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Reducing Irrigation Water Supply to Accomplish the Goal of Designing Sustainable Cropping Systems in the North China Plain

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LIST OF ABBREVIATIONS AND ACRONYMS

a:	Year
ANOVA:	Analysis of Variance
BBCH:	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie
C:	Carbon
CAU:	China Agricultural University
CERES:	Crop-Environment Resource Synthesis
CIGR:	International Commission of Agricultural Engineering
cm:	Centimetre
Co:	Control
CO_2:	Carbon dioxide
CropSyst:	Cropping Systems Simulation Model
CSY:	China Statistical Yearbook
cv.:	Cultivar
d:	Day
DBW:	Dongbeiwang
DFG:	German Research Foundation
DSSAT:	Decision Support System for Agrotechnology Transfer
DM:	Dry matter
dt:	Deciton
DUL:	Drained upper limit of available soil water
e.g.:	For example
EPIC:	Erosion Productivity Impact Calculator
Eq.:	Equation
et al.:	Et alii (and others)
etc.:	Et cetera
FC:	Field capacity
Fig.:	Figure
FM:	Fresh matter
Fp:	Farmer`s practice
g:	Gram
GIS:	Geographic Information System

GS:	Growth stage
h:	Hour
ha:	Hectare
HI:	Harvest Index
IDW:	Inverse distance weighting
i.e.:	That is
IRTG:	International Research Training Group
K:	Potassium
kg:	Kilogram
km:	Kilometre
km^2:	Square kilometre
kPa:	Kilopascal
l:	Litre
LAI:	Leaf area index
LL:	Lower limit of soil water
m:	Metre
m^2:	Square metre
m^3:	Cubic metre
mg:	Milligram
MJ:	Mega Joule
mm:	Millimetre
N:	Nitrogen
NCP:	North China Plain
NH_3:	Ammonia
NIRS:	Near infrared spectroscopy
NO_3^-:	Nitrate
NO_3^--N:	Nitrate nitrogen
N_{min}:	Soil available mineral nitrogen
NUE:	Nitrogen use efficiency
P:	Phosphor
QZ:	Quzhou
R:	Pearson correlation coefficient
r^2:	Coefficient of determination

Re:	Reduced input
RE:	Revenue
resp.:	Respectively
RMB:	Renminbi (Chinese currency)
RMSE:	Root mean square error
SAT:	Saturated limit of available soil water
SNK:	Student-Newmann-Kuels
SpMM:	Spring maize monoculture
SUCROS:	Simple and Universal Crop growth Simulator
Swm:	Soil water measurements
SWC:	Soil water content
t:	Ton
Tab.:	Table
TDR:	Time Domain Reflectometry
TKM:	Thousand kernel mass
TM:	Trockenmasse
usw.:	Und so weiter
V.:	Version
var:	Variety
vs.:	Versus
WQ:	Wuqiao
WUE:	Water use efficiency
yr:	year
z.B.:	Zum Beispiel
°C:	Degree centigrade
°E:	Degree East
°N:	Degree North
¥:	Yuan (Renminbi unit)
%:	Percent
3H2Y:	Three harvests in two years

1 GENERAL INTRODUCTION

China is the world's most populous country with about 1.3 billion people and it is estimated that in the year 2030 Chinas population will increase to about 1.6 billion people (Yuping, 2001). With a cultivated area of 94 million ha (Länderbericht China, 2000) Chinas agricultural area is relatively small compared to its population, leading to a substantial limit in land area available for food production. There is also the fact that China is not particularly well endowed with water (Lohmar et al., 2003). Water resources in China are abundant in the south but scarce in the north, especially in the North China Plain (NCP) (World Bank Group, 2001). The per capita water resource availability in China is only about one quarter of the world average (Hubacek and Sun, 2005).

During the last decades, food demand in China increased substantially due to an increase in population and a strong economic growth (Tongeren and Huang, 2004). Facing the problem of a still rising population interrelated with a limited land area and water scarcity, agriculture has undergone and is still undergoing dramatic changes. In order to achieve the goal of self-sufficiency (Huang, 1998), high yields have to be produced on a limited land area. Over the last decades this has resulted in high inputs of nitrogen and irrigation water in order to achieve high yields.

Chinas grain production increased steadily during the last decades. This increase was attributed with an increased use of irrigation water and mineral fertilizer, especially nitrogen (Böning-Zilkens, 2003; Chen et al., 2006x). About three fourth of Chinas grain production comes from irrigated land, accounting for 40 % of Chinas total arable land (Zhang, 1999). With around 70 % of the total water consumption, agriculture uses the largest share of water (Jin and Yong, 2001). Beside irrigation, fertilization contributes up to 50-60 % to the total increase in grain yield in China (Lu and Shi, 1998). This intensification has been correlated with dramatic environmental problems (Deng et al., 2006). The expansion in irrigation has lead to a steady decrease in groundwater tables (Jia and Liu, 2002; Sun et al., 2006). Furthermore high amounts of N-fertilizer and a poor utilisation rate have lead to nitrate leaching and the pollution of ground and drinking water (Zhang et al., 1995; Jia et al., 2004; Ju et al., 2004). Because of these environmental problems, agriculture in the NCP got under great pressure and is facing an unprecedented challenge for its future (Yang and Zehnder, 2001).

One of the central goals of Chinas national policy is food security (Sonntag et al., 2005). To keep pace with an increased food demand of a rising population, food production in China will have to increase continually (Huang et al., 1999). Due to the limitations on arable land, an increase in productivity will be the primary source to maintain a high food-self-sufficiency level (Nyberg and Rozell, 1999). However, increases in yields will no longer be possible by further increasing the amount of N-fertilizer or irrigation water. Therefore new strategies and cropping systems have to be developed.

The International Research Training Group (IRTG) of the University of Hohenheim and the China Agricultural University, entitled "Modeling Material Flows and Production Systems for Sustainable Resource Use in the North China Plain" was launched in 2004. The major hypothesis was "that adjustments in cropping systems and management practices provide potential for sustainable resource protection on a high yield level".

In the framework of the IRTG-project different field experiments were implemented in the NCP since 2004. Chinese and German scientists were involved in altogether 11 subprojects. Research topics ranged from material flows, pollution analysis to cropping systems and farm level, regional and sectoral assessment. More information can be found at http://rtgchina.uni-hohenheim.de. The research work was sponsored by the German Research Foundation (DFG) [GRK 1070] and the Ministry of Education (MOE) of the People's Republic of China.

The research programme was conducted in one of the most important economic and agricultural regions in China, the NCP. The NCP is located in the north of the eastern part of China and includes the provinces Hebei, Shandong, Jiangsu, Henan and Anhui as well as the cities Beijing and Tianjin (Fig. 1). The total area amounts 350000 km² (Zhang et al., 2004). One-fifth of Chinas food production is produced on this plain (Zhang et al., 1999; Chen, 2003; Deng et al., 2006).

The weather in the NCP is dominated by a typical continental monsoon climate. The mean annual temperature ranges between 10-14 °C (Mack, 2005). Although the average annual precipitation ranges from 500 to 650 mm, about 70 % of the total amount falls in the summer months July to September (Fig. 2) (Zhang et al., 1999). Therefore water is one of the most limiting factors for crop production (Zhang et al., 1999; Wang et al., 2001; Chen, 2003; Zhang et al., 2004).

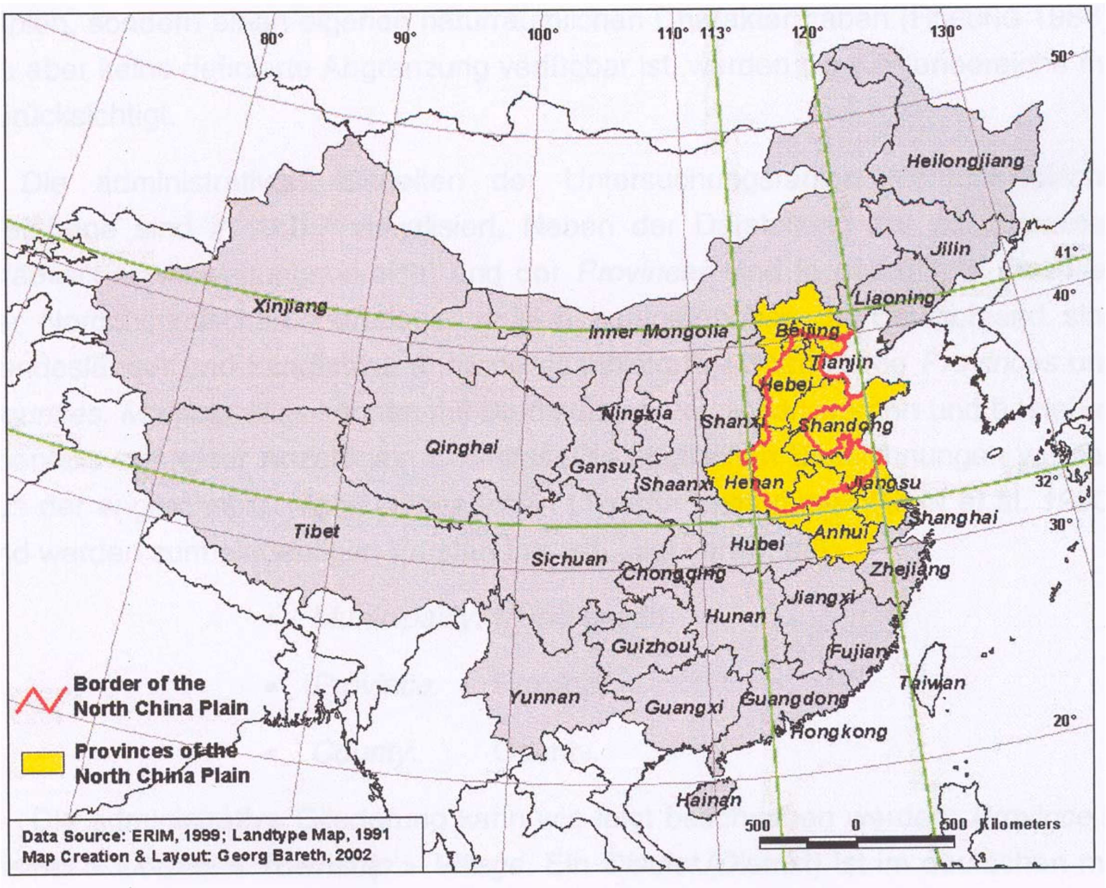


Fig. 1. Location of the North China Plain within China. (Source: Bareth 2003).

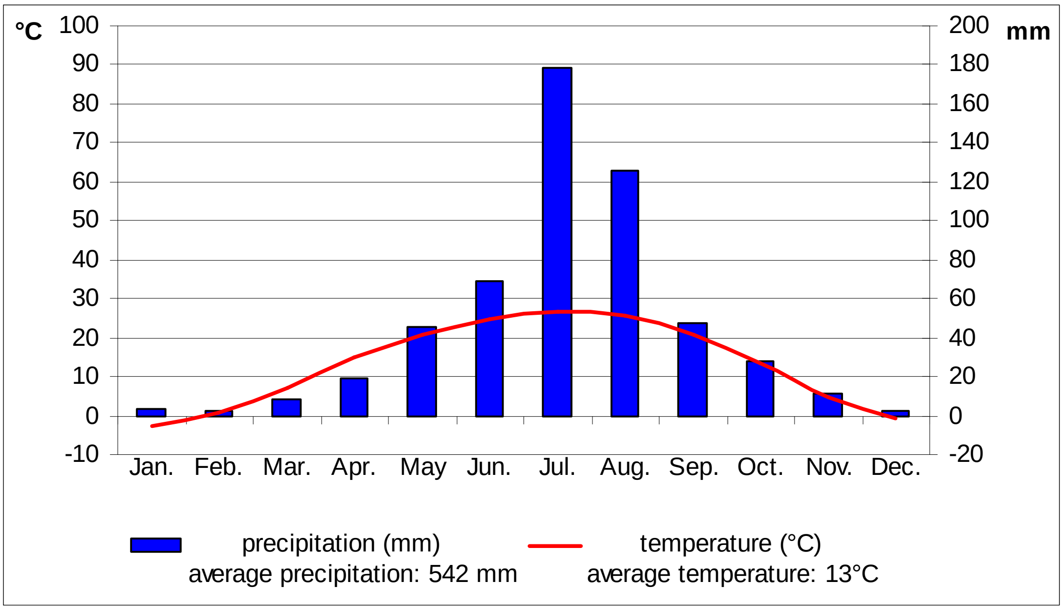


Fig. 2. Climate-diagram for Beijing (mean values 1988-2003) (Source: CSY 1988-2003).

Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) are currently the main cultivated crops in the NCP (Yang and Janssen, 1997; Liu et al., 2001). The two crops are cultivated in a so called double cropping system which is currently the most important agricultural production system in the NCP (Zhao et al., 2006). The double cropping system consists of growing two crops in one year (Yang and Janssen, 1997). Winter wheat is sown in mid October and harvested in mid June. After winter wheat harvest summer maize is sown and harvested at the beginning of October. Winter wheat production depends on a supplemental irrigation (Liu et al., 2001), because precipitation is concentrated in the summer months during the maize growing season (Zhang et al., 1999; Yang and Zehnder, 2001; Zhang et al., 2005). Due to the fact that two crops are grown within a year, the double cropping system realises high yield levels.

The light and heat conditions in the NCP are suitable for growing two crops within a year. However, the water-related conditions permit many areas to grow only one crop a year or three crops in two years (Yang, 1991). A possible system for growing one crop per year is the single cultivation of spring maize. Spring maize is sown in the middle of April and harvested at the end of September. The remaining time of the year the field lies under fallow. As the rainy season coincides with the main part of the maize growing season, relative low amounts of irrigation water may be required for spring maize production. Due to the longer growing season spring maize may realise higher yields in comparison to summer maize. However, the total yield of double copping winter wheat and summer maize may be higher.

The system three harvests in two years forms a balance between the double cropping of winter wheat and summer maize and the single cropping of spring maize. In the first year the double cropping system with growing winter wheat from October until June followed by summer maize from June until September is practiced. Afterwards a fallow period follows. Spring maize is cultivated in the second year from April until September before the rotation starts again with winter wheat. Due to the fact that three crops are grown in two years, total yield is higher in comparison to the single cropping of spring maize (two harvests in two years) but lower in comparison to the double cropping system (four harvests in two years). However, the lower cropping index in contrast to the double cropping of wheat and maize results in a lower demand of the input factors irrigation water and N-fertilizer whereas in comparison to the single cropping of spring maize a higher amount of input factors is required.

Traditionally a large proportion of the area planted with crops in the NCP had been cropped with cereals, but the proportion declined. In the last years an increasing area of land was being diverted into vegetable and fruit production. During the last decade the area cultivated with fruits and vegetables in China increased by 1.3 million ha^{-1} (Gullino et al., 2006). Similar in the NCP the area cropped with vegetables increased from 1.2 million ha^{-1} in 1984 to 6.9 million ha^{-1} in 2003. However, with 27 % respectively 17 % of the total sown area wheat and maize are still the two dominant crops (CSY, 1984 and 2004). The development of the sown area for the individual crops in the NCP during the last two decades is shown in Figure 3.

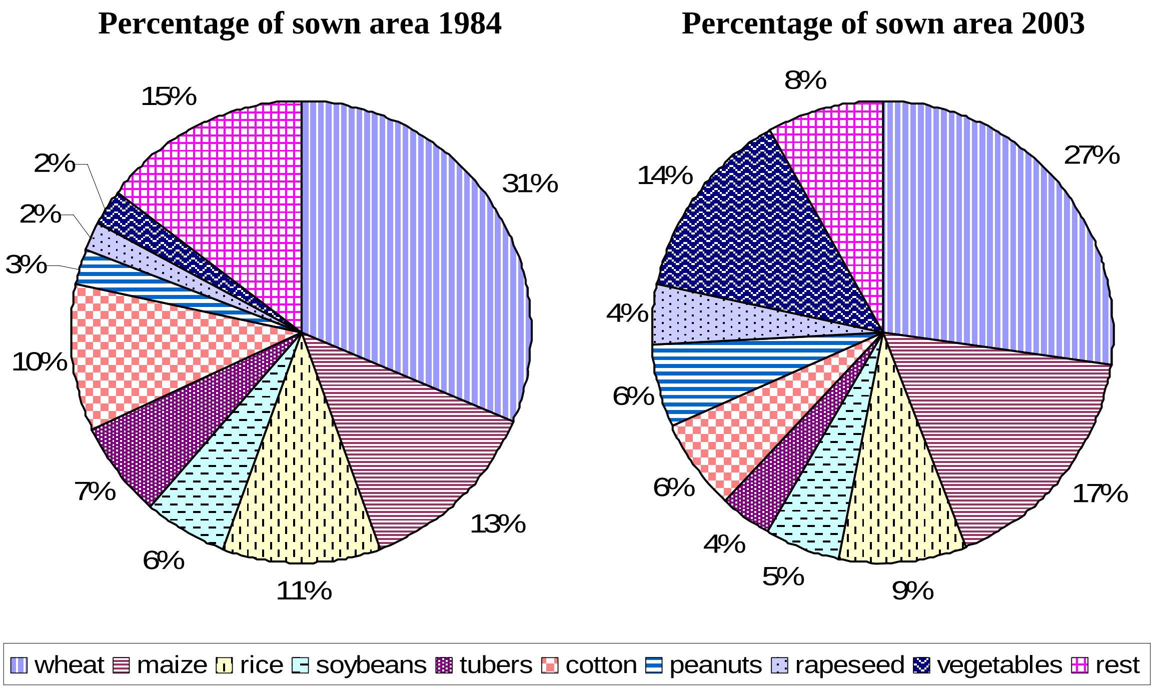


Fig. 3. Percentage of sown area for the individual crops in the NCP in the years 1984 and 2003 (Source: CSY 1984-2003).

Extensive use of irrigation water and nitrogen fertilizer is very common in the winter wheat summer maize double cropping system. In Beijing area, for example, the average N-application rates range around 309 kg N ha^{-1} for winter wheat and 256 kg N ha^{-1} for maize (Zhao et al., 1997). In Huantai County (a high-yielding area) of Shandong Province, 600 kg N $ha^{-1}a^{-1}$ are often applied (Gao et al., 1999). The irrigation application amounts about 200-300 mm (Zhang and You, 1996). However, such an excessive use of irrigation water and N-fertilizer may result in low water use efficiency (WUE) respectively nitrogen use efficiency (NUE) and exerts a high pressure on the environment. Therefore, conserving irrigation water and reducing the N-fertilization is the most important measure for a more productive and sustainable resource use in the NCP.

This Ph.D. thesis was originated in the context of subproject 2.1a "Optimizing Irrigation and N-fertilization for Sustainable Cropping Systems in the North China Plain" of the IRTG. The main objects of this subproject were to test the effects of changes in management practices and cropping systems on grain yield and sustainability by the use of field experiments, crop models and a Geographic Information System (GIS).

The specific objectives of the Ph. D. thesis were to:

- analyze the changes in yield performance of the two main crops winter wheat and summer maize in the NCP during the last 20 years,
- assess the actual cropping system and the trend towards new cropping systems in the NCP,
- evaluate CERES-Wheat and CERES-Maize for their ability to simulate wheat respectively maize growth and yield under the conditions of the NCP,
- demonstrate the potential of using crop growth models to improve sustainability related to water use in the NCP,
- determine the production potential of summer maize and spring maize in the NCP by using a GIS to regionalize obtained results over the whole NCP.

This thesis consists of five papers printed, accepted or submitted to international high standard referenced journals. The articles are presented in the chapters 4-8. They are written in a way that each can be read independently although they are closely connected by the overall goal to reduce irrigation water supply and to develop sustainable cropping systems in the NCP. The articles stretch out the different possibilities to achieve this goal.

In the first article an overview over the development of agriculture in the NCP over the years 1984 till 2003 is given. The changes in cultivated land, grain yields, fertilization and irrigation were analysed for the two main crops wheat and maize. The actual cropping system (double cropping winter wheat and summer maize) is presented. The advantages and disadvantages of this system are described and an alternative cropping system was worked out (single cropping of spring maize).

Based on the results of the first article, the second article deals with the reduction of the irrigation amount during the winter wheat growing season by maintaining high yields in the double cropping system. For this purpose the two crop growth models CERES-Wheat and CERES-Maize, embedded in DSSAT, were calibrated and different strategies for reducing the irrigation amount were tested.

In a more complex approach in the third article besides the irrigation amount also the irrigation frequency and irrigation time were considered. The models CERES-Wheat and CERES-Maize were calibrated and validated. Afterwards a gross margin analysis of the different irrigation and N-fertilizer treatments were carried out. In a next step the treatment with the highest economical profit was used as a starting point to simulate different irrigation scenarios and their effects on grain yield, water consumption and gross margin.

Besides the reduction of the irrigation water amount, also agronomic adaptations within the cropping system itself e.g. a lower sowing density or a reduction in the cropping index could help to save water. In the fourth article the cropping systems three harvests in two years (double cropping winter wheat and summer maize in the first year followed by only spring maize in the second year) and the single cultivation of spring maize were evaluated. The two systems were compared regarding grain yield, NUE, WUE and gross margin.

Maize was found to be one of the most important crops in China, not as food but as feed grain. Besides, maize plays an important role in the cropping systems mentioned before (double cropping system, three harvests in two years, single cultivation of spring maize). Therefore the fifth article aims to determine the production potential of summer maize and spring maize in the NCP by using the CERES-Maize model. The model was calibrated and validated. Temporal and spatial climate variability was taken into account by using up to 30 years of weather data from 14 meteorological stations across the NCP. Simulations were carried out for five different soil texture classes (sand, sandy loam, loam, silt loam and silt). Results were linked to a GIS.

2 FIELD EXPERIMENTS

Field experiments were set up on three locations in the NCP, namely Dongbeiwang, Wuqiao and Quzhou (Fig. 4). The locations were selected in the way that they are well distributed over the NCP and differ in climate and soil conditions. General information on the environments of the locations is given in Table 1.

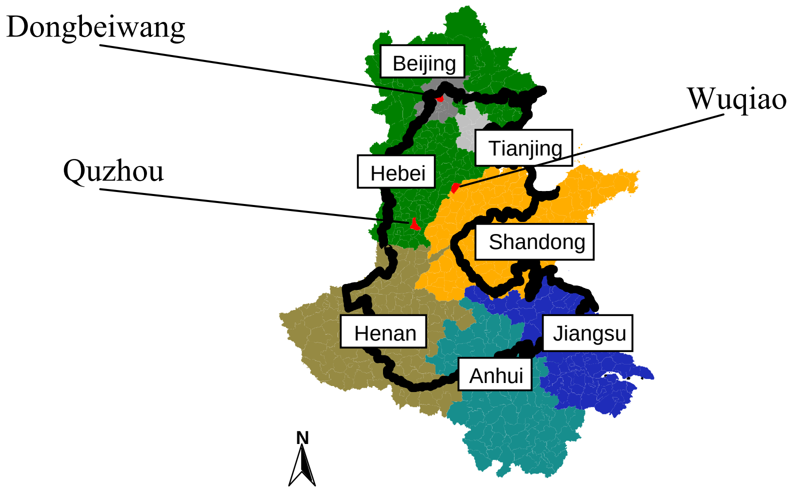


Fig. 4. Experimental locations Dongbeiwang, Wuqiao and Quzhou in the North China Plain (Source: Bareth 2003, adapted and modified).

Table 1. Characterization of the experimental locations Dongbeiwang, Wuqiao and Quzhou (Source: IRTG-Master plan 2005, adapted and modified).

	Dongbeiwang	Wuqiao	Quzhou
Geographical situation	in the north-west of Beijing (40.0° N, 116.3° E)	250 km south of Beijing (37.3° N, 116.3° E)	400 km south-west of Beijing (36.5° N, 115.0° E)
Long-term average			
Air temperature	11.5 °C	12.6 °C	13.2 °C
Precipitation	627 mm	562 mm	514 mm
Soil	silt loam	sandy clay	silt loam

On each location five respectively six different treatments were tested. The different treatments were:

1. *Farmer's practice:* double cropping of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) as practiced on farms in the NCP with a high input of N-fertilizer and irrigation water
2. *Reduced input:* double cropping of winter wheat and summer maize with reduced N-fertilization and irrigation
3. *Three harvests in two years:* winter wheat and summer maize in the first year, spring maize in the second year, N-fertilization and irrigation were carried out under conditions of reduced input
4. *Continuous spring maize:* spring maize monoculture, N-fertilization and irrigation were carried out under conditions of reduced input
5. *Vegetables:* transplanted spring cabbage (*Brassica oleracea* L. var. *capitata* L.), intercropped spring maize and spinach (*Spinacia oleracea*) during one year
6. *Wuqiao system:* double cropping of winter wheat and summer maize, mineral and organic N-fertilizer and a lower irrigation amount in comparison to farmer's practice were applied (only tested at the location Wuqiao)

(Source: IRTG-Master plan 2005, adapted and modified)

The different cropping systems with their crops and the growing duration of the single crops are illustrated in Figure 5.

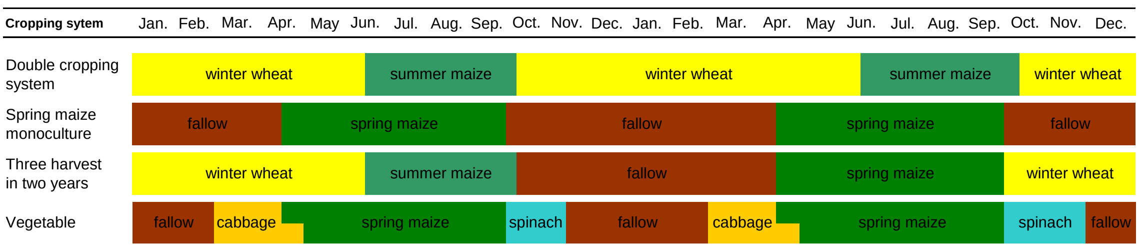


Fig. 5. Growing duration of single crops within the different cropping systems.

