	598	570	2032	1608	48	16	2078	1662	76	74
Paddy2	4011	3765	598	570			48	16	3365	3179	84	84
Paddy3	5388	4446	598	570			48	16	4742	3860	88	87
Bare _{act.}	1642	2082	411	406	1277	1622	42	-2	1189	1678	72	81
Bare_{Epot}	1642	2082	650	618			42	-2	950	1466	58	70
Plastic	1589	2038	465	472	1172	1496	63	-1	1061	1567	67	77

* soil water storage 0-0.6 m; **percentage of percolation in respect to input

Paddy: ET data simulated on basis of average LAI and “Paddy1” soil parameters; Δ refers to Paddy average

Bare_{act.}: ET calculated with simulated actual evaporation and transpiration

Bare_{Epot.}: ET calculated with simulated potential evaporation and actual transpiration

ET simulation start one day before first irrigation

2001

Paddy: 15 May

GCRPS: 6 May

2002

Paddy: 18 May

GCRPS: 5 May

End of ET simulation

True harvest

2001

Paddy: 4 October

6 October

GCRPS: cut on 15 October

15 October

2002

Paddy: 9 October

10 October

GCRPS: cut on 14 October

14 October

The simulated ET can be considered reliable for Paddy with regard to the close relationship of ET_{field} and simulated ET (Figure 6), especially as simulated actual ET was close to potential ET, for which the correlation was obtained. Assuming no major reduction in transpiration for GCRPS Bare under the drier soil conditions, the ET rate calculated as simulated potential evaporation plus actual simulated transpiration should also be adequate. Wopereis et al. (1996b) report that the transpiration rates of well watered rice plants and plants subjected to drought stress remained equal when soil water status was reduced by about 50 %. The situation is more questionable for GCRPS Plastic, where the reduction in evaporation through the plastic film mulch could be estimated only. The reduction compared to potential evaporation was 30 to 36 %. Wang et al. (2002) report in their overview on findings of a reduction of soil evaporation through plastic film by 40 to 60 % under a plant canopy. FAO (1998) states a reduction of evaporation by 50 to 80 % through plastic film mulch, but at the

same time an increase in transpiration by 10 to 30 % due to a transfer of sensible and radiative heat from the plastic film cover to the plant.

The time intervals between initial and final TDR measurements were longer than the rice vegetation phases in Paddy and the GCRPS. The effect of this time gap on the water balance before sowing and after harvest in the two years was probably negligible. Even though this time gap was as long as four weeks in Paddy in 2002 before transplanting, soil conditions were generally dry and little precipitation was recorded. Thus, only a very minor impact on evaporation could be expected. After the 2001 harvest for Paddy only, a relatively long time gap occurred; simulation ended on 4 October, and soil water content measurements were taken 12 days later. During this period a precipitation amount of 19 mm, which accounted for only 1 % of total water input, was recorded. Even the highest changes in soil water storage, e.g. GCRPS Plastic in 2001 (63 mm, Table 7), would account for only 6 % of the percolation calculated for GCRPS Plastic for 2001 (1061 mm, Table 8). Thus, differences in soil water storage were more or less negligible.

The simulated percolation water losses gave a good estimate, especially for Paddy1, where field ET and simulated ET were closely related, also. The similar values of simulated percolation and percolation calculated from water input, simulated ET and difference in measured soil water content imply an adequate simulation of final soil water contents in the root zone. The amount of percolation for Paddy replicates two and three was not simulated. Irrigation requirements to maintain a water layer increased from Paddy1 to Paddy3. This effect may have been caused by different permeability of the single plots, but could have been as well the result of lateral flow on the clay layer, which was observed at the bottom of the soil profiles “Paddy1” and “Paddy3” (Table 3). Under bund flow (Walker, 1999) was prevented by the protective plastic film.