In the double cropping system winter wheat was sown with a drilling machine at the beginning of October. The aspired plant density was about 450 plants m^{-2}. The row space amounted 15 cm at the Dongbeiwang and Quzhou site and 20 cm at the Wuqiao site. For seed bed preparation a rotary tiller was used with a working depth of 25 cm. Winter wheat was harvested by hand at the beginning of June. The straw was left on the field, chopped and equally distributed as straw mulch. Afterwards summer maize was sown directly in the wheat stubble. Sowing was done by hand with a row space of 70 cm. The aspired plant density was 6.5 plants m^{-2}. However, to guarantee emergence and establishment maize was sown with double density. At the five leaf stage a manual reduction to the final plant density was carried out. Summer maize was harvested at the end of September or beginning of October. The straw was left on the field, chopped and equally distributed as straw mulch. Afterwards the field was ploughed with a working depth of about 30 cm.

Spring maize, cultivated as a single crop, was sown after seed bed preparation with a rotary tiller at the middle of April. Row space was 70 cm and the aspired plant density was 7.0 plants m^{-2}. To guarantee emergence and establishment maize was sown with double density. At the five leaf stage a manual reduction to the final plant density was carried out. Spring maize harvest was done by hand at the end of September. The maize straw was left on the field, chopped and equally distributed as straw mulch. Before the start of the fallow period, the field was ploughed with a working depth of about 30 cm.

In the system three harvests in two years sowing, harvest and tillage were similar to the double cropping system respectively the single cultivation of spring maize. In the first year the double cropping system with growing winter wheat from October until June followed by summer maize from June until September was practiced. Afterwards a fallow period followed. Spring maize was cultivated in the second year from April until September before the rotation started again with winter wheat.

The vegetable crop rotation started with spring cabbage, transplanted in five to six true leaves unfolded stage in the middle of March. The aspired plant density was 7.1 plants m^{-2} and the row space 35 cm. Before transplanting the field was prepared with a rotary tiller. Cabbage harvest occurred at the end of April by hand. Spring maize was intercropped about 10 days before cabbage harvest. Row space for maize was 70 cm (every second inter row of cabbage) and the aspired plant density 7.0 plant m^{-2}. To guarantee emergence and establishment maize was sown with double density. At the

five leaf stage a manual reduction to the final plant density was carried out. Spring maize harvest was carried out by hand at the end of September. The maize straw was removed to secure a fine seed bed preparation for spinach. Before spinach sowing the field was ploughed. Afterwards seed bed preparation was done by hand. Spinach was sown at the beginning of October with an aspired density of around 85 plants m^{-2} and a row space of 24 cm. The harvest occurred at the beginning of November by hand.
The genotypes selected for the single crops were representative for the local regions. Therefore the three locations partly differed in the cultivated genotypes. Detailed information on selected genotypes, sowing dates, plant densities, row spaces and sowing depths for the single crops are given in Table 2.

Table 2. Genotype, aspired planting date, planting density, row spacing and sowing depth for winter wheat, summer maize, spring maize, spring cabbage and spinach for the locations Dongbeiwang, Wuqiao and Quzhou (Source: IRTG-Master plan 2005, adapted and modified).

Cultivar	Location	Genotype	Aspired planting date	Aspired plant density	Aspired sowing depth	Aspired row space
Winter wheat	Dongbeiwang Wuqiao Quzhou	Jingdong 8 Shijiazhuang 8	10. Oct. 05. Oct.	450 plants m^{-2}	3 cm	20 cm 15 cm
Summer maize	Dongbeiwang Wuqiao Quzhou	CF 024 Zhengdan 958	20. Jun. 10. Jun. 08. Jun.	6.5 plants m^{-2}	5 cm	70 cm
Spring maize	Dongbeiwang Wuqiao Quzhou	CF 1505	20. Apr. 15. Apr. 13. Apr.	7.0 plants m^{-2}	5 cm	70 cm
Spring cabbage	Dongbeiwang Wuqiao Quzhou	Zhonggan 8398	10.-15. May 05.-10. May	7.1 plants m^{-2}	transplanted (5-6 leaves stage)	35 cm
Spinach	Dongbeiwang Wuqiao Quzhou	Boza 18	10. Sep.	~ 85 plants m^{-2}	2 cm	24 cm

Besides the comparison of different cropping systems, the traditional double cropping system of winter wheat and summer maize as it is practiced by the farmers in the NCP with a high input of nitrogen fertilizer and irrigation water was compared with a system of reduced input.
In the traditional system, termed as "Farmer's practice", 300 kg ha^{-1} nitrogen fertilizer were added to winter wheat (150 kg N ha^{-1} at sowing and 150 kg N ha^{-1} at the beginning

of shooting). Summer maize obtained 250 kg N ha^{-1} (100 kg N ha^{-1} at sowing and 150 kg N ha^{-1} at shooting). Winter wheat was irrigated with 300-315 mm split up in four applications (75 mm after sowing, 75-90 mm after regreening stage, 75 mm at shooting stage and 75 mm at early milking stage). On average summer maize was not irrigated if enough water was available to ensure proper germination and establishment.

In the treatments "Reduced input", "Three harvests in two years" as well as "Continuous spring maize" N-fertilization was based on N_{min}-measurements and target yield. The predicted total N-uptake of winter wheat was 30 kg N t^{-1} grain yield and for summer and spring maize 25 kg N t^{-1} grain yield. For winter wheat fertilizer was broadcast before sowing and at end of tillering in combination with irrigation. In maize, N-fertilization was carried out at four leaf stage and six nodes detectable stage. For winter wheat, irrigation was based on measurements of volumetric soil water content aiming to keep the available field capacity between 45 and 80 % during sensitive growth stages (tillering, early shooting, booting and grain filling). Summer maize was not irrigated if enough water was available to ensure proper germination and establishment. For spring maize, it was necessary to irrigate before planting and at six nodes detectable stage to ensure proper germination, establishment and nutrient supply out of applied mineral fertilizer.

In the treatment "Wuqiao system" a part of the mineral fertilizer was replaced by manure. 150 kg N ha^{-1} in mineral form and additionally 30 t FM ha^{-1} of manure were added to winter wheat. Manure was broadcast and incorporated prior to seeding. Due do the lasting effect of the manure, only 120 kg N ha^{-1} in mineral form were applied to summer maize, split into two applications (40 kg N ha^{-1} at seeding and 80 kg N ha^{-1} at shooting). In this treatment winter wheat was irrigated with 260 mm split into four applications. Summer maize was not irrigated if enough water was available to ensure proper germination and establishment.

The vegetable crop rotation in the experiment included spring cabbage, spring maize and spinach. The irrigation and N-fertilization for spring maize was similar to the treatment "Continuous spring maize". To spring cabbage 6 t FM ha^{-1} organic manure were applied before ploughing. Afterwards N-fertilization was based on N_{min}-measurements. The target value for N-supply was 350 kg N ha^{-1}. The difference between measured and target value was applied before planting and at initial stage of heading. Considering the predicted uptake (soil layer 0-30 cm) the target soil nitrate value at planting was 60 kg N ha^{-1}. In spinach, N-fertilization was based on N_{min}-measurements at planting. The target value of N-supply including measured soil nitrate N was 220-240 kg N ha^{-1}. For cabbage and spinach irrigation was similar. Depending on the precipitation 90-180 mm were applied. Based on the weather data respectively TDR data the soil water tension should not fall below -23 kPa in 23 cm depth otherwise the field was irrigated. For cabbage the amount of irrigated water per event before heading was 25 mm and after heading 35 mm. Spinach was always irrigated with an amount of 25 mm.

In winter wheat, summer maize and spring maize nitrogen was given as urea respectively manure. For the vegetables spring cabbage as well as spinach ammoniumphosphat was used as well as manure. Irrigation was carried out in all treatments by border irrigation. The management of irrigation and N-fertilization for the different crops and systems is summarized in Table 3. At all three locations weed and pest control was done by hand or by using suitable and local available herbicides respectively pesticides. Detailed information on the management of the field experiments can be found in the IRTG-Master plan (2005).

Table 3. N-fertilization and irrigation management in different treatments of double cropping winter wheat and summer maize (A); N-fertilization and irrigation practice in spring maize, spring cabbage and spinach (B) (Source: IRTG-Master plan 2005, adapted and modified).

A

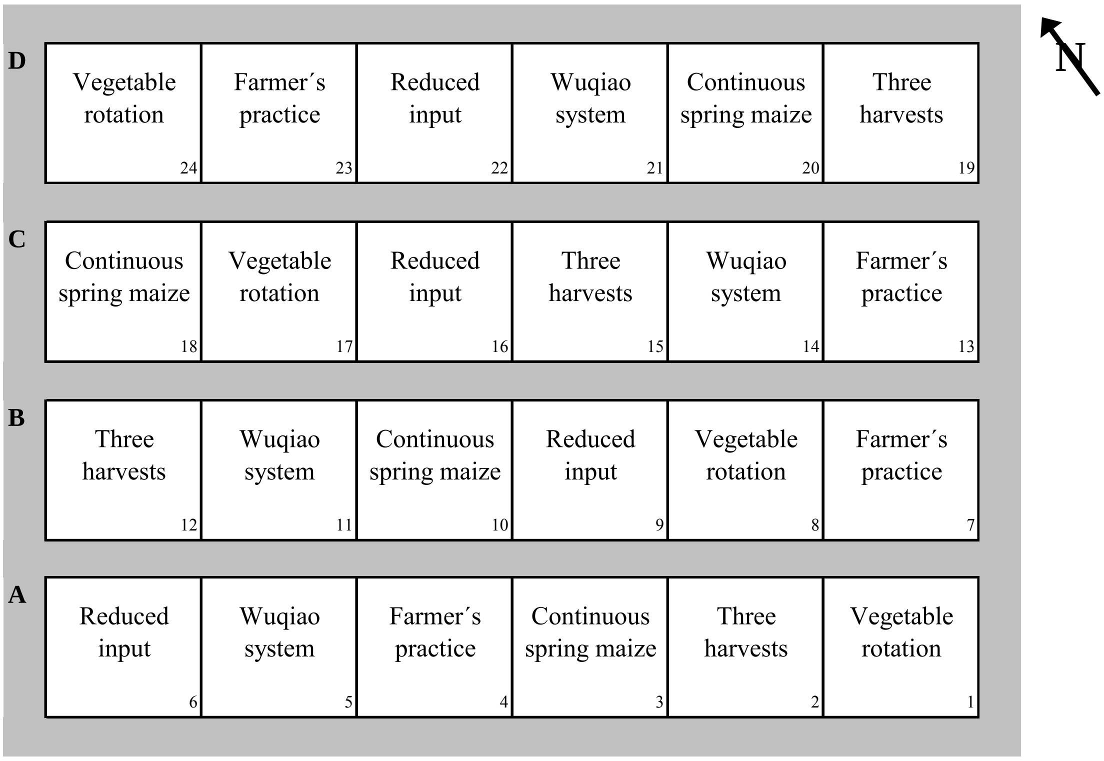
		Total amount	Winter wheat	Summer maize
Farmer´s paractice	N-fertilization	550 kg N ha^{-1}	300 kg N ha^{-1}	250 kg N ha^{-1}
	irrigation	300-315 mm*	300-315 mm*	if required
Reduced input	N-fertilization	based on N_{min}-measurements and target yield		
	irrigation	based on measurements of volumetric soil water content aiming to keep the available field capacity between 45 and 80% during sensitve stages		if required
Wuqiao System	N-fertilization	270 kg N ha^{-1} + 30 t FM ha^{-1} organic manure	150 kg N ha^{-1}(mineral) 30 t FM ha^{-1} (organic)	120 kg N ha^{-1} (mineral)
	irrigation	225 mm	225 mm	if required

* 315 mm in Dongbeiwang, 300 mm in Wuqiao and Quzhou

B

Spring maize	N-fertilization	based on N_{min}-measurements and target yield
	irrigation	if required
Spring cabbage	N-fertilization	6 t ha^{-1} FM (organic manure) + N_{min}-measurements
	irrigation	90-180 mm depending on precipitation
Spinach	N-fertilization	N_{min}-measurements
	irrigation	90-180 mm depending on precipitation

On each site the field experiment was designed as a completely randomized one factorial block design. In Figure 6 exemplary the field plan of the Wuqiao site is shown.



A-D: block; 1-24: plot numbers; ▢ : rim

Fig. 6. Field plan of Wuqiao site (Source: IRTG-Master plan 2005, adapted and modified).

Several crop parameters including emergence, hibernation, different growth stages, leaf area index, biomass development, grain yield and yield parameters were determined during the vegetation period for the crops winter wheat, summer maize and spring maize by subproject 2.1a. A description for measuring the single parameters is given in Table 4. The vegetable treatment was attended by another subproject. Beside the crop parameters numerous measurements regarding soil water-content, N_{min}-content, N-deposition and nitrate leaching were carried out by other subprojects. Detailed information can be found in IRTG-Master plan (2005).

Table 4. Determined crop parameters and their measurements (Source: IRTG-Master plan 2005, adapted and modified).

Parameter	**Determination**
Emergence / hibernation	with test strips wheat: double row of 3 m length maize: double row of 2 m length
Growth stages (GS) / plant development	according to BBCH scale (Meier, 1997) wheat: planting, emergence, regreening, beginning of shooting, mid boot stage, full flowering, medium milk, harvest maize: planting, emergence, 3 leaves unfolded, beginning of stem elongation, flowering, medium milk, harvest
Leaf area index (LAI)	with LI-COR LAI-2000 (*LI-COR* , Lincoln, USA) or measured by hand according to Wei and Dong (2001) LAI was determined in the mentioned GS (last five)
Time harvests	for each crop in the mentioned GS (last five) harvest area: 0.4 resp. 1 m² for each plot plants were divide in leaf, stem and grain for singel plant parts fresh matter and dry matter were determined plants were dried for 24 h at 105°C
Final harvest	half of each plot subtracting a surrounding rim of one meter was harvested (Dongbeiwang 20 m², Wuqiao 9 m², Quzhou 12 m²) plants were separated; grains and kernels were thresed and dried (24 h, 105°C) to obtain total dry matter
Yield components	separate samples (three times 1 m² from each plot) were taken for counting ear number, grains ear^{-1} and kernels cob^{-1}; TKM was determined by counting three times 500 kernels of each plot
C- and N-content	plant parts from time and final harvests were analysed using NIRS-System 5000 (*Foss* Rellingen, Germany); evaluation of the results was done with Win-ISI software (*Foss* , Rellingen, Germany)

3 PROCESS-ORIENTED CROP GROWTH MODELS

In the present research field experiments were conducted at particular points in time and space. However, field experiments are time consuming, laborious and expensive (Jones et al., 2003) and therefore are limited in extent and size. A viable alternative to these problems is the use of crop growth models. Crop growth models are useful tools to quantify the effects of management practices on crop growth, productivity and sustainability of agricultural production (e.g. Pala et al., 1996; Saseendran et al., 2005). They can help to reduce the needs for field experimentation by the extrapolation of research results conducted in one season or location to other seasons, locations and management practices (Pathak et al., 2004).

Models can be defined as an imitation of the reality (Hanks and Ritchie, 1991), but it seems impossible to include all the relations between the environment and the model system. For that reason a model is only a simplification of the real-world system (Hoogenboom, 2000). Therefore for using models a correct understanding of the limitations is important.

Simulation models form a group of models that are designed to guide our understanding of how a system responds to a given set of conditions. They simulate the behaviour of a crop by predicting the growth of its components. Crop simulation models are increasingly being used in agriculture as a tool for managing agricultural systems and for a better understanding of the processes involved in crop production.

The crop growth simulation models can be divided in those which are more mechanistic such as SUCROS (Penning de Vries and Laar, 1982) and those which are more process-oriented such as CERES-Maize (Jones and Kiniry, 1986), CropSyst (Stockle et al., 1994) or EPIC (Williams et al., 1984). In process-oriented models predictions rely on the base of previous experience without knowing the processes whereas the more mechanistic models attempt to represent the physical causes of responses to conditions.

Independent of the category, models include many assumptions, especially when information is inadequate or does not exist (Hoogenboom, 2000). Therefore modeling necessitates adjustments in the form of calibration so that model predictions are close to observed values. After model calibration a validation follows to detect the degree of agreement between predictions of the calibrated model and the observed values. Model validation involves the use of the model with the calibrated values without making any further adjustments of the constants (Gungula et al., 2003).

The DSSAT model (Decision Support Systems for Agrotechnology Transfer) is one of the most widely used modeling systems across the world. The DSSAT software includes the CERES and *GRO models and grew out of previous single-crop models. Altogether the DSSAT package incorporates models of 16 different crops. In DSSAT, the original crop growth models are restructured to a set of sub-modules (soil, crop template, weather and competition) to facilitate a more efficient incorporation of new scientific advances, applications, documentations and maintenance. Jones et al. (2003) described DSSAT as a collection of autonomous programs that work together. Crop simulation models are the centre in this cooperation (Fig. 7).

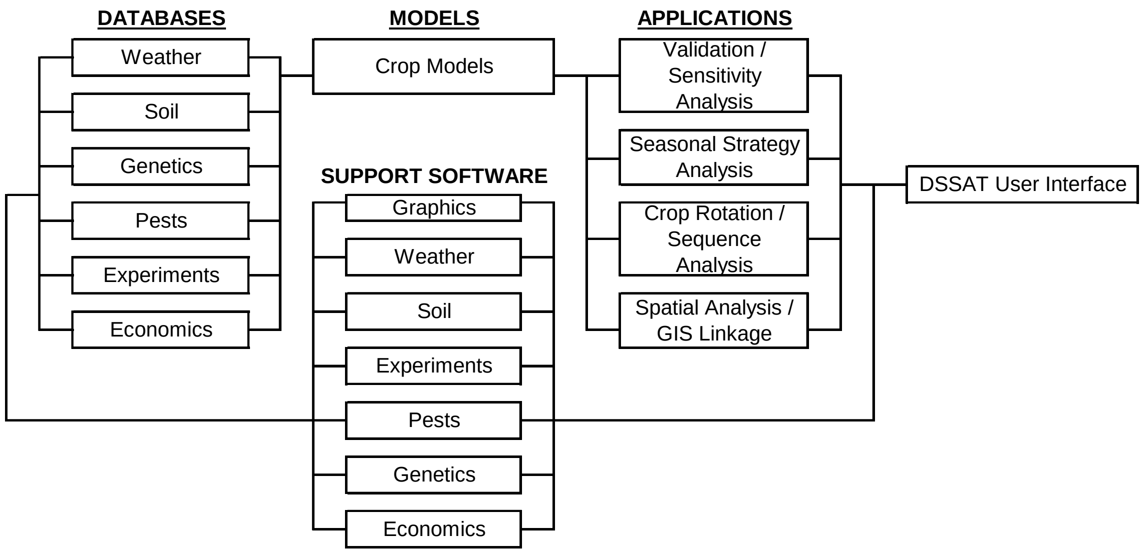


Fig. 7. Diagram of database, application and support software components and their use with crop models for applications in DSSAT V.3.5 (Source: Jones et al. 2003).

The models CERES-Maize and CERES-Wheat, embedded within DSSAT, were used in this thesis. Both models are process-based and management-oriented and simulate the growth and development of maize respectively wheat in a daily time step. The models include the major processes (phenologic development, canopy development, organ formation, photosynthesis, assimilate allocation as well as carbon, water and nitrogen dynamics in the soil and in the plant) governing growth and development. Therefore, the models can simulate the effects of weather, soil water and nitrogen dynamics on growth and yield for individual cultivars. The carbon subroutine of the model is based on Godwin and Singh (1998), the nitrogen subroutine is calculated according to Godwin and Jones (1991), whereas the water movement is based on Ritchie (1998). Crop development is primarily based on growing degree-days, whereas leaf and stem growth rates are calculated depending on phenological stages. CERES-Maize and CERES-Wheat have been used all over the world to successfully estimate grain yield (Otter-Nacke et al., 1986; Hodeges et al., 1987; Wu et al., 1989; Kovacs et al., 1995; Ritchie et al., 1998).

For running the models a minimum data set is required (Jones et al., 2003). The minimum data set consists of weather, soil and management data. The minimum weather data includes daily values of maximum and minimum air temperature, solar radiation and precipitation. Soil input data comprises albedo, upper flux limit of the first stage of soil evaporation, drainage coefficient, runoff curve number and for each soil layer, information on the limit of lower soil water content, drained upper soil water content, field-saturated soil water content and the relative distribution of root growth. If the data are not available, a general description of the physical and chemical characteristics of the soil might be sufficient to estimate the required parameters (Jame and Cutforth, 1996). Crop genetic coefficients are also needed to simulate the difference among varieties. The needed genetic coefficients for wheat and maize are given in Table 5. In this thesis data for modeling were derived from the IRTG-experiments and from Bönning-Zilkens (2003).

Table 5. Genetic coefficients for wheat and maize in DSSAT (Source: Jones et al. 2003).

Wheat	
Paramters	**Description**
P1V	days at optimum vernalizing temperature required to complete vernalization
P1D	percentage reduction in development rate in a photoperiod 10 hour shorter than the optimum relative to that at the optimum
P5	grain filling (excluding lag) period duration (°C.d)
G1	kernel number per unit canopy weight at anthesis (1/g)
G2	standard kernel size under optimum conditions (mg)
G3	standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g)
PHINT	phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

Maize	
Paramters	**Description**
P1	thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photerperiod
P2	extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours)
P5	thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)
G2	maximum possible number of kernels per plant
G3	kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances

*In the **first article** a picture is sketched of the development of Chinese agriculture in the NCP since 1984 up to 2003. On the base of the two main crops wheat and maize changes in cultivated land, grain yields, fertilization and irrigation are evaluated and presented. Furthermore, the actual cropping system (double cropping winter wheat and summer maize) with its advantages and disadvantages is described and an alternative cropping system (single cropping of spring maize) was worked out.*

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An Empirical Evaluation of Yield Performance and Water Saving Strategies in a Winter Wheat - Summer Maize Double Cropping System in the North China Plain

Eine empirische Bewertung von Ertragsleistung und Wassereinsparungsmaßnahmen in einem Winterweizen-Sommermais Double-Cropping System in der Nordchinesischen Tiefebene

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Summary

The North China Plain (NCP) is one of the major agricultural regions in China. Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) are currently the two main crops combined in a single-year rotation also referred to as a double cropping system. Grain production in the NCP has experienced multiple changes over the last decades due to many factors including shortages in water resources, government policy, etc.. This paper analyzes the changes in yield performance of wheat and maize during 1984-2003. Results showed that in general a more intensive use of productive inputs seemed to be associated with higher yields. Further results clearly indicated that water shortage is currently the main problem in the traditional double cropping system and can endanger the desired self-sufficiency of China in the future. Therefore future profound policy changes may make the question of yield performance as important as the questions to adopt new crops or new cropping systems. This study suggests that changes from the traditional double cropping system to single spring maize cultivation might solve parts of the water shortage problems while maintaining at the same time high yields.

Key words: double cropping system, winter wheat, summer maize, North China Plain, water shortage

Zusammenfassung

Die Nordchinesische Tiefebene (NCP) ist eines der wichtigsten Agrarregionen in China. Winterweizen (*Triticum aestivum* L.) und Sommermais (*Zea mays* L.) sind gegenwärtig die zwei Hauptfrüchte und werden in einer einjährigen Rotation kombiniert, die auch als Winterweizen-Sommermais Double-Cropping System bezeichnet wird. Die Getreideproduktion in der NCP hat sich in den letzten Jahrzehnten unter dem Einfluss vieler Faktoren wie beispielsweise Wasserknappheit, politischen Regelungen usw. zunehmend verändert. Im vorliegenden Artikel wurden die Änderungen in der Ertragsleistung von Weizen und Mais während der Jahre 1984-2003 untersucht. Im allgemeinem betrachtet, zeigten die Ergebnisse, dass durch den intensiven Einsatz von Produktionsfaktoren die Erträge anstiegen. Weiterhin wurde deutlich, dass die Verknappung von Wasser gegenwärtig das Hauptproblem im traditionellen Double-Cropping System ist, wodurch die angestrebte Autarkie Chinas im Bereich der Nahrungsmittelversorgung langfristig gefährdet sein könnte. Daher könnte in künftigen tief greifenden politischen Entscheidungen neben der Frage der Ertragsleistung auch der Frage der Einführung neuer Kulturpflanzen oder Anbausysteme eine große Bedeutung bekommen. Die vorliegende Arbeit schlägt einen Wechsel vom gegenwärtigen Double-Cropping System hin zu einem alleinigen Anbau von Frühjahrsmais vor, wodurch die Bewässerungsmenge ohne starke Ertragseinbußen reduziert werden könnte.

Schlüsselworte: Double-Cropping System, Winterweizen, Sommermais, Nord Chinesische Tiefebene, Wassermangel

Introduction

Agriculture in China has undergone tremendous structural changes over the last decades. The average staple crop productivity has doubled in 25 years while the population increased by 25% (China Statistical Yearbook [CSY] 2003). Today China has a population of about 1.3 billion people and it is estimated that by the year 2030 China's population will increase to about 1.6 billion people. In order to achieve the governmental goal of self-sufficiency (Huang 1998), facing the problem of limited land area and a still rising population, agriculture has undergone and is still undergoing dramatic changes. Over the last two decades, China's agricultural production became much more intensive (Mei 1998). This intensification has been correlated with dramatic environmental problems. Especially an increasing water scarcity has put irrigated agriculture under great pressure. Thus, agriculture in China is facing an unprecedented challenge for its future (Yang & Zehnder 2001).

The North China Plain (NCP) is one of the most important areas of agricultural production in China. The NCP, which is also known as the Huang-Huai-Hai Plain, is located in the north of the eastern part of China between 32° and 40° N latitude and 100° and 120° E longitude. The region comprises a total area of 320 000 km² of which

178 000 km^2 are arable land area. The NCP has a continental monsoon climate with cold, dry winters and hot, humid summers. The temperature sum ranges from 4100-5000 °Cd (> 0 °C). With a mean annual temperature between 10 and 15 °C the temperatures are mild enough to grow temperate climate crops. Annual precipitation averages around less than 500 mm in the north and up to 800 mm in the south, but varies unpredictably by more than 30% from year to year. More than 70% of the rainfall happens from July to September. The residual annual precipitation falls during the dry, windy spring planting season (March-May) and is not sufficient for crop growth. Hence, the temporal distribution of rainfall leaves a water deficit for spring seedlings and maturing winter wheat (Zuo 1992).