The established water balance proved that the share of percolation water remained extremely high even under the GCRPS. The necessity to maintain a high soil water content led to frequent irrigation events, even though the average soil water tensions of the bulk soil to 0.6 m were still low. The soil water tension at the lower soil layer was on average 7 kPa during the period of irrigation in 2002 and 2001. In this range the hydraulic conductivity was still relatively high, ($> 1 \text{ cm d}^{-1}$; Figure 14), and led to an increased deep percolation. The limitations of the calculation of deep percolation from field data have been discussed above. Nevertheless, calculated average daily percolation rates ranged from 16 mm on the day after irrigation to 5 mm even on the day before the next irrigation in GCRPS Plastic in 2002. Irrigation was applied at amounts of 40 to 60 mm, which were necessary to assure complete flooding of the respective plots, but which exceeded the amount of water needed to refill soil water of the main rooting zone of 0.6 m. Soil water tensions of the lower soil layer usually remained below the respective irrigation threshold for the upper soil; therefore, assuming a soil water tension of 15 kPa at top soil and 10 kPa in the lower soil, the average soil water tension would be 12.5 kPa. Then, the required amount of water to restore a soil water tension of 6 kPa would be about 32 mm, using the water retention characteristic of the second layer of the “Wheat” profile.

Water use efficiency

Irrigation requirements were high in both years, but highest in Paddy. Likewise, yields were highest in Paddy with a slight decline in 2002. In 2002, the yield of GCRPS Plastic reached a similar range as that of Paddy. Yields in GCRPS Bare were extremely low in both years resulting in low water use efficiencies similar to those of Paddy in 2001 and worse in 2002. For GCRPS Plastic an improved WUE could be obtained in both years, but still WUEs were overall low (Table 9). The transpiration ratio as g water transpired per g dry matter biomass

produced ranged from 212 g g⁻¹ in Paddy in 2001 to 365 g g⁻¹ in GCRPS Bare in 2002 for simulated transpiration and observed total biomass. These values are in good agreement with observations from literature. As a general value for rice, 250 to 350 g g⁻¹ can be assumed, although the transpiration ratio may vary with soil moisture, climate, variety, growth stage and growth duration of a plant and may range from 171 to 766 g g⁻¹ (Matsushima (1962) and Yoshida (1975) in Yoshida, 1981).

Table 9. WUE of Paddy and GCRPS in 2001 and 2002, n=3

	Rain		Irrig				Yield				WUE			
	[mm]		[mm]		sd		[kg ha ⁻¹]		sd		[g L ⁻¹]		sd	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
Paddy1	290	442	2433	1806			7516	6100			0.28	0.27		
Paddy2	290	442	3720	3322			7587	5576			0.19	0.15		
Paddy3	290	442	5098	4004			6865	7379			0.13	0.17		
Bare	314	445	1328	1637	28	13	3631	2463	160	323	0.22	0.12	0.01	0.02
Plastic	314	445	1275	1593	83	35	5042	5824	229	402	0.32	0.29	0.01	0.02

sd: standard deviation

In their survey on water management, based on experiments reported in literature, Bouman and Tuong (2001) show that WUE in continuously flooded rice ranges from 0.2 to 0.4 g L⁻¹ in India to 0.3 to 1.1 g L⁻¹ in the Philippines. They also state that although water saving irrigation could increase WUE to 1.9 g L⁻¹, yields were reduced by 10 to 40 % when soil water potentials of the root zone were only -10 to -30 kPa. Also Lu et al. (2000) observed a yield reduction when soil water potentials at 5 cm deep became lower than -10 kPa and -20 kPa.

Conclusion

The GCRPS, Plastic and Bare, led to a reduction in irrigation water of on average 67 % and 47 % in 2001 and 2002, respectively, as compared to the average of the three Paddy replicates. Nevertheless, the proportion of percolation water loss remained high, especially in 2002. This can be mainly attributed to the high and frequent irrigation. The high amounts of irrigation water also led to only slightly increased WUE in GCRPS Plastic, while in GCRPS Bare the water saving effect was offset by the high yield reductions. The impacts of GCRPS on plant development and yield are discussed in Tao (2004).

The simulated soil water balance for Paddy by Oryza2000 was apparently good, especially with respect to the close correlation between simulated potential ET rates and calculated potential field ET rates (reference ETo * empirical crop-coefficient), but also, simulated soil water tensions matched observed values quite well for larger parts of the vegetation period. Shortcomings were especially the upper soil layer during the late vegetation period and the first half of the vegetation period in 2001. The derived crop-coefficients for ET in Paddy probably would be considered restricted to the specific location from which they were obtained. Although a close correlation between simulated and field ET rates could be established, the experimental ET data were derived from a rather small flooded environment making an “oasis effect” likely. Therefore, these rates, however high, would lead to overestimations in a common paddy rice environment. Bethune et al. (2001) tested the FAO concept and its suggested coefficients for a specific location in Australia. They found the FAO method appropriate when comparing seasonal average coefficients. Nevertheless, they observed different empirical crop-coefficients from their two experimental sites, which underlines the importance of the specific conditions of a site.

Unexpectedly, the importance of evaporation was high in GCRPS Bare, which led to an underestimation of the simulated actual ET for this treatment. The importance of evaporation to the field water balance depends strongly on the rate of plant development and soil wetness; when canopy closure is obtained early and the ground well covered, evaporation will become less significant. Soil characteristics define how long full evaporation can be sustained. Wythers et al. (1999) observed an influence of soil texture on evaporation rates over time. Therefore, the observations we have made here on evaporation were only valid under our field and soil conditions.

Due to permanently high soil moisture and frequent irrigation it was not possible to derive deep percolation from field measurements; therefore, the water balance for GCRPS Plastic is most insecure as neither simulated percolation nor simulated evaporation under plastic film mulch, could be confirmed by field data.

Nevertheless, the model Oryza2000 was helpful to establish a water balance for the two rice cropping periods together with limited field data for Paddy and the GCRPS.

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Summary

Rice production in China is restricted due to limited water resources, especially in northern China. In the Beijing area, lowland rice production is going to be completely banned from 2008 on. Therefore, water-saving cropping systems are increasingly implemented into the production of rice, China's major staple food. As one alternative to the traditional lowland rice production system, in which the soil is submerged by a shallow water layer from transplanting of the young seedlings to several weeks before harvest, the Ground Cover Rice Production System (GCRPS) is being discussed. In the GCRPS, the soil is no longer flooded, but soil water contents are maintained in the upper range of field capacity. Additionally, the soil is covered by mulching materials like plastic film or straw mulch to reduce evaporation. Also in the common paddy rice production system, the soil is allowed to dry for a short time period after the main tillering phase is completed (mid-season drainage) to control plant development. The new GCRPS was tested against the common rice production system in northern China with respect to water consumption and its effect on greenhouse gas emissions. The trace gases methane and nitrous oxide were surveyed by portable closed chambers. The experiment was carried out in the years 2001 and 2002 on a field northwest of Beijing. This site, with its rather light soil texture and low ground water table, represented one of the more extreme rice production environments.

In our study, the high water consumption in the paddy rice could be reduced by 67 % to 47 % on average through the GCRPS. Likewise, the low water use efficiency of the paddy rice could be slightly improved in GCRPS with plastic mulch, but in the GCRPS control without mulch application, water savings were offset by a strong yield decline. Nevertheless, in the GCRPS, irrigation water requirements, although reduced as compared to paddy rice, were still high (1300 to 1600 mm). To maintain a soil moisture content within the upper range of field capacity, frequent irrigation was necessary, and the technique of flooding irrigation led to irrigation depths of 40 to 60 mm each time. Thus, the proportion of water lost by deep percolation was still high and in the range of 60 to 80 % of water input, similar to the paddy rice in our study. In the paddy rice, the site history of the previous cultivation with upland crops and the rather light soil texture led to high seepage and percolation rates in the paddy rice, 12 mm per day and more, as no significant plough layer or hard pan, as is often typical in paddy rice, had developed. Also, no other tight soil layer, inhibiting percolation could be identified within the soil profile. However, seepage and percolation rates, which showed a strong gradient along the replicates of paddy rice, may have been reduced by a deeper, thin clayey soil layer which had been identified at the bottom of the excavated soil profiles in the paddy rice. A complete water balance was derived from field data by the application of the eco-physiological crop model *Oryza2000* in combination with the soil-water balance model PADDY. The modelling results were checked by limited field observations on evapotranspiration in paddy rice, evaporation from bare soil as well as soil water tensions in the top-soil and at a depth of 0.5 to 0.6 m. The model application appeared to be successful for the paddy rice, but applicability to the GCRPS was limited.

With respect to global climate change, paddy rice is known for its methane emission potential. Methane is a trace gas that largely contributes to the greenhouse effect. In paddy rice, flooding of the soil for extended time periods leads to anaerobic soil conditions and to low redox potentials, which then lead to the formation of methane. The paddy rice in our study exhibited an overall low methane flux, which may be attributed largely to the high water consumption and the respective percolation rates. Nevertheless, the observed emission time course was typical for lowland rice with mid-season drainage in northern China. In 2002, an increase in methane fluxes was observed, which was probably due to the organic amendment

in this year. In the GCRPS, on the other hand, methane fluxes were negligible in both years due to the aerated soil conditions. Therefore, the GCRPS was clearly an improvement in regard to the methane emissions.