For hundreds of years, farmers accommodated the weather patterns by producing at most two to three crops every 2 years (Dong 1991, Yang 1991). Increasing the cropping index was limited by the climate. Since the late 1960s the cropping index increased from 1 respectively 1.5 to 2 due to improved irrigation technologies. Since then farmers in the NCP operated a double cropping system which is largely based on winter wheat and summer maize, both named after the season in which they are planted. Winter wheat is sown after ploughing in mid October and harvested in mid June. After winter wheat summer maize is sown directly without time lag and harvested at the beginning of October. Irrigation is essential for the practice of this multiple cropping, especially to winter wheat. Due to the summer-dominant rainfall normally no irrigation is required for summer maize. During its growth period summer maize consumes about 70% of the total rainfall, leaving insufficient soil moisture to produce subsequent winter wheat, making irrigation an essential part of wheat production (Liu et al. 2001).

Winter wheat is one of China's most important staple food crops, with a total farming area of nearly 22 million ha and a production exceeding 86 million t in 2003 (CSY 2004). Following the World Trade Organization agreements, China's decreasing import of wheat is likely to raise the demand for land-intensive cultivation for the domestic market (FAO 2002). Winter wheat growth and productivity are influenced by weather, especially temperature and precipitation, which determine both phenological development and growth rates. The winter wheat production fluctuates interannually with varying meteorological conditions (Tao et al. 2004) and will be further affected in the upcoming years as a result of increasing concentrations of atmospheric carbon dioxide and other greenhouse gases (IPCC 2001).

Beside rice and wheat, maize belongs to the most important grains in China. In 2003 the total cropped area nearly reached 24.1 million ha and the production exceeded 115.8 million t (CSY 2004). The potential for increasing maize yields is high, as the average yields are currently only half of the average of industrial countries. Today an increasing proportion of the maize production is used as feed grain as a result of an increasing demand for meat from the increasing population and rapid economic development. In the 1960s about 80% of the whole maize production in China was used for direct human consumption, in 1996 it was only 10% (Verburg & Veldkamp 2001).

64% of the irrigated area in the NCP relies on groundwater (Yang & Zehnder 2001). The massive extraction of groundwater in the NCP has led to a rapid decline in the groundwater table. Groundwater levels are declining more than 1 m annually, and in some places land subsiding has occurred (Kendy et al. 2003a). In addition, there has been an increase in urban and industrial water use, leading to water shortages in most places of the NCP. To cope with the water shortage problems, it is important to improve water use efficiency of crops by either reducing agricultural water use or guaranteeing the increase in grain production to meet the demand of the increasing population without greatly increasing water utilization. The current NCP production level of more than 50% of the nation's wheat and 33% of its maize (CSY 1999) makes the NCP critical to national food self-sufficiency. However, this level can only be kept through extensive irrigation, making water an even more vital and limiting resource.

In the NCP, on average summer maize is not irrigated whereas winter wheat is irrigated three to five times depending on seasonal rainfall situations. In order to reduce irrigation in winter wheat, knowledge about crop responses to water stress during different growth stages may lead to practical implications for irrigation scheduling (English & Nakamura 1989, Ghahraman & Sepaskhah 1997, Zhang et al. 1999). Different studies have shown that at the beginning of April wheat is not equally sensitive to water stress (Zhang et al. 1999). Its response to water stress varies at different growing stages with the period from stem elongation to milking being particularly sensitive to water stress (Li 1990). Furthermore, farmers have traditionally irrigated winter wheat before the over-wintering period. Results of Zhang et al. (2003) showed that this irrigation could be omitted due to its loss to soil evaporation and its effects on increasing the non-effective tillers in spring. Another way to save water is to trigger irrigation based on measurements of soil water content. Böning-Zilkens (2004) conducted field experiments with wheat and maize in Dongbeiwang, located in the North-West of Beijing (40.0° N and 116.3° E), during 1999-2002. The irrigation levels depended on measurements of soil water content. Thresholds for irrigation application were set to 45-80% of field capacity. The results of the field studies showed that there was a considerable potential for reduction of irrigation water of up to 20%. Additional field experiments of Böning-Zilkens (2004) indicated that changed cropping systems e. g. shortening the period between harvests of winter wheat and sowing of summer maize by e. g. direct drilling methods could improve water use efficiency significantly. Another way to save water might be the adoption of water-saving irrigation techniques, such as drip or sprinkler irrigation. Compared with flood irrigation, drip irrigation is 50% more efficient (Wolff 1999). However flood irrigation is currently predominant. With the increasing water shortage in the NCP, farmers have also started to adopt various agronomic practices to save water. An example was mulching (Chen et al. 2002) as the use of vegetative mulch is considered as an effective way to prevent soil evaporation (Li 1998, Mellouli et al. 2000). Furthermore, there is a considerable potential for improvement in water use efficiency of crops through improved agronomic practice and breeding for improved transpiration efficiency (Turner 1993). While other studies have mostly focussed on the improvement of water use efficiency associated with cultivars and irrigation management (e. g. Zhang et al. 2005), methods to stabilize water levels focussing on essential changes within the traditional cropping system including crop changes have not been explored yet.

The objectives of this study are two-fold. First, we consider an empirical evaluation of the yield performance of winter wheat and summer maize in a double cropping system in the North China Plain over the last two decades. The analysis is pursued of how and why the yield performance has changed across multiple locations and years. Inferences drawn from this analysis may be useful in refining input amounts of water and nitrogen and offer the basis for the second step of the analysis to evaluate the effect of cropping system changes on water use efficiency improvement.

Integrating the overall results of the evaluation, we present a quantitative framework for collaborative land-use and cropping system planning and sustainable water management. The findings counter China's long-standing policy of continually increasing the irrigated area in order to achieve the key societal objective of food self-sufficiency, and they may offer new perspectives of possible changes in the NCP to face the increasing water saving problem.

Material and Methods

Empirical evaluation of yield performance

Our analysis utilizes principal data of agriculture in the NCP derived from the CHINA STATISTICS YEARBOOK. The analysis focuses on data collected from 1984 until 2003. First hand data from farmers were scarcely available. The results represent the conditions of the seven provinces Henan, Hebei, Shandong, Anhui, Jiangsu, Beijing, and Tianjing (Fig. 1).

Wheat and maize are the staple crops of the NCP, therefore the focus was on these two crops. For wheat and maize the changes of cropped area and grain yield were ascertained. The yield per unit for wheat and maize was calculated by dividing the total yield per year by the total cropped area per year (Eq. 1).

$$\text{Grain yield}(\text{kg ha}^{-1}\text{a}^{-1}) = \frac{\text{total production}(\text{kg a}^{-1})}{\text{total cropped area}(\text{ha})}$$

Also the changes in the irrigated area and the changes in the consumption of mineral fertilizer were analyzed. Mineral fertilizer is defined as the sum of nitrogen, phosphate, potash and complex fertilizer. For calculating the consumption of mineral fertilizer per hectare and year the total amount of applied fertilizer per unit and year was divided by the total cropped area per year (Eq. 2).

$$\text{Fertilizer}(\text{kg ha}^{-1}\text{a}^{-1}) = \frac{\text{total fertilizer mass}(\text{kg a}^{-1})}{\text{total cropped area}(\text{ha})}$$

The yield per unit mineral fertilizer use for wheat and maize production was calculated by dividing the average yield per year by the use of fertilizer per year (Eq. 3).

$$\text{Yield per unit fertilizer}(\text{kg kg}^{-1}) = \frac{\text{total production}(\text{kg a}^{-1})}{\text{total fertilizer mass}(\text{kg a}^{-1})}$$

Field trials for the evaluation of water saving strategies

A field experiment was set up in the year 2004 in the framework of the International Research Training Group of the University of Hohenheim and the China Agricultural University to compare different cropping systems in the NCP. The double cropping system of winter wheat and summer maize was compared with a single rotation of spring maize at the locations Dongbeiwang and Wuqiao. The environments of these two locations are characterized in Tab. 1.

The field experiment was designed as a completely randomized one factorial block design. The input factors fertilization and irrigation were varied in different amounts (Tab. 2). Each treatment was replicated four times on every site. In the double cropping treatment tillage, irrigation and fertilization was carried out according to farmers' practice. The irrigation in the spring maize treatment was based on measurements of the volumetric soil water content during sensitive growing stages aiming to keep the

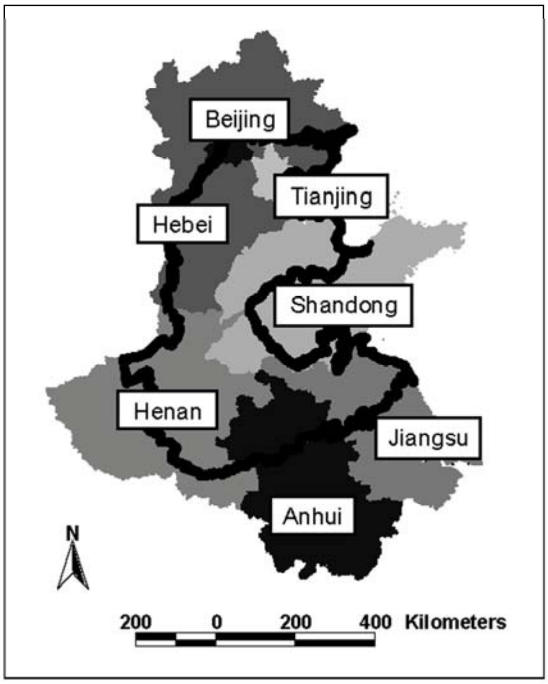

Fig. 1: Provinces of the North China Plain and the border of the North China Plain (black line) (Source: BARETH 2003, adapted and modified)
Provinzen der Nordchinesischen Tiefebene und die Grenze der Nordchinesischen Tiefebene (schwarze Linie) (Quelle: BARETH 2003, angepasst und verändert)

Tab. 1: Characterization of the experimental locations Dongbeiwang and Wuqiao (Source: field experiment)
Beschreibung der Versuchsstandorte Dongbeiwang und Wuqiao (Quelle: Feldversuch)

	Dongbeiwang	Wuqiao
Geographical situation	In the north-west of Beijing (40.0° N, 116.3° E)	250 km south of Beijing (37.3° N, 116.3° E)
Long-term average		
Air temperature	11.5 °C	12.6 °C
Precipitation	627 mm	562 mm
Soil	Silt loam	Sandy clay

Tab. 2: Plant production parameters of the double cropping system of winter wheat and summer maize in comparison with a single crop rotation of spring maize at two different locations in the North China Plain (Source: field experiment)
Pflanzenbauliche Kenndaten des Anbausystems Winterweizen und Sommermais im Vergleich zum Anbau von Frühjahrsmais an zwei verschiedenen Standorten in der Nordchinesischen Tiefebene (Quelle: Feldversuch)

Location	Dongbeiwang			Wuqiao		
Cropping system	double cropping		single crop	double cropping		single crop
	winter wheat	summer maize	spring maize	winter wheat	summer maize	spring maize
Sowing date	11th October 04	19th June 05	29th April 05	16th October 04	16th June 05	21st April 05
Cultivar	Jingdong 8	CF 024	CF 1505	Shijizhuang 8	Zhengdan 958	CF 1505
Row-spacing (cm)	15	70	70	15	60	70
Sowing density (kernels m^{-2})	570	7	7	746	8	7
Tillage	plough + rotory tiller	no	plough + rotory tiller	plough + rotory tiller	no	plough + rotory tiller
Harvest date	18th June 05	5th October 05	14th September 05	8th June 05	3rd October 05	5th September 05
Irrigation (mm)	335	100	125	300	120	100
Fertilization (kg N ha^{-1})	300	250	95	300	250	159

Tab. 3: Determined growth stages (GS) of winter wheat and maize (after Zadoks et al. 1974)
Ermittelte Entwicklungsstadien (GS) für Winterweizen und Mais (nach Zadoks et al. 1974)

Wheat Development stage	GS	Maize Development stage	GS
beginning of shooting	31	3 leaves unfolded	13
mid boot stage	43	beginning of stem elongation	30
full flowering	65	flowering	65
medium milk	75	medium milk	75
final harvest	89	final harvest	89

available field capacity between 45 and 80%. The fertilization was based on soil mineral N measurements and target yield. The sowing density of winter wheat (Tab. 2) was relatively high especially at the Wuqiao site because the tillering ability of the selected cultivars is low.

Crop Measurements

For counting of emergence and hibernation test strips were fixed in every plot. The test strips for winter wheat consisted of a double row of 3 m length (representing 0.9 m^2). Test strips for maize consisted of a double row of 2 m length (representing 2.4 respectively 2.8 m^2). Different growth stages (GS) of winter wheat and maize (Tab. 3) were recorded according to Zadoks et al. (1974). Five leaf area index (LAI) measurements were done with a LI-COR LAI-2000 (LI-COR, Lincoln, USA) in the GS mentioned in Tab. 3. To improve the spatial average the measurements were made along a diagonal transect between the rows. Four measurements were done between two rows by carrying out the first measurement in the row, the second $1/4$ of the way across, the third half-way between the two rows, and the fourth $3/4$ of the way across. The measurements were repeated once, so the recorded value for one plot was the mean over eight single measurements. Five time harvests were done manually from an area of 1 m^2 per plot in the GS mentioned in Tab. 3. Fresh matter was measured by dividing plant samples in leaf, stem and grain (if present). To obtain total dry matter, the samples were dried for 24 h at 105 °C. Final harvest was conducted manually on all plots. For determination of yield, half of each plot subtracting a surrounding rim of one meter was harvested, representing 20 m^2 in Dongbeiwang and 9 m^2 in Wuqiao. Before that, separate samples (three times 1 m^2) were taken for counting the ear number, grains per ear and kernels per cob. After that, plants were separated and grains and kernels were threshed and dried for 24 h at 105 °C to obtain total dry matter. For determining the thousand kernel weight (TKW) of each plot, 500 kernels were counted three times. Grain and straw were analysed for N concentration using the NIRS-System 5000 (Foss, Rellingen, Germany). The evaluation of the results of the N measurements was done with the Win-ISI software (Foss, Rellingen, Germany).

Statistics

Crop yield data were collected without regard to crop practice types and focussed on the changes of the amount of the inputs factors nitrogen and irrigation water. Thus, estimated yield differences are related to cropping practices and do not include farm characteristics such as equipment expenses etc.. An analysis of variance (ANOVA) with subsequent comparison of means was accomplished to compare the different cropping systems. When ANOVA indicated significant differences, these were tested with the TUKEY-Test on a base of 5% likelihood. The statistical analyses were done by using SAS version 9.1 (SAS Institute, Inc., Cary, NC, USA).

Results and discussion

Changes in yield performance

a) Grain production. Fig. 2 (A) shows the grain production of wheat and maize in the NCP over the last 20 years. In general, the grain production of both crops increased. In 1984 53 million t of wheat were produced, in 2003 it were

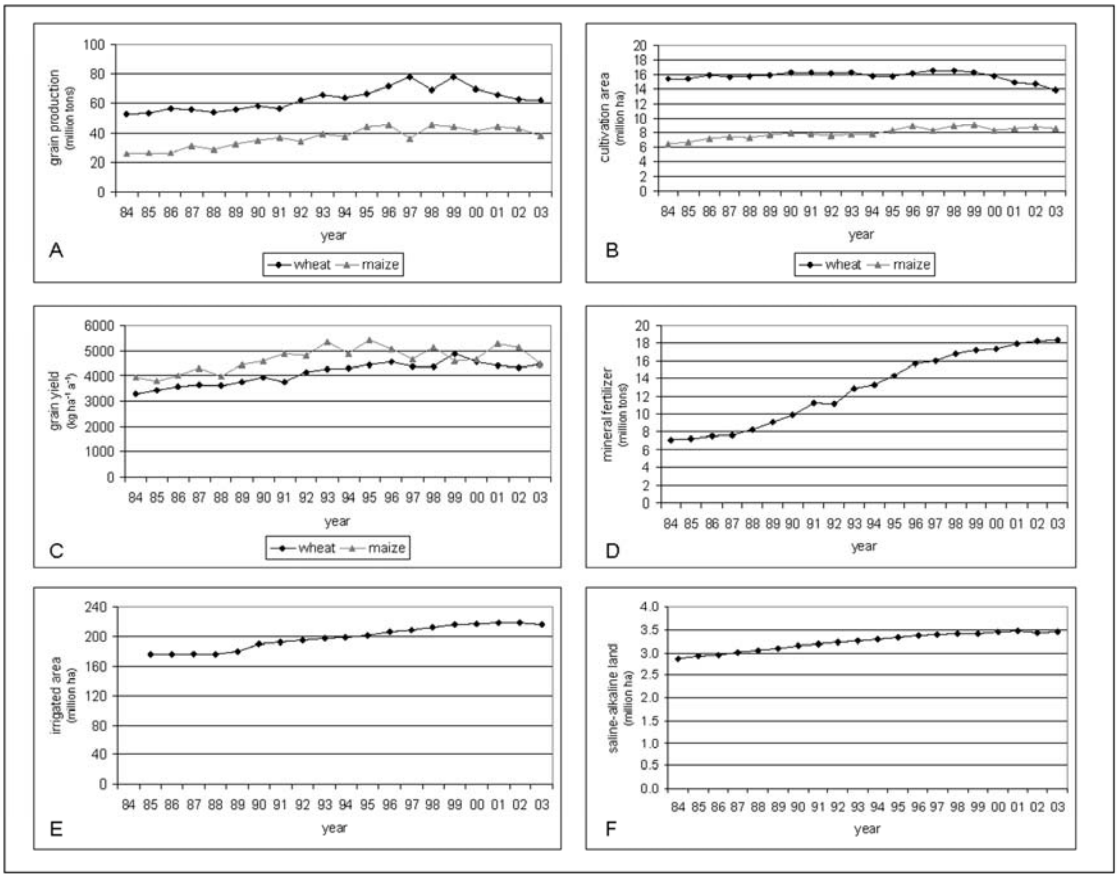

Fig. 2: Development of wheat [♦] and maize grain production [▲] (million t) (A); development of the cultivation area (million ha) of wheat [♦] and maize [▲] (B); grain yield development [kg ha^{-1} a^{-1}] of wheat [♦] and maize [▲] (C); consumption of all mineral fertilizers (million t) (D); increase in irrigated land area (million ha) (E); affected area of saline-alkaline land (million ha) (F); all data refer to the North China Plain, 1984-2003 (Source: CSY, adapted and modified)

Entwicklung der Weizen- [♦] und Maisproduktion [▲] (Millionen t) (A); Entwicklung der Weizen- [♦] und Maisanbaufläche [▲] (Millionen ha) (B); Ertragsentwicklung [kg ha^{-1} a^{-1}] von Weizen [♦] und Mais [▲] (C); Entwicklung des Düngereinsatzes (Millionen t) aller mineralischen Dünger (D); Zunahme der bewässerten Fläche (Millionen ha) (E); von Versalzung betroffene Fläche (Millionen ha) (F); alle Daten beziehen sich auf die Nordchinesische Tiefebene, 1984-2003 (Quelle: CSY, angepasst und verändert)

already 61.8 million t. The highest wheat production with approximately 78 million t was reached in the years 1997 and 1999. Since that time the wheat production shows a downward trend, which is justified by a change in the cultivated area. Maize production increased from 25.7 million t in 1984 to 38.1 million t in 2003 and stayed since 1995 on a constant level.

b) Area cultivated with winter wheat and maize. Fig. 2 (B) shows the expansion of land area cultivated with wheat and maize over the last two decades. The area of wheat amounted to 15.3 million ha in 1984 and 13.9 million ha in 2003 whereby it significantly increased from 1984 to 1991, nearly stagnated then for about 8 years and started to decrease after 1999. In contrast to wheat over the years 1984-2003 the sown area of maize increased continuously from 6.4 to 8.6 million ha. The changes in areas and production of cereals reflected dietary changes that have included a declining consumption of food grains and an increasing consumption of animal products that require feed grain. Traditionally a large proportion of the area planted with crops had been cropped with cereals, but the proportion declined. This reduction mainly affected wheat, which is primarily used for direct human consumption. Production of maize, the dominant feed grain, rose markedly through much of the 1990s but has levelled out since then. At the same time increasing areas of land are being diverted into vegetable and fruit production. However, with 27% respectively 17% of the total sown area wheat and maize are still the two dominant crops in the NCP.

c) Grain yield. Fig. 2 (C) shows the development of wheat and maize yields per hectare in the NCP over the years 1984-2003. Wheat yield increased from 3292 kg ha^{-1} in 1984 to 4448 kg ha^{-1} in 2003. Maize yield increased from 3946 kg ha^{-1} to 4483 kg ha^{-1} in 2003, respectively. The average increase for each crop was 26 and 22%, respectively. The increase in yield can be attributed to an improved use of pesticides, better cultivars, new machinery and other enhanced management techniques. However, one of the main reasons for the increase in yield is probably the increased amount of nitrogen fertilizer applied to the different crops. According to LU & SHI (1998), fertilization contributes up to 50-60% to the total increase in grain yields in China.

d) Fertilization. Extensive use of fertilizer is very common. In Beijing area e. g., the average N application rates range around 309 kg N ha^{-1} for winter wheat and 256 kg N ha^{-1} for maize (ZHAO et al. 1997). In Huantai County - a high-yielding area of the Shandong Province - often a total amount of 600 kg N ha^{-1} is applied to the double cropping system (GAO et al. 1999). Fig. 3 (A) indicates the increased use of mineral fertilizers for the single provinces in China. In all provinces an increase in fertilizer use is ascertainable, but it becomes primarily obvious in the main growing areas such as the NCP. Statistics showed that fertilizer consumption is growing rapidly in developing countries (ISHERWOOD 1998). Fig. 2 (D) clarifies the increased consumption of mineral fertilizer in the NCP. The consumption of mineral fertilizer increased from 7.1 million t in 1984 to 18.3 million t in 2003.

The increased fertilization rates led to an increase in yield, but at the same time the yield per unit mineral fertilizer use for wheat and maize decreased in the NCP from 1984 to 2003 (Fig. 3 B). The production per unit fertilizer for wheat decreased from 24 kg grain kg^{-1} fertilizer in 1984 to 12 kg grain kg^{-1} fertilizer in 2003. The maize productivity decreased from 29 kg grain kg^{-1} fertilizer in 1984 to 12 kg grain kg^{-1} fertilizer in 2003.

The main reasons for the reduced efficiency are high losses of nitrogen to the environment, either in form of nitrate leaching or gaseous losses. Ammonium bicarbonate and urea are the main mineral N fertilizers used in the NCP. By application of these mineral fertilizers, NH_3 emissions up to 70% have been observed, particularly on calcareous soils which are the dominant soil types in Northeast China (SOMMER & JENSEN 1994, ZHU & CHEN 2002). The traditional approach was to throw the fertilizer on the ground and follow this with a lengthy period of flood irrigation. Large amounts of nitrogen and water have been wasted during plant growth by this approach. As a consequence the N fertilizer efficiency was often lower than 25-20% (LIN 1992). There were substantial atmospheric losses of nitrogen through ammonia volatilisation due to the application method. Additionally, over-watering increased nitrogen losses through leaching into the groundwater table (ZHANG et al. 1996). More than 25 and 30% of groundwater samples in Beijing area and Shandong Province, respectively, already exceeded the critical value of 45 mg NO_3 l^{-1} (CHEN et al. 1998).

e) Irrigation. Another key input factor for increasing yield is irrigation water. The continued increase of irrigated land areas has been the major factor that has contributed to the stable expansion of agricultural production capacity (STONE 1993). The irrigated area in the NCP increased during 1984-2003 by 22%. In 1984, 177 million ha arable land

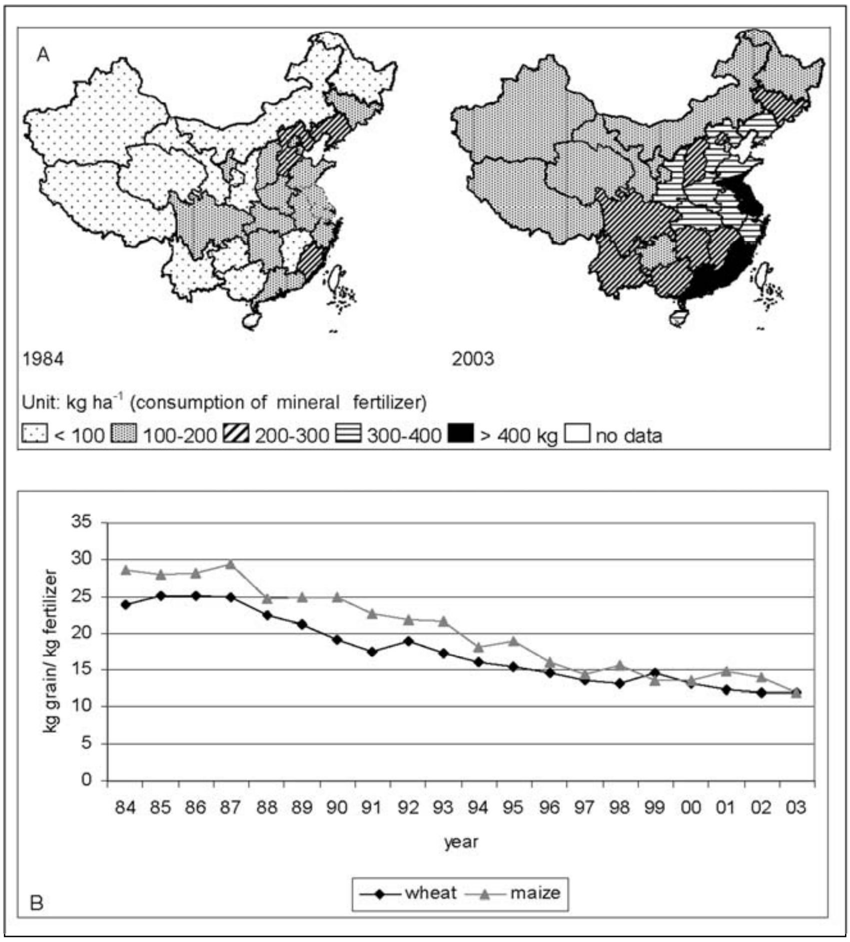

Fig. 3: The application rate of mineral fertilizer per cultivation area in different provinces in China 1984 and 2003 (A) (Source: CHEN 2004, adapted and modified); development of yield (kg) per unit employed mineral fertilizer (kg) on winter wheat [♦] and maize [▲] in the North China Plain, 1984-2003 (B) (Source: CSY, adapted and modified)
Mineraldüngereinsatz je Anbaufläche in den verschiedenen Provinzen Chinas, 1984 und 2003 (A) (Quelle: CHEN 2004, angepasst und verändert); Entwicklung des Ertrags-Dünger-Verhältnis (kg Kornertrag kg^{-1} Düngereinsatz) für Weizen [♦] und Mais [▲] in der Nordchinesischen Tiefebene, 1984-2003 (B) (Quelle: CSY, angepasst und verändert)

area were irrigated which comprised 36% of total cultivated area at that time. In 2003, 216 million ha cultivated land area were irrigated, representing 43% of the total cropped area (Fig. 2 E).

Beside the expansion of the irrigated land area, the amount of irrigation water increased from 100 mm in the 1950s to 200-300 mm in the 1980s (ZHANG & YOU 1996). At the moment no actual quantification of the changes in irrigation amount per unit area is possible, because data are scarcely available.

More than 75% of the crop output in the NCP is generated from irrigated land (JIN & YOUNG 2001). The irrigation water shortage is estimated to be 1.5 billion m^3 a^{-1} (LIU et al. 2001). The demand for high yields has led to an increase in the use of irrigation water for winter wheat (ZANG & YOU 1996). In order to achieve high grain yields, NCP farmers tend to over irrigate (ZHANG et al. 2002). Around 95% of the irrigation is done through flooding methods and open channels (XINHUA NEWS 2001). These methods have an efficiency of less than 50%.

Water is the most critical resource for the agricultural ecosystem in China (HEILIG 1999). Currently over 70% of total water use in China is spent for agriculture, whereupon about 80% of the whole agricultural water consumption is used for wheat production (LI 1993). The major problem of the winter wheat - summer maize rotation system is that about 50-75% of the annual rainfall occurs during July to September, the growing season of maize. Rainfall during the winter wheat growing season is very low, whereupon a supplemental irrigation is necessary (MC VICAR et al. 2000). SPYRA & JAKOB (2004) assumed that a change in wheat production could improve the overall water situation in China and attenuate the water scarcity problem. Studies of ZHANG et al. (2004) showed similar results. They concluded that for a sustainable use of groundwater in a long-term, it is imperative to reduce the wheat-cropped area in the NCP. KENDY et al. (2003b) simulated annual evapotranspiration and groundwater recharge in Luancheng County under five different winter/summer crop combinations and came to the conclusion that regardless of which summer crop is planted, irrigated agriculture is not sustainable if winter wheat is also grown. YANG & ZEHNDER (2001) suggested that one solution could be to increase maize production while decreasing or even stopping wheat production.

Besides the decreased groundwater table badly managed irrigation may cause increasing salinization up to desertification (ZHOU & WANG 1993). In the NCP, 20 years ago the area which was affected by salinization was about 2.9 million ha, currently there are 3.5 million ha concerned (Fig. 2 F). Poorly constructed irrigation systems commonly lead to salinization in some environments, either because of the inadequate application of water or because of substandard drainage. According to HUANG & ROZELLE (1995) salinization becomes serious enough to force producers to remove land from production due to a significant decline in farm productivity.

Water saving strategies based on crop changes in the cropping system

Currently water is the most limiting factor in the NCP (CHEN & MA 1998). Without irrigation grain production in the double cropping system would be low especially in winter wheat. Due to increasing water scarcity, the saving of irrigation water will get more and more important in the near future (GENG et al. 2001). Nowadays profound water saving measures must take place in the NCP whereof especially the agricultural sector will be affected. One possibility to combine the goal of maintaining high yields and at the same time implementing water saving strategies could be the alternation of the actual double cropping system back to a single rotation of spring maize. YANG & ZEHNDER (2001) recommend in their study an increasing maize production while decreasing wheat production and finally stopping wheat production altogether. According to LOHMAR et al. (2003) one effect of water scarcity could be that farmers abandon irrigated wheat production and concentrate on a single cropping of maize.

Tab. 4 and 5 show first results of a field experiment conducted at two different sites in the NCP. The experiment was conducted to evaluate (i) overall yields of the double cropping system winter wheat - summer maize in comparison to single spring maize yields, and (ii) water use efficiency of both cropping systems and thus possible water saving strategies by changing the traditional cropping system.

Tab. 4 indicates that overall yields (sum of grain yield winter wheat plus summer maize) within the double cropping system are generally higher than single spring maize yields. The average total grain yield of wheat and maize in the double cropping system at the Dongbeiwang site was 137.6 dt DM ha^{-1} and in Wuqiao 154.9 dt DM ha^{-1}. Spring maize grain yields were 98.1 and 72.3 dt DM ha^{-1}, i.e. 29 and 53% lower, respectively.

Tab. 5 represents the yield determining and the quality parameters. Due to a longer growing season spring maize

Tab. 4: Grain yield (dt DM ha^{-1}) and efficiency (kg grain per m^3 irrigation water) of the double cropping system of winter wheat and summer maize in comparison with a single crop rotation of spring maize at two different locations in the North China Plain [different letters mark significant differences between different cropping systems in one location ($\alpha \leq 5\%$)] (Source: field experiment)

Kornertrag (dt TM ha^{-1}) und Effizienz (kg Ertrag je m^3 Bewässerungswasser) des Anbausystems Winterweizen und Sommermais im Vergleich zum Anbau von Frühjahrsmais an zwei verschiedenen Standorten in der Nordchinesischen Tiefebene [unterschiedliche Buchstaben kennzeichnen signifikante Unterschiede zwischen den Anbausystemen eines Standorts ($\alpha \leq 5\%$)] (Quelle: Feldversuch)

location	Dongbeiwang				Wuqiao			
system	double cropping (winter wheat + summer maize)		single crop (spring maize)		double cropping (winter wheat + summer maize)		single crop (spring maize)	
yield (dt DM ha^{-1})	137.6	b	98.1	a	154.9	b	72.3	a
efficiency (kg grain per m^3 irrigation water)	3.2	a	7.9	b	3.7	a	7.2	b

Tab. 5: Yield determining parameters and quality parameters of the double cropping system of winter wheat and summer maize in comparison with a single crop rotation of spring maize at two different locations in the North China Plain (Source: field experiment)
Vergleich der Ertrags- und Qualitätsparameter von Winterweizen und Sommermais im Double-Cropping System und im Anbau von Frühjahrsmais an zwei verschiedenen Standorten in der Nordchinesischen Tiefebene (Quelle: Feldversuch)

location	Dongbeiwang			Wuqiao		
system	double cropping		single crop	double cropping		single crop
	winter wheat	summer maize	spring maize	winter wheat	summer maize	spring maize
ear bearning stems resp. cobs m^{-2}	609	6.9	6.7	733	7.9	6.8
TKW (g)	39	275	339	37	275	322
kernels per ear resp. kernels per cob	22	436	514	28	433	364
grain crude protein content (% DM)	15.3	9.4	9.5	17.8	7.5	9.9
grain water content (%) at harvest	15.5	39.2	44.3	31.9	32.5	29.5

realized in comparison to summer maize higher yield determining parameters. The number of kernels per cob of spring maize and summer maize at the Dongbeiwang site was 514 or 436 kernels per cob and in Wuqiao 364 or 433 kernels per cob, respectively. The lower number of kernels per cob of spring maize in Wuqiao was mainly attributed to a water shortage at the 12 leaf stage. Water stress is possibly also a reason for the in general lower yield of spring maize in comparison to the location Dongbeiwang. Independently of the cultivation of spring or summer maize, one cob per plant was produced. However, the longer vegetation period interrelated with a more progressed ripening process of spring maize resulted in higher protein (9.9 vs. 7.5%) and lower water contents at harvest (29.5 vs. 32.5%) in Wuqiao and also may result in a higher starch content (SCHWARZ & ETTLE 2000, WANG 2001). Only small differences between spring and summer maize regarding protein (9.5 vs. 9.4%) and water content (44.3 vs. 39.2%) were found in Dongbeiwang.

The main reason for realizing higher yields in multiple cropping is irrigation (YANG & ZEHNDER 2001). Spring maize is sown in April and harvested at the end of September. The main part of the growing season falls in the rainy season, thus less irrigation is needed to grow spring maize. Within the growing season, the ratio of effective rainfall to water demand is about 90% for maize and 37% for wheat (GENG et al. 2001). In Dongbeiwang spring maize required an irrigation amount of 125 mm and in Wuqiao of 100 mm (Tab. 2). In comparison the irrigation amount in the double cropping system was around 310 mm and 320 mm. The comparison of both cultivation systems regarding the amount of irrigation water in respect to the realized yield indicated that the water use efficiency for spring maize cultivation was much higher than for the double cropping of wheat and summer maize. With the cultivation of spring maize a grain yield of 7.9 kg m^{-3} irrigation water in Dongbeiwang and 7.2 kg m^{-3} irrigation water in Wuqiao was realized. In the double cropping system only 3.2 or 3.7 kg grain yield m^{-3} irrigation water, respectively, was reached. Although the study only presents empirical and preliminary data, the results indicate the advantage of a single maize cropping system when it comes down to water saving strategies and possible future policy changes.

The NCP has relatively favourable natural conditions for producing maize (YANG & ZEHNDER 2001). Spring maize could more easily overcome the high potential evapotranspiration in May and June, because maize as a C4-plant has a much lower evapotranspiration coefficient and a higher crop growth rate in comparison to winter wheat as a C3-plant (BÖNING-ZILKENS 2004). The cultivation of only a single crop could show significantly higher yields due to a longer growing season (LOHMAR et al. 2003). There is also enough time for maturation and the storage of starch and protein. In comparison to summer maize in a double cropping system, the vegetation time for the cultivation of spring maize would be extended to roundabout 29 days (Fig. 4 B, C). The use of new spring maize cultivars, as realized in the USA or South Brazil, promises in the near future a strong increase in yield (RÖMHELD & ZHANG 2004). However, for attaining higher yields a better utilization of the available vegetation time for spring maize must be realized (Fig. 4 D), because a later maturity leads to higher yields (SCHNELL & UTZ 1981). In comparison to the double cropping system yields of spring maize are lower yet, but higher yields in the double cropping system can only be achieved with higher amounts of fertilizer and irrigation water.

Fig. 4 summarizes the main differences between the two cropping systems. Different environmental conditions have a remarkable effect on growth and development of plants. These conditions are reflected by the value of the leaf area index (LAI) (HUNT 1982) which is defined as the leaf area per unit area of land (WATSON 1947). The LAI can be used to predict the photosynthetic primary production and act as a reference tool for crop growth. In Fig. 4 the LAI development in the double cropping system of winter wheat and summer maize (B) and the single rotation of spring maize (C) are shown. The LAI is strongly affected by temperature, solar radiation, water and mineral nutrition of the crops (HUNT 1982). BLACK (1963) e. g. showed that the higher the level of solar radiation, the higher the LAI at which maximum dry matter production in *Trifolium subterraneum* could be sustained.

In Fig. 4 (A) the monthly average temperature and monthly average sunshine hours are shown for Beijing (CSY 1988-2003). During autumn and spring when temperatures and sunlight intensities are moderate, the C3-plant winter wheat is exposed to good growing conditions. C4-plants such as maize are particularly adapted to the hot and dry climate in summer, where photorespira-

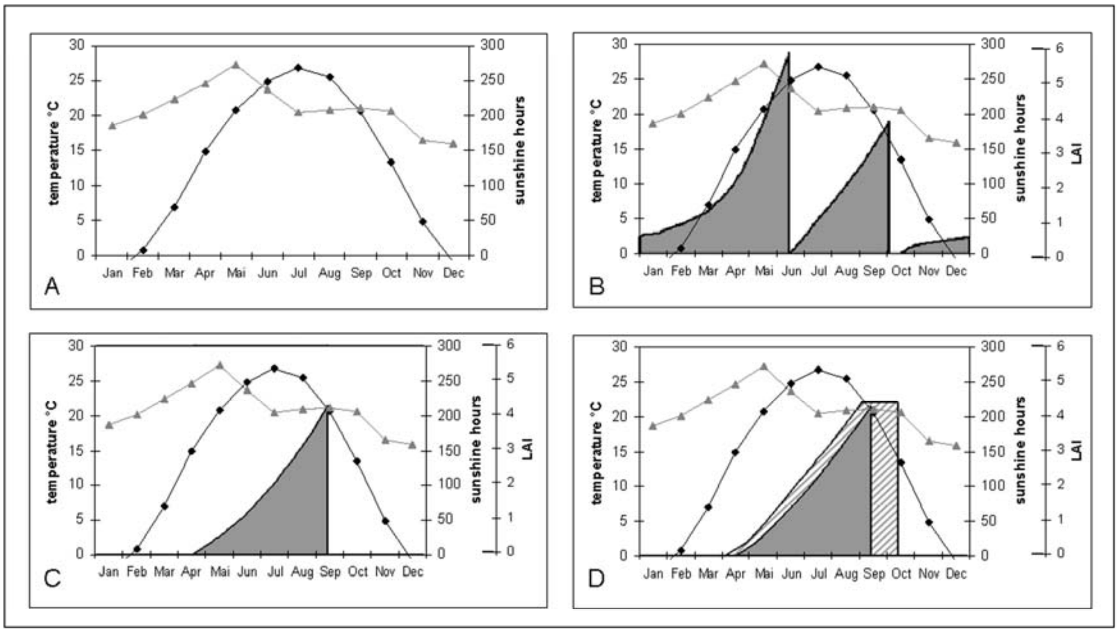

Fig. 4: Monthly average temperature (°C) [♦] and sunshine hours [▲] in Beijing (average 1988-2003) (A) (Source: CSY, adapted and modified); development of leaf area index (LAI) [grey area] in the double cropping system of winter wheat and summer maize (B) in comparison with a single crop rotation of spring maize (C) and the potential LAI [hetched area] of spring maize (D)
Durchschnittliche Monatstemperatur (°C) [♦] und Sonnenscheindauer (h) [▲] in Peking (Mittel 1988-2003) (A) (Quelle: CSY, angepasst und verändert); Jahresverlauf des Blattflächenindex (LAI) [graue Fläche] im Anbausystem Winterweizen und Sommermais (B) im Vergleich zum Anbau von Frühjahrsmais (C), sowie das mögliche Potenzial [schraffierte Fläche] von Frühjahrsmais (D)

tion is particularly activated by high radiation and high temperature. At the same time the CO_2 assimilation is made more difficult by the temperature-dependent and dryness-conditioned small opening degree of the stomata (Fellenberg 1981). Hence, in a double cropping system, constituted of winter wheat and summer maize, these factors can be effectively used over the whole year (Fig. 4 B). This might lead to higher yields in comparison to a single five month cropping of spring maize (Fig. 4 C) and further to an increase in the overall profit resulting from a more complete utilization of climate, land and other resources (Sanford 1982). However, due to the fact that two crops per year are grown in a double cropping system the vegetation time for the individual crop is limited. As a consequence, only cultivars with a short or a medium growing period can be used (Lewis & Phillips 1976, Beuerlein 2005). Yet, plants are often not sufficiently mature at harvest. This may lead to a higher grain water content and a lower grain quality (Beuerlein 2005). Crop maturation is further prolonged by a high application rate of nitrogen fertilizer and a high input of irrigation water (Finck 1991).

However, a note of caution has to be added as the cultivation of spring maize does not only have advantages. A disadvantage of the cultivation of spring maize is the long fallow time (October until March), whereby weed infestation and erosion is favoured. The weed infestation might have a small meaning, because effective soil tillage methods or the application of herbicides may help to solve this problem. Also erosion could be kept small, as maize residues usually remain as mulch on the field. The largest problem to be considered in this cropping system is the lower yield of spring maize when compared to the overall yield of a double cropping system. However, studies of Yang & Zehnder (2001) and Anonymous (2002) have shown that the remaining yield differences could be compensated by increasing the wheat imports. This would counter on the one hand China's goal of self-sufficiency in the context of food production, but on the other hand these studies indicated also that importing grain is a more efficient way to save water, as 1000 tons of water are required for the production of 1 ton of grain. Especially under the extreme situation of water scarcity, it might be more efficient to use the limited resources of water and arable land to produce high-value export products such as fruits or vegetables and import the land-extensive crops such as wheat and rice.

Conclusions

The empirical analysis of wheat and maize yield performance in the NCP over the last two decades showed a positive relationship between the use of mineral fertilizer and irrigation and final yield increase. It should be noted that other factors such as organic fertilizers, pesticide use, improved cultivars, machinery and other management techniques have also contributed to the increase of yield. Compared to other inputs, irrigation and mineral fertilizer appear to be the important factors leading to a significant yield increase. Within the current traditional double cropping system water scarcity is viewed as a major problem for China's long-term food security. The water demand of winter wheat is high and the growing season largely overlaps with the dry period. Therefore a fundamental change of the cultivation system can help to save water. The results of this study indicate that one option could be the alternation of the actual double cropping system of winter wheat and summer maize to a single crop rotation of spring maize. In comparison to the double cropping system the cultivation of spring maize could help to save water without a strong reduction in yield.

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Results of the first article clearly indicated that agricultural production in the NCP has experienced an intensification over the last decades. Water was found to be one of the major factors affecting and currently limiting grain production in the NCP. The low amount of precipitation during the winter wheat growing season makes irrigation essential. However, necessary irrigation amounts to wheat are up to now very high and have led to the severe water scarcity problems of the NCP. Strategies to lower the necessary irrigation amount to winter wheat respectively the whole cropping system are desperately needed.

Based on the findings of article one, ***article two*** *aims to work out different strategies to reduce the irrigation amount during the winter wheat growing season as far as possible without high yield loses in the double cropping system. For this purpose the two crop growth models CERES-Wheat and CERES-Maize, embedded in DSSAT, were calibrated. After model calibration different strategies to reduce the irrigation amount were tested.*

Optimizing irrigation in a double cropping system of winter wheat and summer maize in the North China Plain

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Introduction

The North China Plain (NCP) is one of the most important regions of agricultural production in China. Half of China`s wheat and a third of its maize is produced on this plain (National Bureau of Statistics of China, 1999). The NCP, which is also known as the Huang-Huai-Hai Plain, is located in the north of the eastern part of China between 32° and 40° N latitude and 100° and 120° E longitude. The region comprises a total area of 320 000 km². Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) currently the two main crops of the NCP are combined in a single-year rotation also referred to as a winter wheat summer maize double cropping system (Cao et al. 1995). The climate in the NCP is temperate, semi-humid monsoonal, with dry cold winters and hot humid summers. Annual precipitation ranges from 500 mm in the North to 800 mm in the south. 50 to 70 % of the total rainfall occurs from July to September, the main part of the maize growing season. Rainfall during the winter wheat vegetation period, which is from October to June is low. Due to limited and variable precipitation, agricultural productivity is low without irrigation (Zhang et al. 1999). Therefore a supplemental irrigation is necessary (Mc Vicar et al., 2000). Currently over 70 % of total water consumption in China is used for agriculture. Water use for wheat production occupies about 80 % of the whole agricultural water consumption (Li, 1993). In the NCP, 64 % of irrigated areas rely on groundwater (Yang and Zehnder 2001). The massive extraction of groundwater in the NCP has led to a rapid decline in the groundwater table (Zhang and You, 1996; Jia and Liu, 2002). Groundwater levels are declining more than 1 m annually, and in some places, land subsiding has occurred (Kendy et al. 2003). In addition, there has been an increase in urban and industrial water use, leading to water shortages in most places of the NCP. The aim of this study was to estimate how much irrigation water can be saved in the traditional double cropping system without markedly reducing grain yield. For this purpose the DSSAT crop growth model was evaluated with a data set of three years from the NCP. After that different irrigation strategies and their effects on wheat grain yield were evaluated.

Materials and Methods

The CERES-Maize and CERES-Wheat models distributed with DSSAT V. 4.0 (Jones et al. 2003) were used with field study information of Böning-Zilkens (2004) to evaluate the potential for reducing the amount of irrigation water in the double cropping system while maintaining high yields. The chosen field experiment was conducted from 1999 - 2002 (three vegetation periods, six harvests). The experimental site was Dongbeiwang located in the North-West of Beijing (40.0° N and 116.3° E). The winter wheat cultivar Jindong 8 was sown at the beginning of October with a row spacing of 15 cm and an aspired plant density of 480 plants m^{-2}. Wheat was harvested at the beginning of June. After winter wheat summer maize was sown directly without time lag and harvested at the beginning of October. The cultivar Jingkeng 114 was sown with a density of 6 plants m^{-2} and a row spacing of 70 cm. The whole experiment included three different irrigation regimes and three N-fertilization rates (Tab. 1). For the purpose of this study only the treatments with optimized N-fertilization were used because the focus of the analysis was set on irrigation water. The average fertilizer amounts for the year 1999 - 2001 in the winter wheat growing period were 65, 92 and 52 kg N ha^{-1} and for the summer maize (2000 - 2002) 35, 67 and 76 kg N ha^{-1}. Irrigation treatments varied between 164 and 384 mm (Tab. 1). The traditional irrigation was carried out according to farmers practice and reflects the cultivation situation of the farmers in the NCP with the water input being very high. The optimized irrigation was based on measurements of the volumetric soil water content aiming to keep the available field capacity between 45 and 80 %. The suboptimal irrigation exemplified the control. Irrigation in this treatment was based on the amount of approximately two third of the optimized strategy. Table 1 gives an overview over the different irrigation amounts in the different vegetation periods of winter wheat. Summer maize was not irrigated, because maize production normally relies on precipitation.

Table 1: Irrigation amounts (mm) of winter wheat in the growing seasons 99/00 - 01/02.

	growing season		
treamtment	**99/00**	**00/01**	**01/02**
suboptimal irrigation	184	236	164
traditional irrigation	330	384	347
optimized irrigation	319	310	249

Model description

The CERES models were originally designed to describe the system of crops and their environment. CERES-Maize and CERES-Wheat are process-oriented models and use a daily time step simulation. The CERES-family of model has been integrated as a part of the Decision Support System for Agrotechnology Transfer (DSSAT). In the CERES family of crop growth models the carbon subroutine is based on Godwin and Singh (1998), the nitrogen subroutine is calculated according to Godwin and Jones (1991), whereas the water movement is based on Ritchie (1998). The model simulates the main physiological processes such as plant biomass and grain yield. Biomass and yield production are calculated as a function of radiation, leaf area index and reduction factors for temperature and moisture stress. Crop development is primarily based on growing degree-days, whereas leaf and stem growth rates are calculated depending on phenological stages. In order to run the model a minimum dataset of climate variables, management variables, crop genetic constants and soil parameters are required (Jones et al. 2003). The model was designed to predict how grain yield is affected under alternative crop management strategies, or to predict grain yield for new growing sites with different varieties, soil water, N, and diseases. CERES-Maize and CERES-Wheat are well documented and have been successfully tested in numerous studies.

Model evaluation

Calibration data sets, which were used for model evaluation included crop management, soil and genotype characteristics. Phenology and growth data such as biomass and leaf area index at different growth stages and the dates of phenological events were used to evaluate the genetic parameters (Tab. 2).

Table 2: Genetic parameters of winter wheat and summer maize and their values used in the model evaluation.

winter wheat

parameters	description	value
P1V	sensitivity to vernalisation	55
P1D	sensitivity to photoperiod	30
P5	grain filling duration	500
G1	kernel number per unit weight at anthesis	20
G2	kernel weight under optimum conditions	42
G3	standart stem + spike dry weight at maturity	1.5
PHINT	phyllochron interval	85

summer maize

parameters	description	value
P1	growing degree days from emergence to end of juvenile phase	205
P2	photoperiod sensitivity	0.5
P5	cumulative growing degree days from silking to maturity	850
G2	potential kernel number	800
G3	potential kernel growth rate	8.5
PHINT	phyllochron interval	45

Inputs to the model included site information, soil properties, initial conditions, irrigation management (dates, amounts and schedule), and fertilizer management (dates, amounts, sources, method of incorporation, and depth of placement). Weather data including daily solar radiation, daily maximum and minimum air temperatures, and daily rainfall were collected from a local weather station at Dongbeiwang. Mean annual temperature for 2000-2002 was 11.6, 11.5 and 11.7 °C and did not differ from the long-term average of 11.5 °C. The annual precipitation amounted 448, 366 and 520 mm. In comparison to the long term average (627 mm) all three years were drier. To simulate the water saving potential in this area the optimized treatment was used. Only the irrigation amount was changed, irrigation time was fixed. The maximum acceptable decrease in grain yield was set to 5 %.

Statistical analysis

The correlation coefficient R and the root mean square error (RMSE) were used to estimate the variation between simulated and measured values. For graphical representations the 1:1 line of measured vs. simulated values was used.

Results and discussion

The results of model evaluation (Fig. 1) showed a good fit between simulated and measured yield. The R value for winter wheat was 0.92 and for summer maize 0.81. The average root mean square error (RMSE) between simulated and measured yield was 466 for winter wheat and 667 for summer maize.

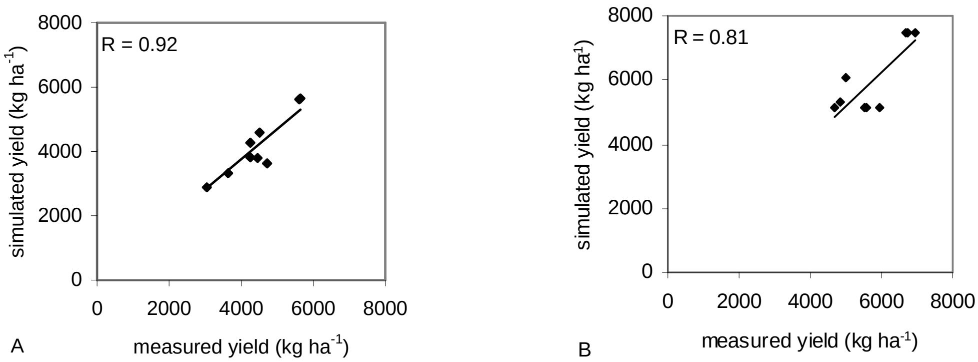

Figure 1: Measured vs. simulated winter wheat (A) and summer maize (B) grain yields (kg ha^{-1}) in the years 1999 - 2002.