However, in the GCRPS, large nitrous oxide fluxes, about 1.7 % of the applied fertiliser nitrogen, were measured in the two years. Nitrous oxide is also an important greenhouse gas and a by-product of nitrification and denitrification processes. Nitrous oxide fluxes in the GCRPS of our study were mainly provoked by fertilisation events, after the high soil water contents had been realised. In the paddy rice, the situation was different in each year; fluxes were very low in the first year, but of the same magnitude as in the GCRPS in the second year. The major difference between the two years in paddy rice lay in the drainage periods. In 2001, fluxes remained low, while in 2002, nitrous oxide fluxes peaked during the drainage period as frequently observed in studies on paddy rice cropping systems. The reason for this change in the flux pattern of nitrous oxide in paddy rice remained speculative. However, the time course of nitrous oxide emissions from paddy rice in 2002 was in agreement with other observations from literature. Therefore, taking the year 2002 for comparison of the two systems, it shows that the GCRPS did not have a significant enhancing impact on nitrous oxide emissions.

To evaluate the impact of the GCRPS as compared to paddy rice on global warming, nitrous oxide and methane fluxes were transferred to CO₂ equivalents according to the IPCC. From the GCRPS, the cumulative CO₂ equivalent flux was almost identical in the two years. On the contrary, in the paddy rice, a large increase was observed in 2002, which was mainly due to the 12-fold increase of nitrous oxide flux. For the year 2002, the comparison showed that cumulative CO₂ equivalent fluxes in the GCRPS and paddy rice were in a similar range of about 175 and 141 g CO₂ m⁻², respectively. Thus, we assume that the GCRPS, under the site conditions of our study, has no significant negative impact on global warming.

Zusammenfassung

Die Reisproduktion ist in China auf Grund limitierter Wasserressourcen, insbesondere im Norden Chinas, eingeschränkt. In Peking soll der Reisanbau von 2008 an ganz eingestellt werden. Daher werden in der Produktion von Reis, Chinas bedeutendstem Grundnahrungsmittel, in immer stärkerem Umfang Wasser sparende Anbausysteme eingesetzt. Als eine Alternative zum traditionellen Sumpfreisanbau, bei dem der Boden nach dem Verpflanzen der Setzlinge bis einige Wochen vor der Ernte von einer Wasserschicht bedeckt ist, wird das „Ground Cover Rice Production System“ (GCRPS) diskutiert. Im GCRPS wird der Boden nicht länger überstaut, sondern die Bodenwasser-Gehalte werden auf einem hohen Niveau, im oberen Bereich der Feldkapazität, gehalten. Zusätzlich wird der Boden mit Mulchmaterialien, wie zum Beispiel Plastikfilm oder Strohmulch, abgedeckt, um die Evaporation zu vermindern. Auch im konventionellen Sumpfreisanbau lässt man den Boden, nachdem die Hauptphase der Bestockung abgeschlossen ist, aus Gründen der Bestandesführung für einen kurzen Zeitraum trocken fallen („Mid-season Drainage“). Das neue GCRPS wurde gegen den herkömmlichen Sumpfreisanbau in Nordchina in Hinblick auf Wasserverbrauch und das Potential zur Emission von Treibhausgasen getestet. Die Spurengase Methan und Lachgas wurden mit Hilfe von tragbaren Gashauben beprobt. Der Versuch wurde in den beiden Jahren 2001 und 2002 auf einem Standort im Nordwesten Pekings durchgeführt. Dieser Standort bot mit seiner relativ leichten Bodentextur und dem tiefen Grundwasserspiegel ein Beispiel für einen extremeren Standort für Reisproduktion.