Based on this calibration different scenarios for reducing the amount of irrigation water were evaluated (Tab. 3). For the simulation of the different scenarios everything was kept constant except the irrigation amount. The simulation of wheat grain yield indicated that a reduction in the amount of irrigation water is possible up to 10 % without any yield loss. A further reduction in the optimized treatment of 97 mm (31 %) is possible with a slight decrease in grain yield of a maximum of 5 %. An additional reduction of irrigation water would lead to the excess of the determined borders of 5 % losses in grain yield. The simulation also indicated that in dry years winter wheat grain yield would be approximately zero without irrigation. The reduced irrigation did not affect the grain yield of the following crop summer maize.

Table 3: Scenarios for reducing the amount of irrigation water (mm) and the effect on winter wheat grain yield (kg ha^{-1}) without chancing irrigation frequency and time.

titel	**irrigation**		**yield**	
	(mm)	(%)	(kg ha^{-1})	(%)
optimezed treatment	310	100	3791	100
scenario 1	280	-9.7	3791	0.0
scenario 2	233	-21.6	3639	-4.0
scenario 3	223	-28.1	3639	-4.0
scenario 4	213	-31.3	3601	-5.0
scenario 5	203	-34.5	3492	-7.9
scenario 6	no irrigation		102	-97.3

In the NCP, water is the most vital and limiting resource (Brown and Halweil 1998). Improving irrigation is one of the most important tools to reduce groundwater declines (Shin 1999). With the small reduction in yield, Chinas goal of self-sufficiency (Huang 1998) is preserved and at the same time a large amount of water could be saved. This would help to stop the further decline of the groundwater table (Jia and Liu 2002). However, winter wheat production without irrigation is not possible due to the seasonally limited precipitation.

One should keep in mind that not only the irrigation amount, but also the irrigation frequency and the cropping system i.e. plant density has a big influence on the yield and the required irrigation amount and has to be considered in further analysis.

Conclusion

The results of the study showed that there is a considerable potential for reduction of irrigation water in the traditional double cropping system of the NCP. Crop models such as DSSAT offer the possibility to estimate crop water use and can help to develop appropriate irrigation strategies.

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In the second article a high potential for reducing the applied irrigation amount to winter wheat was found. This was simply reached by reducing the irrigation amount without further adjustments in the irrigation management. Therefore, in a further step besides the irrigation amount also the irrigation frequency and irrigation time should be considered.

Hence, the purpose of the ***third article*** *was to evaluate the winter wheat and summer maize double cropping system in the NCP under different input scenarios (irrigation water, fertilization). The models CERES-Wheat and CERES-Maize were calibrated and validated. Afterwards a gross margin analysis of the different irrigation and N-fertilizer treatments were carried out. The most profitable treatment was used as a starting point to simulate different irrigation scenarios and their effects on grain yield, water consumption and gross margin.*

Model based scenario analysis of a winter wheat - summer maize double cropping system in the North China Plain

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Abstract

The North China Plain (NCP) is one of the most important regions of agricultural production in China. Currently winter wheat (*Triticum aestivum* L.) - summer maize (*Zea mays* L.) double cropping system dominates in the NCP. The purpose of this paper was to use the CERES-Wheat and CERES-Maize models to evaluate the double cropping of winter wheat and summer maize under different input scenarios regarding water consumption, grain yield and gross margin. The models were calibrated and validated by using data derived from a field experiment conducted in Dongbei-wang, near Beijing. Based on a gross margin analysis the different irrigation and N-fertilizer treatments from the field experiment were evaluated. Originated from the most profitable treatment, different irrigation scenarios for the dry season 2000/2001 and their effects on water consumption, grain yield and gross margin were simulated. The results indicated that a reduction in irrigation amount of about one third may be possible without any major yield loss. Furthermore a reduction of about 50 % is possible without a decrease in the initial gross margin. However, with a complete renouncement of irrigation, grain yield dropped by 76 %, leading to a decrease in gross margin of two third. Therefore, a supplemental irrigation to wheat is required to maintain high yields and to ensure an adequate gross margin to farmers. The highest gross margin was obtained with the highest grain yield because prices for the input factors

nitrogen fertilizer and irrigation water are low. However, with an increasing shortage of water, irrigation costs will rise. Overall the model based simulation of the irrigation may help to save water and lead to an increase in overall grain yield and gross margin.

Keywords: double cropping system, winter wheat, summer maize, North China Plain, gross margin, modeling, DSSAT

1. Introduction

One of the most important regions of agricultural production in China is the North China Plain (NCP) (Kendy et al., 2003). Considering China´s total grain yield, the NCP contributes approximately 41 % of wheat and 25 % of maize grain yield (Länderbericht China, 2000). The NCP, also known as the Huang-Huai-Hai Plain, is located in the north of the eastern part of China between 32° and 40° N latitude and 100° and 120° E longitude (Liu et al., 2001). Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) are currently the two main crops combined in a single-year rotation also referred to as a double cropping system (Zhao et al., 2006). Winter wheat is sown at the beginning of October and harvested in mid June. Summer maize is sown immediately following winter wheat harvest and is harvested at beginning of October.

The climate in the NCP is warm-temperate with cold winter and hot summer. Precipitation shows a high spatial and temporal variability (Wang, 1993; Wu et al., 2006) and ranges from about 500 mm in the north to 800 mm in the south (Liu et al., 2001). About 50 to 75 % of the total precipitation occurs from July to September during the summer monsoon. Depending on the seasonal precipitation situation, farmers usually irrigate winter wheat four to five times (Hu et al., 2006). In consequence, the irrigation water for wheat production comprises about 80 % of the whole agricultural water consumption (Li, 1993).

Extensive use of fertilizer is also very common in the winter wheat summer maize double cropping system. In Beijing area, for example, the average N application rates ranged around 309 kg N ha^{-1} for winter wheat and 256 kg N ha^{-1} for maize (Zhao et al., 1997). In Huantai County, a high-yielding area of Shandong Province, 600 kg N ha^{-1} a^{-1} often were applied (Gao et al., 1999). Besides the positive effects on yield, an increasing input of water and fertilizer is connected with increasing costs for the farmers and leads to environmental problems such as leaching or water scarcity. Therefore better management practices balancing both economic and environmental interests are required.

Numerous agricultural experiments were carried out to test the effects of different management strategies on grain yield and overall sustainability. For instance, Liu et al. (2003) studied in irrigated winter wheat-maize rotations the effect of different N fertilizer rates on grain yield and showed that a 50 % reduction in fertilizer N on the basis of conventional N application is possible while maintaining high yields, improving N utilization and preventing NO_3-N accumulation in the soil profile. Similarly, Fang et al. (2006) indicated that the optimum N rate may be much lower than that used in many areas in the NCP. In other field studies focusing on irrigation management the effect of decreasing the irrigation frequency from four times to one single application was tested (Zhang et al., 1998). Results of the study showed a reduction in grain yield of about 15 % whereas the water use efficiency was increased by 24-30 %. Zhang et al. (2003) demonstrated that in dry years winter wheat yields might be higher with only three irrigations instead of the common practice of four irrigations.

However field experiments have their limitations as they are conducted at particular points in time and space. Besides, field experiments are time consuming, laborious and expensive (Jones et al., 2003) and therefore limited in extent and size. A viable alternative to these problems is to use crop models. Models can be applied as a valuable tool to propose better adapted crop management strategies and to test the hypothetical consequences of varying management practices (e.g. Pala et al., 1996; Saseendran et al., 2005). Furthermore, models can be used to optimize economic efficiency by finding best management strategies under given and future environmental conditions (Paz et al., 1999; Nijbroek et al., 2003; Link et al., 2006). However, studies which use crop models to evaluate crop production systems in the NCP are rare (Yu et al., 2006). Recently crop growth models are getting more and more used. Hu et al. (2006) used the RZWQM model to assess N-management in a double cropping system (winter wheat and summer maize) at Luancheng in the NCP. Results of the study indicated, that both, N and water could be reduced by about half of the typical application rates without a strong reduction in yield. Another example can be found in Yang et al. (2006) who used the CERES-Wheat and CERES-Maize models to estimate agricultural water use and its impact on ground water depletion in the Piedmont region of the NCP. The results showed a strong correlation between the agricultural water use and the ground water depletion. The authors concluded that there is still a sustainable water reduction possible if water-saving technologies are applied.

Future changes in climate will greatly affect agricultural production. Over the last 50 years total precipitation in China has decreased substantially (Zhai et al., 1999) whereas annual temperature has increased by 0.5-0.7 °C (Wang et al., 2004). The change in climate may lead to a reduction of the available water for crop growth and make the water stress stronger (Wang and Wang, 1998).

The aim of our study was to evaluate the double cropping of winter wheat and summer maize in the NCP under water shortage conditions. For this purpose the models CERES-Wheat and CERES-Maize, both implemented in DSSAT V.4.0, were calibrated and validated. Based on a gross margin analysis, different irrigation and N-fertilizer treatments were evaluated. Originated from the most profitable treatment, four different irrigation scenarios for the dry growing season 2000/2001 and their effect on water consumption, grain yield and gross margin were simulated.

2. Materials and Methods

2.1. Study site and field experiment

The CERES-Maize and CERES-Wheat models, distributed with DSSAT V.4.0 (Jones et al., 2003), were used with field study information of Böning-Zilkens (2004) for testing different irrigation scenarios in a double cropping system of winter wheat and summer maize in the NCP. The chosen field experiment was conducted from 1999-2002 (three vegetation periods, six harvests). The experimental site was Dongbeiwang located in the northwest of Beijing (40.0° N and 116.3° E). Soil type was a Calcaric Cambisol (FAO taxonomy) formed of silty loam (Table 3). The winter wheat cultivar Jindong 8 was sown at the beginning of October with a row spacing of 15 cm and an aspired plant density of 480 plants m^{-2}. Wheat was harvested at the beginning of June each year. After winter wheat summer maize was sown directly without time lag and harvested at the beginning of October. The maize cultivar Jingkeng 114 was sown with a density of

6 plants m^{-2} and a row spacing of 70 cm. The experiment was designed as a three factorial split-split-plot design with four replications and included three different irrigation regimes, three N-fertilization rates as well as a treatment with and without straw. No major diseases were reported during the growing period. For the purpose of this study only the treatments without straw removal were used because this is the usual practice in the NCP.

Fertilization treatments varied between 0 and 600 kg N ha^{-1} a^{-1} (Table 1). In the traditional treatment N-fertilization was carried out according to farmers practice. The treatment reflects the standard production system in the NCP with the fertilizer inputs being very high. The fertilization of the optimized treatment was based on measured soil available nitrogen (N_{min}-content) and target yield. No nitrogen fertilizer was applied in the control treatment.

Irrigation treatments varied between 195 and 354 mm (Table 1). The traditional irrigation was carried out according to farmers practice using border irrigation. The optimized irrigation was based on measurements of the volumetric soil water content aiming to keep the available field capacity between 45 and 80 % following Hobbs et al. (1963), Stegman (1983) and Steiner et al. (1995). Available field capacity was defined as field capacity minus the amount of water which is retained through high soil water tension (pF < 4.2) and therefore not available to the plant (Arbeitsgruppe Boden, 1994). The volumetric soil water content was measured manually with tensiometers and TDR (time domain reflectometry) probes (0-15, 15-30, 30-45, 45-60, 60-90, 90-120 cm depth) every four days. The suboptimal irrigation exemplified the control. Irrigation in this treatment was based on the amount of approximately two third of the optimized strategy. In the optimized and suboptimal irrigation treatments irrigation was carried out using sprinkler irrigation. Plot size for the factor irrigation was 50 x 70 m. Two-jet complete circle sprinkler with a height of 1 m were used, adjusted in a grid of 12 x 18 m. Summer maize was not irrigated in any of the experimental years (Böning-Zilkens, 2004), as precipitation is usually sufficient (Lohmar et al., 2003). Different growth stages of winter wheat (emergence, hibernation, jointing, full flowering, medium milk, ripening) and maize (emergence, beginning of stem elongation, heading, end of flowering, medium milk) were recorded according to Zadoks et al. (1974). Leaf area index

Table 1

Average amounts of nitrogen fertilizer (kg ha^{-1} a^{-1}) and irrigation amounts (mm) for winter wheat and summer maize over the three vegetation periods (1999/2000-2001/2002) of field experiments.

Treatment	**Management**		**N-fertilization** (kg N ha^{-1} a^{-1})			**Irrigation** (mm)	
	irrigation	fertilization	wheat	maize	total	wheat	maize
1	suboptimal	suboptimal	0	0	0	195	0
2	suboptimal	traditional	300	300	600	195	0
3	suboptimal	optimized	50	53	103	195	0
4	traditional	suboptimal	0	0	0	354	0
5	traditional	traditional	300	300	600	354	0
6	traditional	optimized	87	59	146	354	0
7	optimized	suboptimal	0	0	0	293	0
8	optimized	traditional	300	300	600	293	0
9	optimized	optimized	72	65	137	293	0

(LAI) measurements were done with a LI-COR LAI-2000 (LI-COR, Lincoln, USA) in four growth stages (winter wheat: jointing, full flowering, medium milk, ripening; summer maize: beginning of stem elongation, heading, end of flowering, medium milk). To improve the spatial average the measurements were made along a diagonal transect between the rows. Four measurements were done between two rows by carrying out the first measurement in the row, the second 1/4 of the way across, the third half-away between the two rows, and the fourth 3/4 of the way across. The measurements were repeated once, so the measured value for one plot was the mean over eight single measurements. Four time harvests were done by hand in the growth stages mentioned before on 1.05 m^2 for winter wheat and 2.1 m^2 for summer maize in each plot. To obtain total dry matter plant samples were dried to constant weight at 105 °C. Final harvest was done manually by cutting three times 3 m^2 of winter wheat and one time 39.2 m^2 of summer maize. Winter wheat ears and maize plants were counted. After harvest, plants were separated and grains and kernels were threshed and dried to constant weight to obtain total dry matter. Thousand kernel mass, grains ear^{-1}, kernels row^{-1}, kernels cob^{-1} and rows cob^{-1} were determined.

Weather data were collected from a local weather station at Dongbeiwang and including daily solar radiation, maximum and minimum air temperatures and precipitation. Mean annual temperature for 2000-2002 ranged between 11.5-11.7 °C and did not differ from the long-term average of 11.5 °C. The annual precipitation amounted 448, 366 and 520 mm. In comparison to the long-term average (627 mm), all three years were drier.

2.2. Model description

In this study, two crop-environment resource synthesis (CERES) models were used, namely CERES-Maize (Jones and Kiniry, 1986) and CERES-Wheat (Godwin et al., 1989). Both models have been designed to simulate crop growth and development within the framework of the DSSAT V.4.0 Decision Support System for Agrotechnology Transfer (Jones et al., 2003). The CERES models were designed to describe the system of crops and their environment. They are process-oriented and use a daily time step simulation. Dry matter accumulation is calculated as a linear function based on intercepted photosynthetically active radiation. The potential dry matter production depends on the amount of biomass already produced and the actual LAI. This is then corrected for actual daily biomass by applying factors for water stress, non-optimal temperature and nitrogen stress. Phenological development and growth are specified by cultivar specific genetic coefficients (Table 2) depending on photoperiod, thermal time, temperature response and dry matter partitioning. More details about DSSAT and CERES can be found in Tsuji et al. (1998) and Jones et al. (2003).

2.3. Model calibration and validation

The CERES-Maize and CERES-Wheat models were calibrated and validated using data from Böning-Zilkens (2004). The growing seasons 1999/2000 and 2001/2002 were used for model calibration. Calibration datasets included information on weather, soil (Table 3) and crop management. Besides weather, site characteristics and management, crop yield depends on cultivar coefficients (O´Neal et al., 2002). Phenology and growth data such as biomass and LAI at different growth stages and the dates of phenological events were used to determine the cultivar coefficients for wheat and maize (Table 2). The calibration of these parameters followed a sequence of variables suggested by the DSSAT manual (Boote, 1999). Due to a very warm climate in 2000 plant development occurred too fast in the model. As suggested by Andales et al. (2000) the planting date for summer maize was set two weeks later than originally. As irrigation was carried out by border irrigation, irrigation efficiency was set to 0.45, according to Xinhua

Table 2

Cultivar coefficients of winter wheat cv. Jindong 8 and summer maize cv. Jingkeng 114 used for model calibration and validation.

Winter wheat

Parameter	Description	Value
P1V	Sensitivity to vernalisation	35
P1D	Sensitivity to photoperiod	50
P5	Grain filling duration	500
G1	Kernel number per unit weight at anthesis	20
G2	Kernel weight under optimum conditions	36
G3	standart stem + spike dry weight at maturity	1.8
PHINT	Phyllochron interval	95

Summer maize

Parameter	Description	Value
P1	Growing degree days from emergence to end of juvenile phase	180
P2	Photoperiod sensitivity	0.3
P5	Cumulative growing degree days from silking to maturity	685
G2	Potential kernel number	730
G3	Potential kernel growth rate	8.0
PHINT	Phyllochron interval	44

Table 3

Physical properties of the soil Calcaric Cambisol (FAO taxonomy) at the Dongbeiwang experimental site used for model calibration and validation (Source: Böning-Zilkens 2004, adapted and modified).

Depth (cm)	**Particle size distribution** Clay (%)	Silt (%)	Sand (%)	**Bulk density** (g cm^{-3})	**LL** (m^3 m^{-3})	**DUL** (m^3 m^{-3})	**SAT** (m^3 m^{-3})	**Saturated hydraulic conductivity** (cm h^{-1})
0-15	15.9	57.2	26.9	1.34	0.14	0.26	0.54	10.88
15-30	15.8	57.2	27.0	1.34	0.12	0.22	0.43	9.25
30-60	17.7	60.1	22.2	1.51	0.14	0.24	0.38	8.29
60-90	13.6	55.6	30.8	1.42	0.10	0.23	0.36	9.79

LL = lower limit of soil water; DUL = drained upper limit of available water; SAT = saturated limit of available soil water

News (2001). For sprinkler irrigation the irrigation efficiency was set to 0.55 as strong winds during the experiment diminished the water distribution.

The validation was carried out with an independent dataset from the dry growing season 2000/20001 using the cultivar coefficients obtained by calibration. The model validation involved the use of the model with the calibrated values without making any further adjustments of the constants (Gungula et al., 2003).

2.4. Economic analysis

Gross margins in Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$) have been developed with information provided from literature to compare the different treatments form the field experiments used for model calibration and validation as well as to compare the simulated scenarios. The analysis was carried out according to the following equation:

gross margin = revenue – variable costs

where gross margin is ¥ ha^{-1} a^{-1}.

The revenue parameter is the result of equation 1:

$$\text{revenue} = Y_{Wt} \times P_W + Y_{Mt} \times P_M \qquad [1]$$

where Y_{Wt} is the grain yield (kg ha^{-1}) of winter wheat W per year t, P_W is the price of winter wheat W (¥ kg^{-1}), Y_{Mt} is the grain yield (kg ha^{-1}) of summer maize M per year t, and P_M is the price of summer maize M (¥ kg^{-1}).

The variable cost parameter is the result of the equation 2:

$$\text{variable costs} = (N_{Wt} + N_{Mt}) \times P_N + W_{Wt} \times P_W \qquad [2]$$

where N_{Wt} is the N-fertilizer rate (kg ha^{-1}) applied to winter wheat W in year t, N_{Mt} is the N-fertilizer rate (kg ha^{-1}) applied to summer maize M in year t, P_N is the price of N fertilizer (¥ kg^{-1} N), W_{Wt} is the amount of irrigation water (m^3 ha^{-1}) used for winter wheat W in year t, and P_W is the price for the irrigation water (¥ m^{-3}).

The prices for nitrogen fertilizer (4.0 ¥ kg N^{-1}), winter wheat (1.10 ¥ kg^{-1}) and summer maize (1.00 ¥ kg^{-1}) were obtained from Chen et al. (2004). In the study of Chen et al. (2004) prices for wheat and maize were based on grain moisture of 15 %. However, as the model input requires a grain moisture of 0 % the price for maize was set to 1.18 ¥ kg^{-1} dry matter (DM) and to 1.29 ¥ kg^{-1} DM for winter wheat. The price for irrigation water was set to 0.60 ¥ m^{-3} based on information from Li et al. (2005). The initial investment for irrigation was not considered, because it was assumed that the irrigation system was already in place.

Note, that all the prices represent average prices for the NCP and will vary from region to region and year to year.

2.5. Simulated irrigation scenarios

To achieve high yields farmers in the NCP tend to overirrigate winter wheat (Zhang et al., 2004). In our simulations we want show the potential saving of irrigation water and its effect on grain yield and gross margin under the conditions at the Dongbeiwang site. Based on the treatment with the highest gross margin of the field experiment, different irrigation scenarios for the dry growing season 2000-2001 were simulated. The simulated scenarios are listed in Table 4. In scenario one the treatment with the highest gross margin of the field experiment was used as baseline. In scenario two the extreme situation of possible changes in grain yield and gross margin when no irrigation is applied and wheat growth is solely be based on precipitation was simulated. The simulation in scenario three aims at maximizing the possible amount of saving irrigation water without changing the initial gross margin. The aim of the simulation in scenario four was to maximize the saving of irrigation water without changing the initial grain yield. The simulation in scenario five strived for the general maximization of gross margin. In all the simulations all parameters were kept constant except the irrigation amount and schedules. The variation in the irrigation schedule considered sensitive stages mentioned by Zhang et al. (1999).

Table 4

Simulated irrigation scenarios.

Scenario	Discription
1	treatment with the highest gross margin = starting point
2	rainfed = no irrigation
3	max. water saving without reducing gross margin
4	max. water saving without reducing grain yield
5	max. gross margin

3. Results and Discussion

3.1. Model calibration and validation

From the calibration and validation results, the CERES-Maize and CERES-Wheat models were found to simulate yields well (Table 5). The average RMSE between simulated and measured yield for winter wheat was 432 kg ha^{-1} (calibration) and 342 kg ha^{-1} (validation). Similar results were obtained for summer maize with an average RMSE of 253 kg ha^{-1} (calibration) and 414 kg ha^{-1} (validation).

The results of our study showed in general that the differences between the simulated and measured grain yields were within the range of differences reported in the literature. Mati (2000) e.g. used the CERES-Maize model to simulate the crop response to changes in climate, management variables, soils and different CO_2 levels in the semi-humid-arid areas of Kenya. With an error of 5-10 % after calibration the model was found to simulate yields well within acceptable limits. Another example is given by Liu et al. (1989) who used the CERES-Maize model to simulate the growth and yield of a Brazilian maize hybrid in the years 1983-1987. Estimated yields were within the 10 % error range except for one year.

Table 5

Average results of model calibration and validation for winter wheat and summer maize.

		Growing season	**Average grain yield** (kg ha^{-1}) measured	simulated	varicance	**RMSE**
Winter wheat	calibration	1999/2000 2001/2002	4268	4317	1.2 %	432
	validation	2000/2001	3981	4108	3.2 %	342
Summer maize	calibration	1999/2000 2001/2002	5138	5186	1.0 %	253
	validation	2000/2001	6554	6894	5.2 %	414

3.2. Field experiment

Maximizing yield and gross margin as a function of inputs and production costs is one of the main goals when making management decisions such as fertilizer and irrigation applications (Bannayan et al., 2003). The effects of different management strategies on grain yield in the field experiment were represented in Table 6.

The average winter wheat grain yields over the three vegetation periods indicated that, independent of irrigation regimes, the highest grain yields were reached by the treatments “optimized fertilization”, followed by the treatments “traditional” and “suboptimal fertilization”. However between the treatments “optimized” and “traditional fertilization” no significant difference existed, whereas grain yields in the “suboptimal” treatments decreased significantly. Considering the different irrigation treatments the highest winter wheat grain yields were reached by the “traditional treatments”, followed by the “optimized” and “suboptimal treatments”. However the differences between the “traditional” and “optimized irrigation” treatments were not significant whereas the grain yield of the “suboptimal irrigation” treatments was significantly reduced.

Summer maize was not irrigated and the different irrigation treatments applied to winter wheat showed only small effects on the grain yield of succeeding maize. The same was true for the fertilization treatments. The highest grain yield was reached by the treatments “optimized fertilization” followed by the treatments “traditional” and “suboptimal fertilization”.

Overall, the results showed, that the differences in grain yield between “traditional” and “optimized fertilization” were not significant. One possible reason could be that crop N demand of wheat and summer maize is much lower than the applied rates of N in the NCP (Gao et al., 1999). This corresponds with results of Jia et al. (2001) and Chen et al. (2004) who showed that without any risk of yield decrease N fertilizer rates for winter wheat in the NCP could be reduced to < 180 kg N ha^{-1} when soil NO_3 testing or a yield response curve method was used. Similar results were found for irrigation management. According to Zhang et al. (2005) winter wheat could attain its maximum yield with less than full application of the current irrigation practice.

Beside the effects on grain yield, Table 6 indicates also the effects of different irrigation and N-fertilizer amounts on gross margin. The highest gross margin regarding the different fertilizer amounts was reached within the “optimized” treatments followed by the “suboptimal” and “traditional fertilizer” treatments independently of the cultivar. Even if grain yields of the “suboptimal” treatments were significantly lower than grain yields of the “traditional” treatments they reached the same level of gross margin because the "suboptimal fertilizer" treatments went along without any costs for nitrogen fertilization. The gross margin of the different irrigation treatments increased by the order "suboptimal", "optimized" and "traditional irrigation". However, the differences between the "traditional" and "optimized" treatments were small. The highest gross margin in the double cropping of winter wheat and summer maize was observed with treatment number 9 ("optimized irrigation" and "optimized N-fertilization").

The analysis of the different irrigation and N-fertilizer treatments of the field experiment showed that with a higher input of nitrogen fertilizer and irrigation water grain yields did not equally rise as the costs for the input factors. Therefore, the highest gross margin was not reached with the highest input of nitrogen and irrigation. This result corresponds with the report of Zhu and Chen (2002) who had reviewed the nitrogen fertilizer use in China. They found that the maximum yield, demonstrated by yield versus N application rate curves, is usually higher than the yield of the maximum economic efficiency. In China the N application rate by farmers is considerably higher than the peak with maximum economic efficiency. As a consequence, additional N applied to achieve maximum yields inevitably results in high N losses (Zhu and Chen, 2002).

Table 6

Average grain yield (kg DM ha^{-1} a^{-1}) and gross margin (¥ ha^{-1} a^{-1}) over the three vegetation periods (1999/2001-2001/2002) for winter wheat, summer maize and the double cropping of both cultivars regarding different nitrogen fertilizer and irrigation treatments in the field experiment.

Treatment	**Management**		**Grain yield** (kg DM ha^{-1} a^{-1})			**Gross margin** (¥ ha^{-1} a^{-1})*		
	irrigation	fertilization	wheat	maize	total	wheat	maize	total
1	suboptimal	suboptimal	3280	5435	8715	3061	6413	9475
2	suboptimal	traditional	3493	5786	9279	2136	5627	7763
3	suboptimal	optimized	3647	5834	9480	3334	6672	10006
4	traditional	suboptimal	4077	5397	9473	3135	6368	9503
5	traditional	traditional	4940	5590	10530	3049	5397	8445
6	traditional	optimized	4947	5707	10653	3909	6498	10407
7	optimized	suboptimal	3730	5364	9094	3054	6330	9384
8	optimized	traditional	4657	5600	10257	3049	5408	8457
9	optimized	optimized	4780	5780	10560	4120	6560	10680

* Currency Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$)

3.3. Simulated scenarios

Based on the model calibration and validation different irrigation scenarios for winter wheat and their effects on grain yield, water consumption and gross margin were simulated for the dry season 2000/2001 (Table 4). As a starting point (= scenario 1) for the simulation of different irrigation scenarios treatment 9 ("optimized irrigation" and "optimized fertilization") was used because this treatment reached the highest gross margin (Table 6). The nitrogen fertilization amount for winter wheat in treatment 9 was 65 kg N ha^{-1}. The costs for the N-fertilizer amounted to 260 ¥ ha^{-1} (4.00 ¥ kg N^{-1}) and were considered in all succeeding scenarios. Table 7 shows the irrigation schedules and amounts for the simulated scenarios and Table 8 gives an overview on the changes in irrigation amount, total water supply, grain yield and gross margin.

One of the most important aspects of water-saving in irrigated agriculture is the irrigation scheduling because the water sensitivity varies among different growth stages (Zhang et al., 1999). The irrigation in scenario one took place at six different growth stages (Table 7). However the results of scenario three, four and five demonstrated that a reduction in irrigation frequency may not always lead to a decrease in grain yield. Commonly grain crops are more sensitive to water stress during flowering and early seed formation than during vegetative or grain filling phases (Doorenbos and Kassam, 1979). Results of Zhang et al. (2003) showed that irrigation before the over-wintering period could be omitted due to its loss to soil evaporation and its effects on increasing the non-effective tillers in spring. According to Zhang et al. (1999) wheat is particularly sensitive to water stress in the growth stages from jointing to heading and from heading to milk stage. Similar results were found in our study. The results showed that irrigation during seedling development (before winter) and at milk stage was not essential for the formation of grain yield. However, our study also showed that an additional irrigation during the regreen-ing stage (scenario five) might lead to a further increase in grain yield.

Besides the irrigation frequency also the irrigation amount affected grain yield. With a complete renouncement of irrigation like in scenario two grain yield dropped to 1089 kg ha^{-1} leading to a decrease of 68.2 % in gross margin, as the yield reduction could not be compensated by the saved irrigation costs (Table 8). Hence, a supplemental irrigation is required in wheat to maintain high yields (Wang et al., 2001) and to ensure an adequate gross margin for the farmers. Besides the necessity of irrigation for wheat, scenario three demonstrates the enormous potential for water saving without a financial deterioration for the farmers. The simulation indicated that a reduction in the irrigation frequency from six to four times and a reduction in the irrigation amount of up to 50 % was possible without any decrease in gross margin. The model results indicated that if wheat grain yield dropped by 16.1 % to a level of 3721 kg ha^{-1} this reduction will be balanced by reduced irrigation costs.

As the Chinese government aims to achieve the goal of self-sufficiency (Huang 1998), scenario four tested the considerable potential for reducing the irrigation amount without any decrease in actual yield level. The simulation indicated that a reduction of the amount of irrigation water of up to one third is possible without any yield losses. This was reached mainly by reducing the irrigation frequency from six to four times. The saved irrigation costs would lead to an increase in gross margin of up to 672 ¥ ha^{-1} (18.6 %).

A maximum gross margin of 4763 ¥ ha^{-1} was reached in scenario five. The result was obtained with an irrigation amount of 290 mm which is 6.5 % (20 mm) lower in comparison to the starting point and with an reduction in the irrigation frequency from six to five times. The maximum gross margin was connected with the highest grain yield 5243 kg ha^{-1}.

Table 7

Irrigation scheduling and amounts (mm) to winter wheat for the simulated scenarios.

	Irrigation (mm)							
Scenario	seedling development (Nov.)	regreening (Mar.)	tillering (Mar.)	jointing (Apr.)	booting (May)	flowering (May)	milk (May)	total
1	77	0	49	51	53	40	40	310
2	0	0	0	0	0	0	0	0
3	0	0	50	50	25	30	0	155
4	0	0	50	60	50	40	0	200
5	0	30	60	70	60	70	0	290

Table 8

Irrigation amount (mm), total water supply (mm), grain yield (kg ha^{-1} a^{-1}) and gross margin (¥ ha^{-1} a^{-1}) of winter wheat for the simulated scenarios (scenario 1 = 100%).

Scenario	Irrigation		Total water supply**		Grain yield		Gross margin	
	(mm)	(%)	(mm)	(%)	(kg ha^{-1} a^{-1})	(%)	(¥ ha^{-1} a^{-1})*	(%)
1	310	100,0	452	100,0	4436	100,0	3602	100,0
2	0	-100,0	262	-42,0	1089	-75,5	1144	-68,2
3	155	-50,0	370	-18,1	3721	-16,1	3610	0,2
4	200	-35,5	394	-12,8	4445	0,2	4274	18,6
5	290	-6,5	442	-2,2	5243	18,2	4763	32,2

* Currency Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$)

** Total water supply = effective irrigation + precipitation + depletion of the initial soil water content

Changes in the irrigation amounts and frequencies to winter wheat showed only small effect on yields of the following crop summer maize because there was enough precipitation. In 2001, the simulated yields for summer maize ranged between 6982 and 7244 kg ha^{-1}. With a price of 1.18 ¥ kg^{-1} this corresponded to 8239 respectively 8548 ¥ ha^{-1}. The fertilizer costs amounted to 300 ¥ ha^{-1} and resulted in a gross margin between 7939 and 8248 ¥ ha^{-1} for summer maize. The total gross margin for the different scenarios of double cropping winter wheat and summer maize is given in Table 9.

Table 9

Gross margin (¥ ha^{-1} a^{-1}) of the simulated scenarios .

Scenario	Gross margin (¥ ha^{-1} a^{-1})*		
	winter wheat	summer maize	total
1	3602	7051	10654
2	1144	7244	8388
3	3610	6982	10592
4	4274	6994	11268
5	4763	7134	11897

* Currency Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$)

The results of the simulated scenarios showed that there is a considerable potential for saving irrigation water even under dry conditions like in the growing season 2000/2001. Similar results were found by Zhang et al. (1999) and Wang et al. (2001) who suggested a reduction of irrigation frequency and amount of current irrigation practices in the NCP to improve overall irrigation efficiency. For the purpose of improvement of gross margin, models can help to determine an optimum value for total water consumption where grain yield and gross margin were all relatively high. However this value largely depends on the cost of irrigation water. Due to industrialization and urbanization there is an increasing competition for water in China (Anderson and Peng, 1998; Rosegrant and Ringler, 2000). In 1997, the ratio of water used in the agriculture-industry-domestic sector was 70:20:10. It is estimated that in 2050 the ratio will change to 54:30:16 (Jin and Young, 2001). The rapid economic development as well as changes in climate will make water for agricultural production more scarce and more expensive.

4. Conclusion

Grain yield and gross margin are important parameters to select an appropriate irrigation management under water scarcity like in the NCP. Crop models such as DSSAT offer the possibility to estimate crop water use and can help to develop appropriate irrigation strategies. Although many irrigation scenarios can be simulated with DSSAT our simulations cannot give a precise irrigation schedule for winter wheat due to the unpredictability in precipitation. However the model results showed that there might be a considerable potential for a reduction of irrigation water during the winter wheat growing season.

It can be concluded that in areas with similar conditions as in the simulations, the common irrigation amount to wheat could be reduced by about one third without any yield losses. Furthermore, a reduction of about 50 % may be possible without a decrease in the initial gross margin. However, without irrigation gross margin would be very low, because the saved water costs could not balance the losses in grain yield. Therefore, a supplemental irrigation at critical growth stages seems to be essential to maintain high yields and to ensure an adequate gross margin for the farmers.

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Results of the third article indicated an enormous potential for saving irrigation water without any decline in yield or a financial loss for the farmers. This was possible by the optimization of the irrigation amount, the irrigation frequency and the temporal distribution of the irrigation events to winter wheat. However, the results also indicated that a supplemental irrigation to winter wheat at critical growth stages seems to be essential.

*Besides the optimization of irrigation in the double cropping system, there is also the possibility of agronomic adaptations within the cropping systems itself e.g. a lower sowing density or a reduction in the cropping index which could help to save water. The **fourth article** introduces the cropping systems three harvests in two years (double cropping winter wheat and summer maize in the first year followed by only spring maize in the second year) and the single cultivation of spring maize. The two systems were compared regarding grain yield, nitrogen use efficiency, water use efficiency and gross margin.*

Prototyping and evaluation of two sustainable cropping systems for the North China Plain - spring maize monoculture versus three harvests in two years

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Abstract

Field experiments aiming at prototyping and evaluating the cropping systems spring maize monoculture (SpMM) and three harvests in two years (3H2Y) (winter wheat - summer maize - spring maize) were conducted in Dongbeiwang (DBW), Quzhou (QZ) and Wuqiao (WQ) experimental stations in the North China Plain (NCP) from 2004 to 2006. SpMM and 3H2Y were evaluated and compared considering grain yield, gross margin, nitrogen use efficiency (NUE) and water use efficiency (WUE). The comparison of the systems SpMM and 3H2Y indicated no significant differences in grain yield, biomass accumulation and gross margin at the DBW and QZ site. Low spring maize yields at the WQ site resulted in significant differences between the two systems. Enhanced NUE (68-122 %) and WUE (68-84 %) were observed in both locations DBW and QZ for the system SpMM. A second field study focused on the evaluation of different sowing densities, nitrogen managements, irrigated water amount, and sowing dates on grain yield, biomass yield, harvest index and yield parameters of spring maize. Within the tested four sowing densities and four sowing dates, the sowing density of 6.7 plants m^{-2} and the sowing date of 28th of May resulted in highest yields. The tested three nitrogen managements indicated that neither optimized management nor traditional management could signify-cantly increase grain yields in both years. Grain yields were highly correlated with irrigated water amounts. Overall, the

study indicated that SpMM has the potential to reduce water and nitrogen input at relatively minor yield and profit penalties and to increase NUE and WUE. As the system 3H2Y performed more sustainable in WQ, it is concluded that future adaptations in cropping systems have to be tested for different locations and regions in the NCP.

Keywords: spring maize, three harvests in two years, double cropping system, North China Plain, intensive agriculture

Abbreviations: ANOVA (analysis of variance), CAU (China Agricultural University), DBW (Dongbeiwang), DM (dry matter), FC (field capacity), K (potassium), LAI (leaf area index), N (nitrogen), NCP (North China Plain), NUE (nitrogen use efficiency), P (phosphorus), QZ (Quzhou), RE (revenue), RMB (currency, Chinese Yuan), SNK (Student-Newmann-Keuls), SPMM (spring maize monoculture), SWC (soil water content), TKM (thousand kernel mass), WQ (Wuqiao), WUE (water use efficiency), 3H2Y (three harvests in two years)

1. Introduction

As a large agricultural country, China feeds 21 % of the world population by 7 % of the world arable land area. One-fifth of Chinas food production is produced in the North China Plain (NCP) (Zhang et al., 1999; Chen, 2003; Deng et al., 2006). High yields are accomplished by widely utilizing intensive agricultural production. However, this has led to more and more severe problems such as environmental pollution and resource shortage.

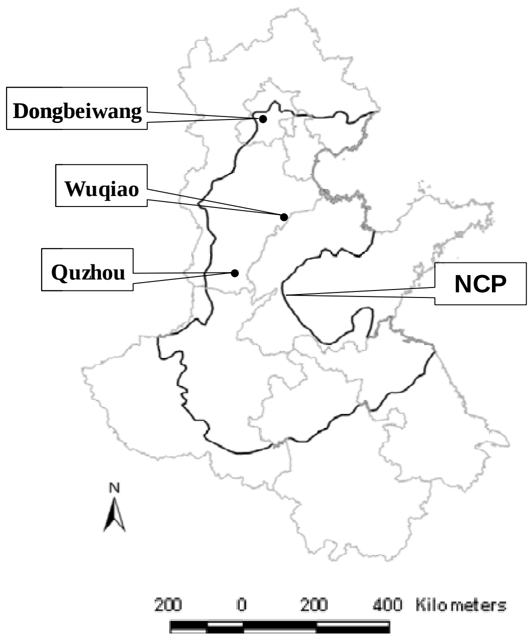

Fig. 1. Border of the North China Plain (NCP) and the three experimental locations Dongbeiwang, Quzhou and Wuqiao.

The NCP (Fig. 1) is located between 32^{o} and 40^{o} N latitude and 100^{o} and 120^{o} E longitude in the north of the eastern part of China, which covers an area of about 350000 km^2. The NCP has a continental monsoon climate with cold and dry winters, hot and humid summers, and obvious seasons. The average annual temperature and precipitation range between 8 and 15 °C, and 500 and 1000 mm, respectively. The distribution of the annual precipitation is not even, almost 80 % of the precipitation occurs from July to September. Therefore drought is likely to happen in spring and early summer, which is the main growing season of winter wheat (Zhu, 1998).

In 2005, the sowing area in NCP was 33.9 million hectares, which produced 167.7 million tones of grain (including all seven provinces and cities), which is roundabout 35 % of the total national grain yield. The double cropping system is the most popular cropping system in the NCP comprises 57 % of total farming area. The double cropping system normally consists of winter wheat and another crop planted in summer, such as summer maize, soybean or cotton, among which the area of a winter wheat - summer maize rotation comprises around 60 % (China Statistical Yearbook, 2003). Winter wheat is sown after ploughing in mid October and harvested in mid June. After winter wheat, summer maize is sown directly without time lag and harvested at the beginning of October. Because of the limited time, farmers usually harvest summer maize without grain being mature, which is of disadvantage for the overall yield of summer maize.

As a high intensive agricultural system, the winter wheat - summer maize rotation played a leading role in the NCP in the past 30 years (Zhang et al., 2005). The system almost occupied all the resources of solar radiation, heat, water and gas, and utilized soil productivity completely. Although it has improved grain production greatly, nowadays it represents some malpractices when people are advocating sustainable agricultural development and pursuing environmental protection.

China is a country with a problem of severe water shortage. The water resources per capita are only 2152 m^3 in 2005 (China Statistic Yearbook, 2005). In the NCP there are only 335 m^3 per capita water resources of which 73 % are used in agriculture (China Statistic Yearbook, 2002; China Geological Survey, 2005). Irrigation is a basic necessity for winter wheat production, ensuring a high yield level due to the low precipitation amounts from October until June. Precipitation amounts during that period are dissatisfying the overall water demand of winter wheat. Winter wheat is usually irrigated 3 to 5 times depending of seasonal precipitation situation, with a total irrigation amount of 300-400 mm. The water used for winter wheat represents about 70 % of total agricultural water use (Wang et al., 2000). 64 % of the irrigated area in the NCP relies on groundwater (Yang and Zehnder, 2001). During the last 57 years, groundwater levels have declined more than 1 m annually (Li, 2006). As a consequence of the intensive irrigation practices, the water resource crisis in the NCP will become more and more severe.

In contrast to winter wheat, summer maize is grown in parallel to the rainy season in the NCP. Normally there is no irrigation or only a small amount of irrigation water applied to summer maize. Nevertheless, due to the concentrative precipitation, nitrogen losses are easier to happen, especially under a superfluous nitrogen input. During the last decades either winter wheat or summer maize have been given excessive nitrogen applications by most farmers in the NCP. For example, in Beijing suburb the average nitrogen fertilizer amount applied in 1995 to both crops was estimated to 569 kg ha^{-1}, which results in a dramatically low nitrogen use efficiency (Zhao et al., 1997). Besides fertilization, the double cropping system usually relies heavily on the use of herbicides, insecticides, plant growth regulators, and mechanization. This intensive use of arable land is prone to loss of soil organic matter, resulting in soil structure decline, land degradation and loss of soil productivity (Sharma and Campbell, 2003). Hence in the long term, the double cropping system cannot be considered as suitable for a sustainable agricultural development. In intending sustainable agriculture, the double cropping system probably will have to be substituted by other cropping systems in the future.

Currently numerous alternative cropping systems are being discussed. However, for most of the copping systems no data or agronomic advices on sowing density, nitrogen fertilization or irrigation, etc. are available right now. Two of the most promising alternative cropping systems are spring maize monoculture (SpMM) and three harvests in two years (3H2Y). In the northern part of the NCP, and some mountainous areas, the amount of suitable growing degree day cannot satisfy two crops. In these regions, farmers only plant spring maize which is sown between the end of April and the beginning of May year by year. This cropping system is regarded as SpMM.

Due to lower temperatures during the seedling phase, spring maize usually needs a longer growing period and more resources to develop, when compared to summer maize. However, spring maize has a higher yield potential than summer maize. For example, in Beijing region, the grain yield of spring maize averages around 9.0 t ha^{-1}, whereas grain yield of summer maize ranges between 6.0 and 7.5 t ha^{-1} a^{-1} (Jiu, 2005). Normally spring maize is irrigated with no more than 200 mm to guarantee a normal growth. Nitrogen fertilizer amounts range around 250 kg ha^{-1} a^{-1}. In comparison to the traditional double cropping, there is little decline in the grain yield, and yet the cultivation of spring maize could save about 50 % water, nitrogen or any other input resource. Therefore, the cultivation of spring maize seems to be more reasonable and favourable for the implementation of a sustainable cropping system in the NCP taking into account especially the problems of low water use efficiency (WUE) and nitrogen use efficiency (NUE). However, the disadvantages of slightly lower yields, more diseases and insects sometimes found in SPMM have to be considered and suitable agronomic strategies for successfully implementing SPMM systems have to be worked out. Instead of the sole cultivation of spring maize, the cropping system 3H2Y, consisting of the double cropping of winter wheat and summer maize in the first year, and the cultivation of spring maize in the second year, has been a transitional cropping system from monoculture to double cropping in the history of the NCP. Nowadays, this cropping system is only practiced in a few parts of the NCP. However, especially in the context of sustainability and improved nitrogen and irrigation management, it is considered as another possible substitute cropping system. As for both cropping systems actual data sets on grain yield, WUE, NUE and gross margin are widely missing and agronomic management strategies on sowing density, nitrogen fertilizer and irrigation amount are lacking, the objectives of this study were to prototype and compare the cropping systems SpMM and 3H2Y considering grain yield and yield components, nitrogen and water input at three locations in the NCP. Effects of sowing densities and dates, nitrogen and irrigation regimes of spring maize were specially studied for further improvements in grain yield of both cropping systems.

2. Materials and Methods

2.1. Experiment one - spring maize monoculture (SpMM) versus three harvests in two years (3H2Y)

2.1.1. Sites description and experimental design

A field experiment was conducted from 2004 to 2006 to compare different cropping systems in the NCP. The evaluation and comparison on SpMM and 3H2Y were carried out at three locations: Dongbeiwang (DBW) (north-west of Beijing, 39.6° N, 116.2° E), Quzhou (QZ) (400 km southwest of Beijing, 36.5° N, 115.0° E) and Wuqiao (WQ) (250 km south of Beijing, 37.3° N, 116.3° E) (Fig. 1). Soils were Calcaric Cambisol (FAO taxonomy) with a texture of silty loam in DBW and QZ, and alluvial Meadow soil (FAO taxonomy) with a soil texture of sandy clay in WQ, respectively. The average annual temperature and precipitation of the investigated locations were 11.5 °C and 627 mm (DBW), 12.6 °C and 514 mm (QZ), and 13.2 °C and 562 mm (WQ) respectively. Monthly average air temperatures and precipitation of the three locations over the time period of the field trials are given in Figure 2. Determined soil characteristics of the different sites at the time of planting are presented in Table 1.

Table 1

Characteristics of surface soil (0-30 cm) at sowing for the experiments 1 and 2.

Experiment	**Location**	**N** (%)	**P** (mg kg^{-1})	**K** (mg kg^{-1})	**Organic C** (%)	**Bulk density** (g cm^{-3})
1	Dongbeiwang	-	20	120	1.80	1.42
	Wuqiao	-	5	68	1.27	1.39
	Quzhou	-	15	73	0.84	1.54
2	Dongbeiwang	0.11	43	192	2.35	1.42

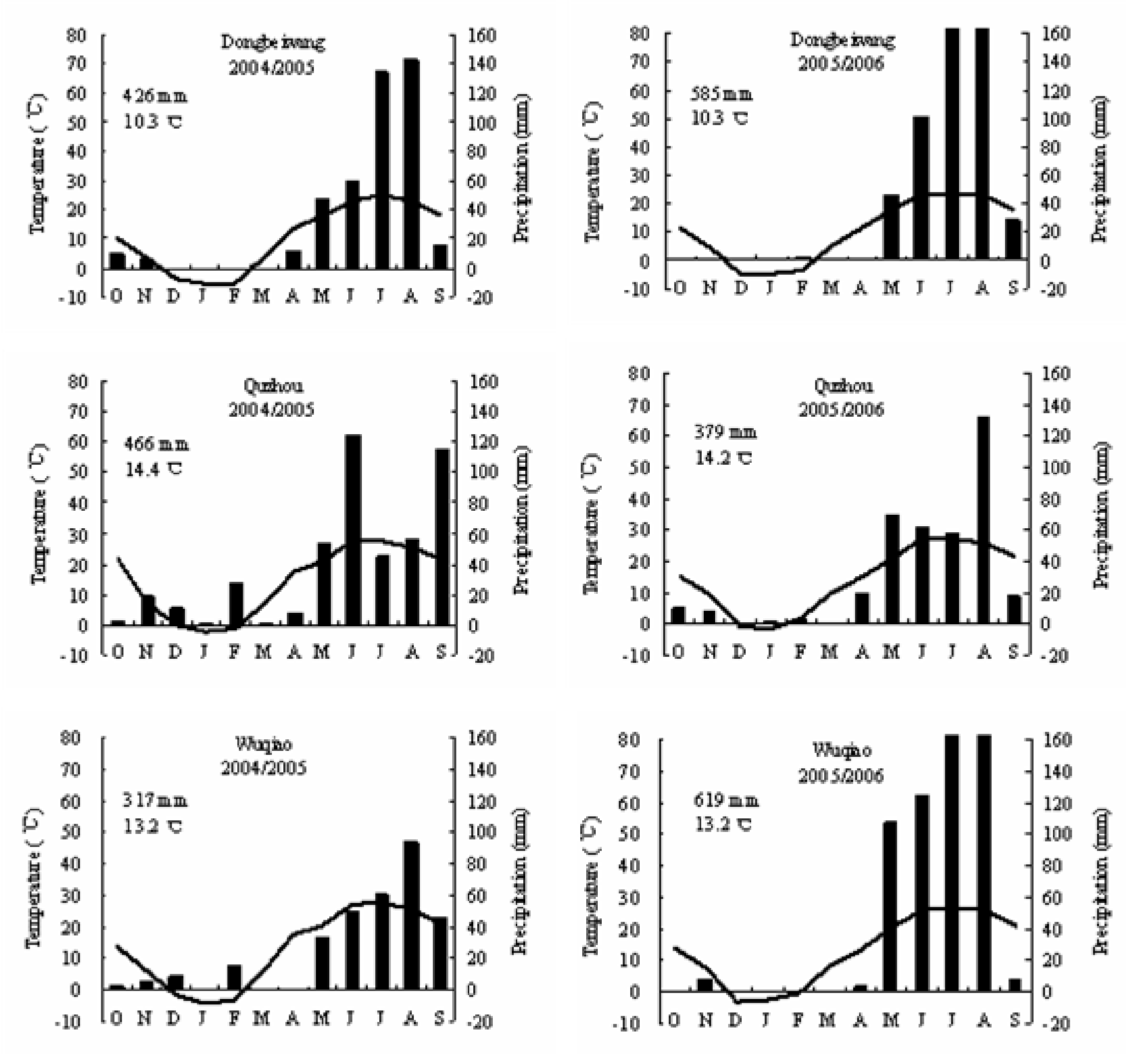

Fig. 2. Monthly average air temperature (^{o}C) [line] and precipitation (mm) [bars] of the locations Dongbeiwang, Quzhou and Wuqiao in the growing periods 2004/2005 and 2005/2006.

The experiment was conducted using a one factorial, completely randomized block design. There were two cropping system treatments: (i) SpMM and (ii) 3H2Y, in which winter wheat, summer maize, and spring maize were planted over two years. Every treatment had four replications at each location. Sowing of wheat was done with a drilling machine, while that of maize was done by hand. The sowing and harvest date of the different crops are given in Table 2. The experiment consisted of different cultivars. Selected cultivars were representative for the local regions (Table 2). In 2005, the sowing densities of winter wheat were 570 (DBW), 402 (QZ), 746 (WQ) plants m^{-2}, respectively. Row spaces were set to 0.15 m in all locations. The sowing densities of summer maize and spring maize were all 6.5 and 7.0 plants m^{-2} at three locations in both years. The row spaces were 0.70 m in DBW and WQ, while a row spacing of 0.60 m was used in QZ.