In unserer Studie wurde der hohe Wasserverbrauch im Sumpfreisanbau durch das GCRPS um durchschnittlich 67 % bis 47 % verringert. In gleicher Weise konnte die Wassernutzungseffizienz im GCRPS mit Plastikfilm Mulch leicht verbessert werden, während im GCRPS ohne Mulch die Wassereinsparungen durch starke Ertragseinbußen überlagert wurden. Dennoch waren im GCRPS die benötigten Mengen an Bewässerungswasser, obwohl sie im Vergleich mit dem Sumpfreisanbau reduziert waren, immer noch hoch (1300 bis 1600 mm). Um den hohen Bodenwassergehalt im Bereich der Feldkapazität zu erhalten, war eine häufige Bewässerung nötig, und die Bewässerung durch kurzzeitige Überstauung führte jedes mal zu Bewässerungstiefen von 40 bis 60 mm. Daher blieb der Anteil des Wassers, der durch Tiefenversickerung verloren ging hoch (60 % bis 80 % des zugeführten Wassers), ähnlich dem konventionellen Sumpfreisanbau unserer Studie. Im Sumpfreisanbau führten die Standortsgeschichte, vorhergehende Bestellung mit nicht überstauten Feldfrüchten, und die relativ leichte Bodentextur zu hohen Versickerungsraten, 12 mm pro Tag und mehr, da sich keine Pflugsohle oder „Hard Pan“, wie sie häufig typisch im Sumpfreisanbau ist, gebildet hatte. Auch sonst konnte keine dichte Bodenschicht, die die Perkolation behinderte, im Profil identifiziert werden. Dennoch könnten die Versickerungsraten, die einen starken Gradienten entlang der Wiederholungen zeigten, durch eine tiefere tonige Schicht am Boden der Profile, die im Sumpfreis ausgehoben worden waren, begrenzt gewesen sein. Eine vollständige Wasserbilanz wurde anhand von Felddaten mit Hilfe des Modells Oryza2000 in Kombination mit dem Bodenwassermodell PADDY erstellt. Die Ergebnisse der Modellierung wurden durch begrenzte Feldbeobachtungen in Hinblick auf Evapotranspiration im Sumpfreisanbau, Evaporation von unbedecktem Boden wie auch Bodenwasserspannungen im Oberboden und in 0,5 bis 0,6 m Tiefe überprüft. Die Modellanwendung schien für den Sumpfreisanbau erfolgreich zu sein, war aber im GCRPS begrenzt.

In Hinsicht auf den globalen Klimawandel ist Sumpfreisanbau bekannt für sein Potential, Methan zu produzieren. Methan ist ein Spurengas, das in großem Umfang zum Treibhauseffekt beiträgt. Im Sumpfreisanbau führt das Überstauen des Bodens über

ausgedehnte Zeiträume zu anaeroben Boden-Verhältnissen und niedrigen Redox-Potentialen und damit zur Entstehung von Methan.

Der Sumpfreisanbau in unserer Studie zeigte im Allgemeinen niedrige Methan-Emissionen, was hauptsächlich in dem hohen Wasserverbrauch und den damit einhergehenden hohen Versickerungsraten begründet sein mag. Dennoch war der zeitliche Verlauf der Methan-Emissionen typisch für einen Sumpfreisanbau mit „Mid-season Drainage“ in Nordchina. Für 2002 wurde ein Anstieg der Methan-Emissionen beobachtet, der wahrscheinlich durch die organische Düngung in diesem Jahr herbeigeführt worden war. Im GCRPS waren die Methan-Emissionen wegen der aeroben Boden-Verhältnisse zu vernachlässigen und damit war das GCRPS in Hinsicht auf die Methan-Emissionen eine klare Verbesserung.

Jedoch wurden im GCRPS hohe Lachgas-Emissionen, ungefähr 1,7 % des ausgebrachten Dünger N, gemessen. Lachgas ist ein weiteres wichtiges Treibhausgas und entsteht als Nebenprodukt in Nitrifikation- und Denitrifikationsprozessen. Die Lachgas-Emissionen im GCRPS folgten in unserer Studie hauptsächlich den Düngungsmaßnahmen, nachdem die hohen Bodenwassergehalte realisiert worden waren. Im Sumpfreisanbau war die Situation zwischen den beiden Jahren unterschiedlich: Die Flüsse waren im ersten Jahr sehr niedrig, aber im zweiten Jahr von ähnlichem Ausmaß wie im GCRPS. Der größte Unterschied zwischen den beiden Jahren lag in der „Mid-season Drainage“. In 2001 blieben die Flüsse niedrig, während es in 2002 zu dieser Zeit zu einer Emissionsspitze kam, wie es häufig für Sumpfreisanbau mit einer „Mid-season Drainage“ beobachtet wird. Der Grund für diesen Wechsel im Emissionsmuster blieb unklar. Jedoch war der zeitliche Verlauf der Lachgas-Emissionen im Sumpfreisanbau in 2002 in Übereinstimmung mit Beobachtungen aus der Literatur. Wenn man das Jahr 2002 zum Vergleich von Sumpfreisanbau und GCRPS nimmt, zeigt sich, dass GCRPS, keinen signifikanten steigernden Einfluss auf die Lachgas-Emissionen hatte.

Um den Einfluss von GCRPS im Vergleich zum Sumpfreisanbau auf die globale Erwärmung zu evaluieren, wurden Lachgas- und Methan-Flüsse gemäß IPCC in CO₂-Äquivalente umgerechnet. Im GCRPS waren die kumulativen CO₂-Äquivalente in den beiden Jahren fast identisch. Im Gegensatz dazu wurde im Sumpfreisanbau ein starker Anstieg in 2002 beobachtet, der hauptsächlich auf den 12-fachen Anstieg der Lachgas-Emissionen zurückging. Für das Jahr 2002 zeigte der Vergleich, dass die kumulativen CO₂-Äquivalent-Flüsse im GCRPS und im Sumpfreisanbau in 2002 ähnlich waren, jeweils ca. 175 und 141 g CO₂ m⁻². Daher nehmen wir an, dass GCRPS unter den Feldbedingungen unseres Standortes keinen negativen Einfluss auf die globale Erwärmung hat.

Appendix

Table A1. Average N₂O emission rats at various days between vegetation periods at 12:00, n = 3

Day	Paddy		Plastic		Mulch	
	mean [mg m ⁻² h ⁻¹]	sd	mean [mg m ⁻² h ⁻¹]	sd	mean [mg m ⁻² h ⁻¹]	sd
26.10.01	-0.002	0.004	0.006	0.007		
10.11.01	0.010	0.003	0.005	0.012		
10.12.01	0.000	0.007	0.003	0.007		
07.03.02	0.005	0.003	0.010	0.005		
09.03.02	-0.001	0.009	-0.002	0.005		
11.03.02	0.001	0.002	0.015	0.008		
24.10.02	0.023	0.003	0.015	0.019	0.030	0.008
31.10.02	0.018	0.004	0.008	0.019	0.014	0.001
07.11.02	0.033	0.016	0.020	0.008	0.010	0.011
14.11.02	0.012	0.006	0.020	0.005	0.015	0.006
21.11.02	0.018	0.008	0.005	0.003	0.003	0.002
05.12.02	0.014	0.005	0.005	0.004	0.010	0.008
17.12.02	0.013	0.007	0.007	0.002	0.005	0.007
09.01.03	0.011	0.019	0.003	0.007		
11.04.03	0.002	0.032	0.015	0.002		

Table A2. N₂O emission rates measured at three day times in Paddy in 2001, n =3

day	1.6	11.6	19.6	4.7	5.7	6.7	7.7	15.7	21.7	5.8	4.9	12.9	21.9	28.9	12.10
	Mean [mg m ⁻² h ⁻¹]														
06:00	-0.007	0.001	-0.004	-0.017	0.010	0.002	0.019	0.019	0.010	0.012	-0.015	0.050	0.046	0.035	0.022
12:00	-0.002	0.005	-0.003	-0.009	-0.005	0.000	0.000	0.017	-0.017	-0.024	-0.012	0.052	0.064	0.023	0.025
18:00	0.001	-0.003	0.006	0.020	-0.023	-0.001	-0.011	-0.022	-0.001	0.007	0.006	0.062	0.050	-0.025	0.005
	sd														
06:00	0.007	0.008	0.004	0.018	0.023	0.022	0.014	0.100	0.005	0.016	0.026	0.023	0.063	0.026	0.044
12:00	0.014	0.021	0.010	0.039	0.037	0.046	0.043	0.036	0.025	0.049	0.061	0.057	0.021	0.045	0.009
18:00	0.010	0.007	0.008	0.032	0.019	0.023	0.027	0.050	0.019	0.068	0.054	0.048	0.061	0.102	0.031

Impact of day time tested by Tukey test (probability level: 0.05); no differences were found