2.1.2. Field management

Target grain yields of maize and winter wheat were used for calculating the necessary nitrogen fertilization amount. In all treatments nitrogen was applied as urea. Additionally, nitrogen fertilization was based on N_{min}-measurements (NO_3^--N) in specified soil layers (0-30 cm, 30-60 cm, 60-90 cm). Fertilizer was broadcast before planting and at end of tillering stage in combination with irrigation in winter wheat, and at four leaf stage and 6 nodes detectable stage in maize. The applied amounts of phosphorus (P) and potassium (K) were based on data according to the China Agricultural University (CAU)-system in the two cropping systems (Zhao, 2002). In the first year of 3H2Y, P fertilizer was applied before sowing of winter wheat as calcium superphosphate. K fertilizer was applied before sowing of summer maize as potassium sulphate. In SpMM and the second year of 3H2Y, P and K fertilizers were applied just before sowing. Table 2 shows the amounts of N, P and K fertilizers for winter wheat, summer maize and spring maize in the different cropping systems.

The same irrigation system was applied for the same crops in all three locations. For winter wheat, irrigation was based on measurements of volumetric soil water content (SWC) aiming to keep available field capacity (FC) between 45 and 80 % during sensitive growth stages (tillering, early shooting, booting and grain filling). Irrigation for summer maize was provided just after nitrogen fertilization to ensure that the fertilizer could be dissolved. The irrigation amount was based on attaining 80 % plant available FC. For spring maize, it was necessary to irrigate before sowing and at 6 nodes detectable stage to ensure proper germination establishment and nutrient supply out of applied mineral fertilizer. Irrigation amount was based on attaining 80 % plant available FC similar to summer maize. Table 2 shows the irrigation amount applied to the different crops at all three locations from 2005 to 2006.

Table 2

Field management parameters (experiment 1) of the cropping system three harvests in two years (3H2Y) (winter wheat and summer maize in the first year and only spring maize in the second year) in comparison to the single cultivation of spring maize (SpMM) at the locations Dongbeiwang, Quzhou and Wuqiao in the growing periods 2004/2005 and 2005/2006.

Growing period	Location	Treatment	Crop	Cultivar	Sowing date	Irrigation (mm)	Fertilization (kg ha^{-1}) N	P	K	Harvesting date
2004/2005	Dongbeiwang	3H2Y	Winter wheat	JD8	11. Oct. 2004	305	190	40	0	18. Jun. 2005
			Summer maize	CF024	19. Jun. 2005	100	75	0	0	04. Oct. 2005
		SpMM	Spring maize	CF1505	29. Apr. 2005	125	65	40	0	20. Sep. 2005
	Quzhou	3H2Y	Winter wheat	SJZ8	12. Oct. 2004	180	154	60	0	11. Jun. 2005
			Summer maize	ZD958	13. Jun. 2005	75	65	0	85	04. Oct. 2005
		SpMM	Spring maize	CF1505	27. Apr. 2005	80	40	130	85	10. Sep. 2005
	Wuqiao	3H2Y	Winter wheat	SJZ8	16. Oct. 2004	105	105	58	0	11. Jun. 2005
			Summer maize	ZD958	16. Jun. 2005	132	30	0	50	03. Oct. 2005
		SpMM	Spring maize	CF1505	21. Apr. 2005	120	72	58	50	05. Sep. 2005
2005/2006	Dongbeiwang	3H2Y	Spring maize	CF1505	29. Apr. 2006	140	70	50	50	23. Sep. 2006
		SpMM	Spring maize	CF1505	29. Apr. 2006	140	70	50	50	23. Sep. 2006
	Quzhou	3H2Y	Spring maize	CF1505	02. May 2006	168	130	113	102	25. Sep. 2006
		SpMM	Spring maize	CF1505	02. May 2006	168	130	113	102	25. Sep. 2006
	Wuqiao	3H2Y	Spring maize	CF1505	27. Apr. 2006	60	30	50	50	10. Sep. 2006
		SpMM	Spring maize	CF1505	27. Apr.2006	60	70	50	50	10. Sep. 2006

2.1.3. Data collection

Different growth stages were recorded according to the extended BBCH scale (Meier, 1997). Samples were collected from an area of 1 m^2 per plot at five growth stages for measuring dry matter accumulation and leaf area index (LAI). The five growth stages of winter wheat were shooting stage, mid boot stage, flowering stage, medium milk stage and maturity, and those for maize (both spring and summer maize) were shooting stage, 6 nodes detectable stage, flowering stage, medium milk stage and maturity. Fresh matter was measured by dividing plant samples in leaf, stem, grain and cop. Samples were dried at 80 °C until constant weight for dry matter. Four plants were randomly selected to calculate LAI by measuring leaf length and maximum leaf width of all leaves on each plant. Leaf area was estimated as the sum of leaf length x leaf width x 0.75 (Montgomery, 1911) of all leaves of a plant. At maturity, yields were determined by harvesting areas of 20 (DBW), 9 (QZ) and 12 (WQ) m^2 per plot. Before harvesting, separate samples (three times 1 m^2) were taken for counting the ear number and grains per ear. After counting, the plants were separated and dried at 80 ^oC until constant weight was reached to determine dry matter. Thousand kernel mass (TKM) was determined by counting and weighting five hundred kernels for three times of each plot.

2.2. Experiment two - different management strategies of spring maize monoculture (SpMM)

2.2.1. Site description and experimental design

Experiment two was conducted beside experiment one in DBW over the growing seasons of 2005 and 2006. The objective was to prototype a SpMM cropping system, wherefore the effects of different management strategies on grain yield of spring maize were evaluated. The experiment consisted of four independent one-factorial sub-experiments. Base soil fertility was obviously higher than in experiment one (Table 1), which could be classified as high fertility soil according to a soil fertility classification in Beijing farmland (Liu et al., 1999)

Sub-experiment one tested the effect of four different sowing densities (5.2, 6.7, 8.2 and 9.7 plants m^{-2}) on yield of spring maize. Sub-experiment two investigated the effect of three different nitrogen managements applied as: 1) no nitrogen fertilization 2) optimized nitrogen fertilization with 140 kg N ha^{-1} (based on N_{min}-measurements and target yield) and 3) farmer's practice with 240 kg N ha^{-1}. The total amount of nitrogen was split into two rates in treatment two, 30 kg ha^{-1} were applied at planting and 110 kg ha^{-1} were applied at 6 nodes detectable stage. In treatment three, nitrogen fertilizer was applied in three rates at a ratio of 1:2:3 at planting, beginning of stem elongation and 6 nodes detectable stage. Sub-experiment three investigated the effect of three different irrigation amounts on yield of spring maize. In all three treatments, the amount of 80 mm irrigation water was applied before ploughing. Treatment one was only irrigated before ploughing, treatment two was additionally irrigated at 6 nodes detectable stage with an amount of 60 mm. Treatment three was irrigated at 6 nodes detectable stage with an amount of 120 mm. Sub-experiment four investigated the effect of four different sowing dates on yield of spring maize. Spring maize was sown every 17 days starting from April 24 in 2006, resulting in the different sowing dates April 24, May 11, May 28 and June 14.

All the sub-experiments were implemented as one-factorial completely randomized block design with four replications. Sub-experiment one and two were carried out in 2005 and 2006, while sub-experiment three and four were only conducted in 2006. The complete management dates are listed in Table 3. In all sub-experiments grain yield and numbers of cobs were determined by harvesting an area of 7.2 m^2 per plot. Grain number per cob and TKM were measured by randomly selecting 20 cobs from each plot.

Table 3

Field management parameters for spring maize (experiment 2) of the four sub-experiments at the Dongbeiwang site in the growing periods 2005 and 2006.

Sub-experiment	Growing period	Cultivar	Sowing date	Irrigation amount (mm)	Nitrogen mangement	Sowing denstity (plants m^{-2})	Row spacing (m)	Harvesting date
2.1- Sowing density	2005	CF1505	12. May 2005	100+120[b]	Farmer's practice	F[a]	0.6	21. Sep. 2005
	2006	CF1505	24. Apr. 2006	100+120[b]	Farmer's practice	F[a]	0.6	14. Sep.2006
2.2 - Nitrogen mangement	2005	CF1505	11. May 2005	100+120[b]	F[a]	6.7	0.6	21. Sep. 2005
	2006	CF1505	26. Apr. 2006	100+120[b]	F[a]	6.7	0.6	15 Sep. 2006
2.3 - Irrigation amount	2006	CF1505	26. Apr. 2006	F[a]	Farmer's practice	6.7	0.6	15 Sep. 2006
2.4 - Sowing date	2006	CF1505	F[a]	100+120[b]	Farmer's practice	8.3	0.6	Maturity

[a] F means the treatment factor of each sub-experiment.

[b] Irrigation was divided into two times (before ploughing and 6 nodes detectable stage).

2.3. Economic analysis

A comparison of gross margin between the cropping systems SpMM and 3H2Y was carried out at all three locations. Gross margin was calculated by subtracting the variable costs of all input factors from the revenue (RE). RE was calculated according to the equation 1:

$$RE = W_y \times W_p + M_y \times M_p \qquad [1]$$

where RE = revenue, W_y = wheat grainyield, W_p = wheat price, M_y = maize grain yield, M_p = maize price. Wheat and maize grain yields were based on 14 % moisture. For the calculation of gross margin, the variable costs: fertilizer, irrigation water, seeds, pesticides, herbicides and mechanization were considered. Table 4 lists the considered costs for each factor. The prices of seeds, irrigated water, mechanization, pesticides and herbicides were taken from results of a survey of farmers and market in the NCP. The prices of fertilizers were obtained from the website of http://www.npk.cc in 2006. The grain prices of wheat and maize were based on the quotation of 2006 at the website http://www.agri.gov.cn/.

2.4. Statistic analysis

Analysis of variance (ANOVA) was conducted for each experiment and sub-experiment, respectively. Comparison of means was done by using the test of Student-Newmann-Keuls (SNK) in SAS version 9.0 (SAS Institute Inc., Cary, NC, USA, 2002).

Table 4

Prices for the economical analysis.

Factor	Item (Unit)*	Winter wheat	Summer maize	Spring maize
Seeds	Seeds (¥ ha^{-1})	340.00	603.00	630.00
Pesticides	Imidacloprid (¥ ha^{-1})	60.00	-	-
	Furadan (¥ ha^{-1})	-	150.00	150.00
Herbicides	Atrazine (¥ ha^{-1})	-	32.00	32.00
	Acetochlor (¥ ha^{-1})	-	9.00	9.00
Mechanization	Plowing (¥ ha^{-1})	400.00	-	300.00
	Drill (¥ ha^{-1})	150.00	150.00	150.00
	Reaping (¥ ha^{-1})	200.00	200.00	200.00
	Rototiller (¥ ha^{-1})	-	-	150.00
Irrigation	(¥ m^{-3})	0.30	0.30	0.30
Fertilization	N (¥ kg^{-1} N)	3.74	3.74	3.74
	P (¥ kg^{-1} P)	8.24	8.24	8.24
	K (¥ kg^{-1} K)	6.40	6.40	6.40
Grain	Revenue (¥ t^{-1})	1540.00	1351.00	1351.00

* Currency Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$)

The prices of seeds, irrigated water, mechanization, pesticides and herbicides were sourced from results of survey of farmers and market in the North China Plain. The prices of fertilizers were got from the website of http://www.npk.cc in 2006. The grain prices of wheat and maize were sourced from the quotation in 2006 at the website http://www.agri.gov.cn/.

3. Results and Discussion

The challenge confronting agriculture in China is to produce sufficient food to meet the demand of its growing population. In quest of augmenting production, there has been a tendency to adopt high application rates of N and irrigation water (Home et al., 2002). In the main agricultural areas of eastern China including the NCP, farmers often applied excessive quantities of nitrogen fertilizer in order to attain high levels of food security (Jin, 1998; Chen et al., 2006).

Table 5

Grain yield (t DM ha^{-1}), biomass yield (t DM ha^{-1}), nitrogen use efficiency (kg kg^{-1}) [NUE], water use efficiency (kg l^{-1}) [WUE_I and WUE_{I+P}] and gross margin (¥ ha^{-1} a^{-2}) of the cropping system three harvests in two years (3H2Y) (winter wheat and summer maize in the first year and only spring maize in the second year) in comparison to the single cultivation of spring maize (SpMM) at the locations Dongbeiwang, Quzhou and Wuqiao in the growing periods 2004/2005 and 2005/2006 (experiment 1).

Location	**Cultivation system**	**Grain yield** (t DM ha^{-1})	**Biomass** (t DM ha^{-1})	**NUE** (kg kg^{-1})	**WUE_I**[a] (kg l^{-1})	**WUE_{I+P}**[b] (kg l^{-1})	**Gross margin**[c] (¥ ha^{-1} a^{-2})
Dongbeiwang	3H2Y	20.1 a	42.4 a	60 b	37 b	13 a	24722 a
	SpMM	18.0 a	40.3 a	133 a	68 a	15 a	22650 a
Quzhou	3H2Y	17.2 a	36.0 a	76 b	58 b	11 b	15000 a
	SpMM	17.1 a	35.5 a	121 a	96 a	14 a	14698 a
Wuqiao	3H2Y	23.0 a	48.0 a	102 a	77 a	19 a	30241 a
	SpMM	14.7 b	23.5 b	104 a	82 a	15 b	16740 b

Figures within each column and each location followed by the same letter are not significantly different, $p \leq 0.05$.

[a] WUE_I: grain yield per amount of irrigated water

[b] WUE_{I+P}: grain yield per amount of irrigated water plus precipitation

[c] Currency Chinese Yuan (¥) (RMB, 1 ¥ ~ 0.12 US$)

The results of the comparison of the systems 3H2Y and SpMM indicated no significant differences in grain yield, biomass and gross margin at the DBW and QZ site. At the WQ site however, grain and biomass yields as well as gross margin were significantly different between both systems as the system

3H2Y reached the highest and SpMM reached the lowest grain yield compared to all other sites (Table 5). The lower input of N-fertilizer of up to 60 % in the system SpMM resulted in a significantly higher NUE in comparison to the system 3H2Y at the DBW and QZ site. Due to low spring maize yields no significant differences in NUE were found at the WQ site. Similar WUE_I was significantly higher at the DBW and QZ site while no significant differences were found at the WQ site. Taking the amount of precipitation at the different locations into account, WUE_{I+P} for SpMM was only significant higher at QZ site, while no significant different was found at DBW site. Due to low spring maize yields a significant higher WUE_{I+P} for 3H2Y were found at the WQ site.

Grain yields for the individual crops of the two cropping systems are listed in Table 6. The highest yield in the growing period 2004/2005 was reached by spring maize (9.5 t DM ha^{-1}) followed by summer maize (7.5 t DM ha^{-1}) and winter wheat (5.3 t DM ha^{-1}). In the growing period 2005/2006 only spring maize was cultivated resulting in an average yield of 7.2 t DM ha^{-1}. In general, spring maize yields were significantly lower (-24 %) in 2005/2006 due to lodging and a serious abortion of pollination. In 2005, grain yields of winter wheat were 4.8, 5.1

Table 6

Grain yield (t DM ha^{-1}) for the individual crops of the cropping system three harvests in two years (3H2Y) (winter wheat and summer maize in the first year and only spring maize in the second year) and the single cultivation of spring maize (SpMM) at the locations Dongbeiwang, Quzhou and Wuqiao in the growing periods 2004/2005 and 2005/2006 (experiment 1).

Growing period	**Cropping System**	**Crop**	**Grain yield** (t DM ha^{-1})		
			Dongbeiwang	Quzhou	Wuqiao
2004/2005	3H2Y	Winter wheat	4.8 a	5.1 a	6.0 a
	3H2Y	Summer maize	8.3 a	5.3 b	8.9 a
	SpMM	Spring maize	10.3 a	10.9 a	7.2 b
2005/2006	3H2Y	Spring maize	6.9 a	6.7 a	8.1 a
	SpMM	Spring maize	7.7 a	6.3 b	7.5 a

Figures within each line for the individual crops followed by the same letter are not significantly different, $p \leq 0.05$.

and 6.0 t DM ha^{-1} in the DBW, QZ and WQ respectively. Over all three locations, no significant differences were found in winter wheat grain yield. Also, grain yields of summer maize were not significantly different between DBW and WQ, while grain yield in QZ was significantly lower due to a lower kernel number per ear. In 2006, besides QZ, grain yields of spring maize were lower than yields of summer maize. Among the three locations, spring maize yield in WQ were higher than those in DBW and QZ, though the differences were not statistically significant.

An economic analysis should be the dominant factor for evaluating different cropping systems (Wesley et al., 1995). However as no significant differences in gross margin and grain yield were found between the tested cropping systems, environmental protection and sustainable utilization of resources are considered as key indictors (Liebig and Varvel, 1995).

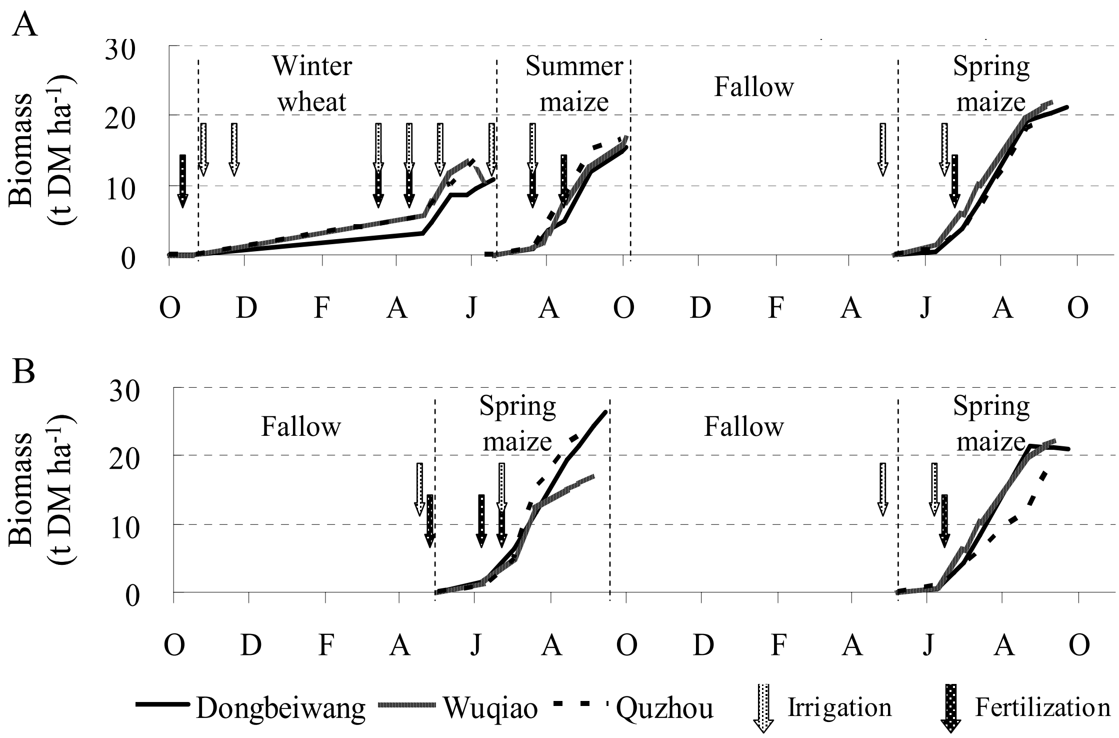

Fig. 3. Biomass accumulation in the cropping system three harvests in two years (winter wheat and summer maize in the first year and only spring maize in the second year) [A] in comparison to the single cultivation of spring maize [B] at the locations Dongbeiwang, Quzhou and Wuqiao in the growing periods 2004/2005 till 2005/2006.

Comparison of the two cropping systems: Different environmental conditions have a remarkable effect on growth and development of plants. Biomass accumulation dynamics of the two cropping systems for the three locations across the NCP are shown in Figure 3.

Within the system 3H2Y, the individual crops specify the management. For winter wheat five irrigations were applied because precipitation can only meet 20-40 % of the crop water requirement (Li et al., 2005). In total nine irrigation applications with a total amount of 300-545 mm and six N-fertilizer applications with an overall total of 165-350 kg N ha^{-1} were carried out. The results of this study correspond with results of Geng et al. (2001) who found that the overall growing conditions and mainly the factors light and temperature in the Huabei Plain (major part of the NCP) are favourable for the system 3H2Y. However, in most cases this system was implemented the amount of precipitation was not sufficient to support high yields. In comparison the system SpMM consumed a lot less water and nitrogen. Four irrigation and N-fertilization events, with a total amount of 180-265 mm water and 135-170 kg N ha^{-1} were applied. Besides the lower input of N and water, the field maintained in fallow once every two years with a duration of about 200 days in 3H2Y, while SpMM got twice fallows in a duration of more than 420 days.

Measures concerning the adjustment of sowing date, sowing density, as well as fertilization and irrigation are important issues for realizing high spring maize yields. In the NCP the knowledge of spring maize production is insufficient and agronomic guidelines for spring maize cultivation are widely missing. In order to grain more knowledge in spring maize cultivation, four sub-experiments were run in parallel to the main experiment at the DBW site. Results for the single experiments are given in Table 7.

Sowing density:

Results of the sub-experiment on sowing density indicated no clear trend in grain yield development. Grain yield first increased then decreased when the sowing density increased from 5.2 to 9.7 plants m^{-2} in both years. The highest grain yields were reached with a sowing density of 6.7 plants m^{-2}, in both years, while the results were only significant different in 2006. In general, the sowing density of 9.7 plants m^{-2} resulted in the lowest grain yields in the two growing seasons. In both years, total biomass

Table 7

Spring maize grain yield (t DM ha^{-1}), biomass yield (t DM ha^{-1}), harvest index [HI], number of kernels ear^{-1}, thousand kernel mass [TKM] and number of ears m^{-2} for the different treatments in experiment 2.

Sub-experiment	Growing period	Treatment	Grain yield (t DM ha^{-1})	Biomass (t DM ha^{-1})	HI (%)	Kernels ear^{-1}	TKM (g)	Ears m^{-2}
2.1 - Sowing density	2005	5.2 plants m^{-2}	9.1 a	19.9 b	0.46 a	595 a	341 a	4.5 d
		6.7 plants m^{-2}	9.4 a	21.5 ab	0.44 a	520 b	323 b	5.6 c
		8.2 plants m^{-2}	8.9 ab	22.2 a	0.40 b	437 c	314 c	6.5 b
		9.7 plants m^{-2}	8.2 b	21.5 ab	0.38 b	392 d	275 d	7.6 a
	2006	5.2 plants m^{-2}	8.1 a	16.9 b	0.48 a	561 a	325 a	4.5 d
		6.7 plants m^{-2}	8.8 a	18.0 ab	0.49 a	497 b	319 ab	5.6 c
		8.2 plants m^{-2}	7.8 a	18.1 ab	0.44 a	370 c	310 b	6.8 b
		9.7 plants m^{-2}	7.1 a	19.4 a	0.37 b	330 c	266 c	8.1 a
2.2 - Nitrogen mangement	2005	No	9.6 a	21.7 a	0.44 a	502 a	343 a	5.6 a
		Opitmized	9.0 a	21.3 a	0.42 a	495 a	340 a	5.4 a
		Farmer´s practice	9.4 a	21.5 a	0.44 a	520 a	341 a	5.3 a
	2006	No	7.8 a	18.0 a	0.44 a	433 a	316 a	5.7 a
		Opitmized	8.0 a	17.2 a	0.47 a	446 a	321 a	5.6 a
		Farmer´s practice	8.3 a	19.2 a	0.44 a	451 a	326 a	5.7 a
2.3 - Irrigation amount	2006	120 + 0 mm	7.5 a	17.8 a	0.43 a	422 a	319 a	5.6 a
		120 + 60 mm	8.0 a	20.0 a	0.40 a	446 a	321 a	5.6 a
		120 + 120 mm	8.3 a	20.2 a	0.41 a	431 a	332 a	5.8 a
2.4 - Sowing date	2006	24 April	7.9 b	19.6 ab	0.41 a	362 c	311 b	7.1 a
		11 May	7.7 b	17.2 b	0.45 a	430 b	253 c	7.1 a
		28 May	8.8 a	20.3 a	0.43 a	472 a	259 c	7.2 a
		14 June	6.8 c	16.1 b	0.42 a	297 d	323 a	7.1 a

Figures within each column and each growing period for the individual experiments followed by the same letter are not significantly different, $p \leq 0.05$.

yields increased with increasing sowing density. In contrast to biomass yields, harvest index, kernels per ear and TKM decreased when sowing density increased. Knowledge on suitable sowing densities for the cultivation of spring maize is one of the key factors for planning maize production (Bavec and Bavec, 2002). Due to the effects of interplant competition the grain yield of a single maize plant is reduced by the nearness of its neighbours (Duncan, 1984). Beside, an increasing sowing density increases water demand and thereby also plant stress (Shaw, 1988). To ensure a sufficient amount of water for crop growth over the growing season, the chosen sowing density in the NCP should not be to high. Further, plant populations above a critical density have a negative effect on yield per plant due to the effects of interplant competition for water, light, nutrients and other growth factors (Modarres et al., 1998). Therefore under the conditions of the NCP we recommend to sow spring maize with a density of 6.7 plants m^{-2}.

Nitrogen management:

Grain yield, biomass yield, HI and yield parameters did not show any significant differences under the tested different nitrogen managements (Table 7). In 2005, grain yield of treatment one (no nitrogen fertilizer) was even higher than that of the optimized (treatment two) and farmer's practice treatment (treatment three). In 2006, the treatment with no nitrogen fertilizer management presented a lower productivity when compared to the other treatments, although the differences were not significantly different. Due to the high application of N-fertilizer in the traditional double cropping system (winter wheat and summer maize) high amounts of NO_3 are accumulated in the soils of the NCP (Liu et al., 2003). As a consequence N is often not limiting plant growth. This could be one possible reason why no significant differences in yield were found for the tested individual N-treatments in our experiments as the field was used by farmers before. However the soil available N-supply decreased with time (Zhao et al., 2006) making fertilization required. Therefore the N-rate for spring maize in the NCP should be about 140 kg ha^{-1} such as in the optimized treatment because it take into account the soil N_{min}-content as well as the target yield.