Table A3. N₂O emission rates measured at three day times in GCRPS Plastic in 2001, n =3

day	1.6	11.6	19.6	4.7	6.7	8.7	21.7	5.8	4.9	12.9	21.9	28.9	12.10
	Mean [mg m ⁻² h ⁻¹]												
06:00	0.100	0.059	0.060		-0.011	0.001	0.015	-0.009	-0.006	0.000	-0.009	-0.001	0.018
12:00	0.138	0.062	-0.005	0.023	0.021	0.015	0.008	0.016	0.009	-0.041	0.014	-0.003	0.006
18:00	0.160	0.072	0.058	-0.023	0.041		0.004	0.017	-0.005	0.014	0.007	0.009	0.007
	sd												
06:00	0.101	0.048	0.058		0.050	0.029	0.010	0.056	0.049	0.078	0.043	0.004	0.019
12:00	0.110	0.060	0.077	0.018	0.084	0.010	0.041	0.075	0.035	0.130	0.018	0.032	0.028
18:00	0.185	0.057	0.031	0.068	0.024		0.023	0.012	0.036	0.045	0.067	0.013	0.027

Impact of day time tested by Tukey test (probability level: 0.05); no differences were found

Days with missing data were not used for statistical analysis

Table A4. LAI of Paddy and GCRPS Plastic and Bare in 2001

Julian Day	LAI		
	Paddy	Plastic	Bare
142	<i>0.03</i>		
159	1.29		
151		0.12	0.12
169	1.41	0.45	0.11
183	7.05	1.48	0.46
197	7.35	2.20	1.32
211	9.69	3.80	2.14
216		4.73	
220			2.25
225	10.40	5.99	2.58
237	8.83	5.91	3.82
243		7.81	
247			3.71
254	6.11	3.62	3.06
268		3.45	2.09
279	1.48		
288		0.52	0.27

Figures in italics are estimates

Table A5. LAI of Paddy and GCRPS Plastic and Bare in 2002

Julian Day	LAI		
	Paddy	Plastic	Bare
139	<i>0.03</i>		
155	0.10	0.07	0.03
169	0.63	0.36	0.07
184	1.91	2.36	0.12
197	4.55	2.11	0.51
207	6.93		
211	8.43	3.74	1.07
219		4.79	
224	7.90	8.44	2.13
233	8.79		
240	6.71	5.25	2.06
246		6.17	
249			3.07
255	4.82	5.25	2.41
268		4.22	2.51
283	0.29		
287		0.08	0.05

Figures in italics are estimates

Table A6. Parameterisation of phenological development rates (Oryza2000) for Paddy in 2001 and 2002

[°C d ⁻¹]	2001	2002
DVRJ	0.000600	0.000508
DVRI	0.000758	0.000758
DVRP	0.000775	0.000971
DVRR	0.001647	0.001839

Data were derived from partitioning of plant dry biomass (green leaves, dead leaves, stem and panicle) at bi-weekly plant harvests using the DRATES model of Oryza2000; for details on plant harvest refer to Tao (2004).

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Curriculum Vitae

Work Experience

Sept. 2000 – April 2004	Junior research fellow and preparation of doctoral dissertation Institute of Plant Nutrition and Soil Science, University of Kiel, Germany Studies on greenhouse gas emissions and water balance in the Sino-German research project on “Improving water and fertilizer use efficiency in lowland rice production by utilisation of different ground cover production systems”
Sept. 1996 - Oct. 1999	Teaching assistant Department of Animal Production in the Tropics, University of Göttingen, Germany
Nov. 1997 - May 1998	Fieldwork for diploma thesis in Brazil Embrapa Amazônia Oriental, Belém-Pa., Brazil
July 1996 - Oct. 1996	Intern Green Pastures Farm of INF (International Nepal Fellowship), rehabilitation farm for people affected by leprosy, in Pokhara, Nepal

Education

April 2004	Completion of doctoral thesis and disputation
Sept. 1992 – April 1999	Diploma (M.Sc.), Agricultural studies, Georg August University, Göttingen, Germany Diploma thesis “Impact of pasture management on regeneration of secondary vegetation in north-eastern Pará state, Brazil” Diploma exams in: crop science, plant nutrition, plant protection, animal production and breeding systems in the tropics and subtropics, plant production in the tropics and subtropics, and socioeconomics of rural development 1-year internship (Pig breeding and farming), Wilhelm-Hartwig Schenkel, near Soest, Germany
May 1992	Abitur (English A-levels) in Lehrte, Germany