Irrigation amount:

Grain yield and biomass yield increased with an increasing irrigation amount. Irrigation seems to be critical because water in the NCP is scarce and its availability will be further reduced by the competition of non-agricultural users (Liu et al., 1998). Therefore irrigation management and planning is one of the most important aspects in the design of future cropping systems. In our experiment one respectively two irrigations for spring maize (at sowing respectively 6 nodes detectable stage) were applied. In wet years the first irrigation is not obligate however in dry it is, in order to guarantee emergence and establishment. The second irrigation was implemented because the water demand of maize peaked during flowering and early seed formation (Denmead and Shaw, 1960; Doorenbos and Kassam, 1979; Grant et al., 1989). However results in our study indicated no significant differences in grain yield for the different irrigation treatments. As moisture environment is unpredictable and may vary to a large extent between years especially in the NCP, at least a minimum of 80 mm irrigation water at sowing has to be ensured for maize growth. Depending on available amounts of precipitation irrigation amounts have to be adapted for each year.

Sowing date:

The sowing date resulted in significant effects on grain yield in 2006. Grain yields of maize sowed on May 28th were significantly higher than the obtained grain yields of the other sowing dates. Also, grain number per ear was significantly higher, leading probably to the higher grain yields. Grain yields of the last sowing date (June 14th) were the lowest among the four sowing dates due to an obviously decreased number of grains per ear. A longer growth duration is often associated with a higher yield potential (Olson and Sander, 1988). Consequently, a delay in sowing especially when the moisture environment is sufficient may lead to substantial yield losses. Results of our experiment showed that sowing dates at the end of April or beginning of May extended the growing period but did not result in higher grain yields. The highest grain yield was reached with a sowing date at the 28th of May. A further delay in sowing resulted in the lowest yield, as the tested variety did not reach physiological maturity. The optimum sowing date varies over different areas and depends also on the chosen cultivars. Due to a lack of agronomic guidelines on sowing date for maize, farmers always planted spring maize at the end of April or beginning of May without regard to whether it matched the optimum sowing date or not. At flowering and early ear formation maize is very sensitive to water stress (Denmead and Shaw, 1960; Doorenbos and Kassam, 1979; Grant et al., 1989). Hence, the early sowing dates of the first two treatments resulted in a coincidence of the flowering period with the dry period resulting in a lower number of kernels per ear and consequently lower yields. Therefore, the agronomic management should focus on a sowing date and a variety that both ensure a maximum water supply and availability during the late vegetative, flowering and grain filling stages. Maize sowed on or near the optimum sowing date could produce the most consistent and profitable grain yield (Hicks and Thomison, 2004). However the optimum sowing date varies in different areas and for different varieties. Therefore further experiments are necessary.

5. Conclusion

The results of the study indicated that SpMM has the potential to reduce water and nitrogen input at relatively minor yield and profit penalties and to increase WUE and NUE in DBW and QZ, while the system 3H2Y performed more sustainable in WQ. In general, the results determine the necessity to develop appropriate adapted cropping strategies for each location and not to arbitrarily attempt what is unsuitable. As replaceable cropping systems, SpMM and 3H2Y can confront a more or less grain and profit reduction, while the protection of resources and environment should be paid more attention. Besides SpMM and 3H2Y, other cropping systems such as winter wheat monoculture, four harvests in three years (spring maize - winter wheat - summer maize - spring maize), five harvests in three years (winter wheat - summer maize - spring maize - winter wheat - summer maize) also could come under the selection scope. As one of the most important aspects of possible future cropping systems, spring maize should be studied in more detail and more locations. The results indicated that spring maize should be sown with a sowing density of 6.7 plants m^{-2} and at latest around middle or late May. Under these management guidelines SpMM has the potential to reduce water and nitrogen input at relatively minor yield and profit penalties and to increases NUE and WUE greatly and to compete with the traditional double cropping of winter wheat and summer maize.

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Results of the fourth article showed that the system three harvests in two years as well as the single cultivation of spring maize offer the possibility to reduce the use of the input factors irrigation water and N-fertilization. Contemporary the input efficiency increased. Further, the results indicated a strong variation in spring maize yields due to less experience in cultivation. To get more knowledge in spring maize production further experiments across the whole NCP are needed. Furthermore new spring maize varieties with a higher yield potential and a full utilization of the growing period have to be developed.

In former times maize was one of the main food crops in China. However, during the last decades maize has become more and more important as feed grain and the demand is further increasing. As mentioned before, maize plays an important role in the double cropping system, the system three harvests in two years and in the single cultivation of spring maize. Therefore, the ***fifth article*** *aims to determine the production potential of summer maize and spring maize in the NCP. For this purpose the CERES-Maize model was calibrated and validated. Temporal and spatial climate variability was taken into account by using up to 30 years of weather data from 14 meteorological stations across the NCP. Simulations were carried out for five different soil texture classes (sand, sandy loam, loam, silt loam and silt). Results were linked to a GIS.*

Model-based approach to quantify production potentials of summer maize and spring maize in the North China Plain

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Abstract

The North China Plain (NCP) belongs to the major maize (*Zea maize* L.) growing areas in China. Maize yields have increased steadily over the last decades, but in recent years average yields have stabilized around 5000 kg ha^{-1}. Due to the increase in population and the change in diet, the demand for maize in China is still rising. The potential for further increases in maize yields seems to be high, as the average yields are currently only half of the average of industrial countries. The objective of this study was to quantify the production potential of summer maize and spring maize in the NCP. For this purpose the CERES-Maize model was calibrated and validated. The spatial and temporal variability caused by climate was considered by using up to 30 years of weather data from 14 meteorological stations across the NCP. Simulations were carried out for five different soil texture classes (sand, sandy loam, loam, silt loam and silt). Results were linked to a Geographic Information System (GIS). The results of the model calibration and validation showed a good fit between simulated and measured yield. Average simulated grain yield for summer maize was 4800 kg ha^{-1} and for spring maize was 5700 kg ha^{-1}. Maize yields decreased from north to south and increased from west to east. Yields of summer maize were limited by the duration of the growing period. Water deficit at flowering was identified as the major factor limiting spring maize yields. In order to increase spring maize yields, two strategies were developed. The first

approach was to sow spring maize at a time when water deficit was least likely to occur during the late vegetative, flowering and grain filling stages. A delay in sowing of 30 days shifted maize development closer to the rainy season and increased average yield by 13 %. In a second test the use of a variety with a later flowering date as a result of a longer vegetative growth led to an average increase in yield of 15 %. Combining the two strategies, delay in sowing and the use of a cultivar with a later flowering date, led to an average increase in yield of 32 %. Overall the results indicated that there is a potential for increasing spring maize yields.

Keywords: potential maize yield, summer maize, spring maize, North China Plain, CERES-Maize, GIS

1. Introduction

One of the most important regions of agricultural production in China is the North China Plain (NCP), also known as the Huang-Huai-Hai Plain (Fig. 1 A). The NCP is located in the north of the eastern part of China between 32° and 40° N latitude and 100° and 120° E longitude.

Within this region, maize is grown in 17 % of the sown area and is just behind wheat as the most important crop. Currently, maize is one of the most important grains in China (Meng et al., 2006). In 2003, the total cropped area for maize in China reached nearly 24.1 million ha and the production exceeded 115.8 million Mg (CSY, 2004). One-third of total maize production in China was produced in the provinces of the NCP. Over the last two decades, the sown area of maize in the provinces of the NCP increased continuously from 6.4 to 8.6 million ha. In general, maize production in NCP rose from 25.7 million Mg in 1984 to 38.1 million Mg in 2003.

Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) are currently the two main crops combined in a single-year rotation also referred to as a double cropping system (Zhao et al., 2006). Winter wheat is sown at the beginning of October and harvested in mid June. Summer maize is sown immediately following winter wheat harvest and is harvested at the end of September or beginning of October. Afterwards the rotation continues with winter wheat cultivation. Due to the short time frame, the growing period of summer maize is limited to 100-120 days. Therefore only early or medium maturity maize cultivars characterized by a rather low yield potential can be used (Sun et al., 2007). Besides the dominant double cropping of winter wheat and summer maize, there is also the possibility of monocropping maize. Spring maize is sown in April and harvested in October (Geng et al., 2001), followed by a fallow period from October until the next April. The long growing period enables the use of medium and late maturity cultivars, characterized by a high yield potential.

The climate in the NCP (Table 1 and 2) is warm-temperate with cold winters and hot summers. Of the total rainfall, 50 to 75 % occurs from July to September during the summer monsoon and overlaps with the growing season of maize (Zhang et al., 1999; Yang and Zehnder, 2001). Precipitation during the winter wheat growing season is very low and necessitates supplemental irrigation (Liu et al., 2001; Zhang et al., 2006). Due to the summer-dominant rainfall, normally no irrigation is required for summer maize and only a slight amount is required for spring maize. High amounts of irrigation water are essential for wheat production, but water has become more and more scarce in the NCP (Geng et al., 2001). Therefore, some studies have suggested reducing or even stopping the wheat production (Yang and Zehnder, 2001; Spyra and Jakob, 2004; Zhang et al., 2004). Alternatively plants with a higher efficiency of water utilization such as maize should be planted (Yang and Zehnder, 2001). Böning-Zilkens (2004) conducted field experiments with winter wheat and summer maize in Dongbeiwang located in the northwest of Beijing (40.0° N and 116.3° E) during 1999-2002. Different water and N-fertilizer scenarios and their effects on grain yield and water use efficiency (WUE) were tested. Average WUE values were 9.8 kg mm^{-1} ha^{-1} for winter wheat and 19.8 kg mm^{-1} ha^{-1} for summer maize.

In the provinces of the NCP average maize yields including both summer maize and spring maize showed a steady increase between 1984 and 1995, but recently have stabilized around 5000 kg ha^{-1} (CSY, 1985-2004). The increase in yield can be attributed to increased amounts of nitrogen fertilizer, improved use of pesticides, better cultivars, new machinery and other enhanced management techniques. However, the potential for further increases in maize yields seems to be high, as the average yields are currently only half of the average of industrial countries (Yang and Zehnder, 2001).

In this paper we explore the production potential of summer maize and spring maize in the NCP using the CERES-Maize model linked to a Geographic Information System (GIS). The model results were analyzed to possibilities of increasing production in the NCP. The study contributes to the identification of limiting factors for improving maize yields in the NCP.

The specific objectives of this study were to (i) quantify the production potential of summer maize and spring maize at different locations in the NCP using a crop modeling and GIS method, (ii) identify the spatial and temporal variability of summer maize and spring maize yields due to climatic differences, (iii) classify the variability of summer maize and spring maize yields due to different soil texture classes and (iv) contribute to the identification of agronomic and cultivar parameters for yield improvements in spring maize.

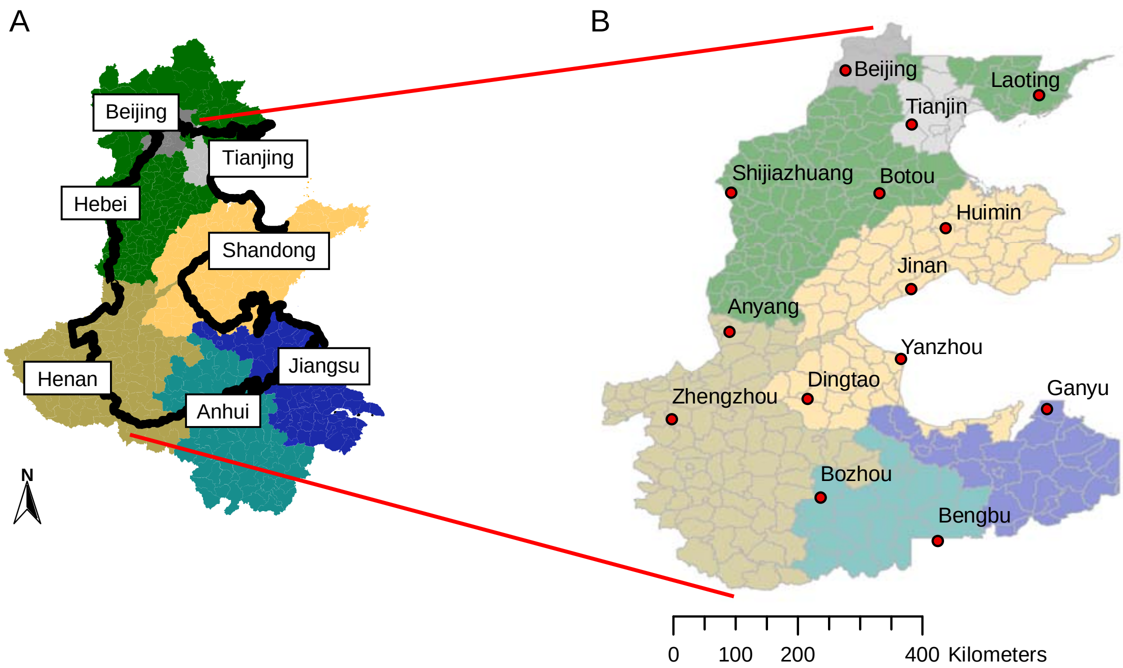

Fig. 1. Provinces of the North China Plain and the border of the North China Plain (black line) [A] (Source: Bareth 2003, adapted and modified); location of the meteorological stations [B] (Source: China Meteorological Administration 2007).

Table 1. Station key, name, province, longitude, latitude, elevation and time-period for the 14 weather stations used in the analysis.

Station key	Station name	Province	Longitude	Latitude	Elevation	Time-period
54511	Beijing	Beijing	116.28	39.48	31	1976-2005
54527	Tianjin	Tianjin	117.04	39.05	3	1976-2005
53698	Shijiazhuang	Hebei	114.25	38.02	81	1976-2005
54539	Laoting	Hebei	118.53	39.26	11	1976-2005
54618	Botou	Hebei	116.33	38.05	13	1996-2005
54725	Huimin	Shandong	117.31	37.30	12	1976-2005
54823	Jinan	Shandong	117.03	36.36	170	1976-2005
54909	Dingtao	Shandong	115.33	35.06	51	1995-2005
54916	Yanzhou	Shandong	116.51	35.34	52	1976-2005
53898	Anyang	Henan	114.24	36.03	63	1976-2005
57083	Zhengzhou	Henan	113.39	34.43	110	1976-2005
58040	Ganyu	Jiangsu	119.07	34.50	3	1976-2005
58102	Bozhou	Anhui	115.46	33.52	38	1976-2005
58221	Bengbu	Anhui	117.23	32.57	19	1976-2005

Table 2. Average main weather variables and their variance (brackets) for the weather stations used in the analysis.

Station name	Average amount of precipitation (mm)		Average maximum temperature (°C)		Average minimum temperature (°C)		Average solar radiation (MJ m^{-2} d^{-1})	
Beijing	555	(151)	18.1	(0.7)	7.6	(0.8)	15.5	(0.5)
Tianjin	542	(139)	18.2	(0.6)	8.4	(0.5)	15.0	(0.7)
Shijiazhuang	518	(159)	19.4	(0.6)	8.9	(0.9)	14.9	(0.9)
Laoting	589	(167)	16.6	(0.6)	6.1	(1.0)	15.5	(0.5)
Botou	477	(152)	19.3	(0.5)	8.7	(0.3)	15.8	(0.9)
Huimin	543	(153)	18.8	(0.6)	7.8	(0.8)	15.8	(0.5)
Jinan	683	(187)	19.7	(0.6)	10.6	(0.6)	15.6	(0.7)
Dingtao	680	(254)	19.7	(0.6)	9.6	(0.4)	15.1	(0.6)
Yanzhou	657	(204)	19.7	(0.6)	8.4	(0.5)	15.6	(0.9)
Anyang	539	(151)	19.8	(0.6)	9.3	(0.8)	14.8	(0.7)
Zhengzhou	630	(155)	20.3	(0.6)	9.6	(0.7)	14.8	(0.8)
Ganyu	864	(223)	18.5	(0.6)	9.9	(0.8)	15.9	(0.7)
Bozhou	798	(210)	20.4	(0.7)	10.4	(0.8)	15.2	(0.8)
Bengbu	906	(228)	20.6	(0.7)	11.7	(0.6)	14.9	(0.7)
Average	**641**	**(181)**	**19.2**	**(0.7)**	**9.1**	**(0.7)**	**15.3**	**(0.7)**

2. Materials and Methods

2.1. Model description

CERES-Maize is a process-oriented model that uses a daily time step simulation and has been integrated as a part of the Decision Support System for Agrotechnology Transfer (DSSAT V. 4.0) (Jones et al., 2003). The model simulates daily growth, development and production of maize under given climatic and cultural conditions. Biomass and yield production is calculated as a function of radiation, leaf area index and reduction factors for temperature and moisture stress. Crop development is primarily based on growing degree-days, whereas leaf and stem growth rates are calculated depending on phenological stages. In order to run the model, a minimum dataset of management practices (cultivar, row spacing, plant population, fertilizer and irrigation application amounts and dates) and environmental conditions (soil texture, daily maximum and minimum air temperature, rainfall and solar radiation) is required. The model was designed to predict how grain yield is affected under alternative management strategies, different environments or by crop variety, soil water and applied nitrogen. The CERES-Maize model is well documented and has been successfully tested in numerous studies to estimate maize yield (Hodges et al., 1987; Wu et al., 1989; Kovacs et al., 1995). The model has the potential for large area yield estimation where daily maximum and minimum temperatures, precipitation, and solar radiation data are available (Hodges et al., 1987).

2.2. Data for model calibration and validation

The CERES-Maize model was calibrated and validated using data of experiments conducted at the experimental site Dongbeiwang in the northwest of Beijing (40.0° N and 116.3° E). The soil type was a Calcaric Cambisol (FAO Classification) formed from silt loam. Weather data including daily solar radiation, daily maximum and minimum air temperatures and daily precipitation were from a local weather station. Information on crop management relative to cultivar, sowing date, sowing density, row spacing, irrigation and N-fertilization in the different field experiments used for model calibration and validation is given in Table 3.

For summer maize, calibration was carried out using three years of field data from 1999-2002 (Böning-Zilkens, 2004). A double cropping system consisting of winter wheat and summer maize was tested relative to improving nitrogen and irrigation investments. The experiment was designed as a three factorial split-split-plot design with four replications. Three different irrigation regimes, three N-fertilization rates as well as a treatment with and without straw were tested. For spring maize the CERES-Maize model was calibrated using two years of data collected from trials of the International Research Training Group (IRTG) (Binder et al., 2007). The chosen experiment was set up to compare different cropping systems in the NCP. The double cropping of winter wheat and summer maize was compared with a single rotation of spring maize. The field experiment was designed as a completely randomized single factorial block design with four replications.

Besides weather and site characteristics, maize yield in CERES-Maize depends on genetic coefficients (O´Neal et al., 2002). The required cultivar coefficients are: P1 (degree-days from seedling emergence to end of juvenile phase), P2 (degree-days from silking to maturity), P5 (delay in development per hour increase in photoperiod above 12.5 h), G2 (kernels per plant) and G3 (kernel filling rate). The calibration of these parameters followed a sequence of variables suggested by the DSSAT manual (Boote, 1999). Coefficients P1, P2 and P5 were calibrated against timing of phenological events and G2 and G3 against yield (Table 4).

Table 3. Management data for model calibration and validation.

Crop	Process	Year	Cultivar	Sowing date	Sowing density	Row space	Irrigation	Fertilization
Summer maize	calibration	2000	Jingkeng 114	21. Jun.	6 plants m^{-2}	0.7 m	-	Fp Re Co
		2001		21. Jun.	6 plants m^{-2}	0.7 m	-	Fp Re Co
		2002		19. Jun.	6 plants m^{-2}	0.7 m	-	Fp Re Co
	validation	2005	CF024	19. Jun.	7 plants m^{-2}	0.7 m	Swm Swm	Fp Re
		2006		18. Jun.	7 plants m^{-2}	0.7 m	Swm Swm	Fp Re
Spring maize	calibration	2005	CF1505	29. Apr.	7 plants m^{-2}	0.7 m	Swm	Re
		2006		29. Apr.	7 plants m^{-2}	0.7 m	Swm	Re
	validation	2005		11. May	6.7 plants m^{-2}	0.6 m	220 mm	Fp Re Co

Fp: farmers practice (standart production system with N-fertilization being very high [240-300 kg N ha^{-1}])
Re: reduced input (N-fertilization according to target yield and N_{min} measurements [30-140 kg N ha^{-1}])
Co: controll (no N-fertilization)
Swm: irrigation according to soil water measurements [50-140 mm]

Table 4. Cultivar coefficients for summer maize (cv. Jingkeng 114 resp. CF024) and spring maize (cv. CF1505) used for model calibration and validation.

Summer maize cv. Jingkeng 114 and CF024

Parameters	**Description**	Value
P1	growing degree days from emergence to end of juvenile phase	180
P2	photoperiod sensitivity	0.30
P5	cumulative growing degree days from silking to maturity	685
G2	potential kernel number	730
G3	potential kernel growth rate	8.0
PHINT	phyllochron interval	44

Spring maize cv. CF1505

Parameters	**Description**	Value
P1	growing degree days from emergence to end of juvenile phase	260
P2	photoperiod sensitivity	0.75
P5	cumulative growing degree days from silking to maturity	830
G2	potential kernel number	730
G3	potential kernel growth rate	8.0
PHINT	phyllochron interval	44

The validation for summer maize and spring maize was carried out using the genotype coefficients obtained by calibration (Table 4). For the two similar summer maize cultivar Jingkeng 114 and CF024, the same cultivar coefficients were used. For summer maize the model was validated using two years of field data collected in the IRTG-project. An independent experiment was used for spring maize. The chosen experiment for spring maize investigated the effects of three N-fertilization rates on yield in 2005. Fertilization treatments varied between 0 and 240 kg N ha^{-1} yr^{-1}. The field experiment was designed as a completely randomized single factorial block design with four replications.

2.3. Simulations

Settings

In general, model settings were based on data from the field experiments used for model calibration and validation. Simulations throughout the study area were carried out with the same summer maize (Jingkeng 114 and CF024) and spring maize (CF1505) cultivars. The sowing density was 7 plants m^{-2} and row spacing was 0.7 m for both summer maize and spring maize. Due to climate conditions across the NCP, sowing dates were delayed from south to north (Wu et al., 1989) and varied between 6 June to

24 June for summer maize and 5 April to 5 May for spring maize (Fig. 2).

In a normal year, precipitation can generally meet water requirements of summer maize, but problems occur in dry years. Therefore, summer maize was irrigated after sowing with 50 mm to guarantee seedling emergence and establishment. Spring maize was irrigated with 90 mm at sowing and 50 mm 50 days after sowing. As irrigation is carried out by furrow irrigation, irrigation efficiency was set to 0.50, according to Xinhua News (2001). Summer maize was fertilized with 50 kg N ha^{-1} 20 days after sowing and 90 kg N ha^{-1} 50 days after sowing. Nitrogen fertilization for spring maize was 70 kg N ha^{-1} applied 50 days after sowing. Nitrogen fertilization for summer maize was higher than for spring maize due to the fact that two crops (winter wheat and summer maize) are grown on the same plot each year and to accelerate growth in the shorter vegetation period. Spring maize and summer maize harvests occurred at physiological maturity at the end of September.

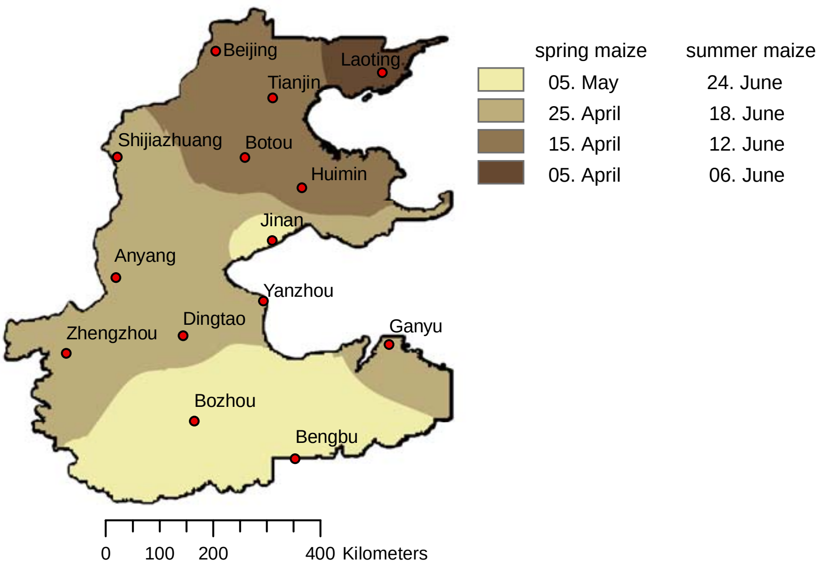

Fig. 2. Sowing date variation for spring maize and summer maize across the NCP.

<u>Soil data</u>

Since potential yields may be affected by location-specific soil water characteristics, different simulation scenarios were set up to account for spatial variability in soil across the NCP. Simulations were based on the soil texture classes sand, sandy loam, loam, silt loam and silt which occur in the study area (Table 5). The soil data were obtained from Chinese Academy of Science (1997) and Böning-Zilkens (2004).

Table 5. Physical properties of different soil texture classes used in the analysis (Source: Böning-Zilkens 2004 and Chinese Academy of Science 1997, adapted and modified).

Soil texture class	**Depth** (cm)	**Particle size distribution**			**Bulk density** (g cm^{-3})	**LL** (m^3 m^{-3})	**DUL** (m^3 m^{-3})	**SAT** (m^3 m^{-3})
		clay (%)	**silt** (%)	**sand** (%)				
Sand	0-20	6.2	1.4	92.4	1.47	0.06	0.14	0.42
	20-40	7.2	2.9	89.9	1.41	0.07	0.14	0.44
	40-60	7.0	2.5	90.5	1.44	0.07	0.14	0.43
	60-80	5.7	0.6	93.7	1.52	0.06	0.13	0.40
	80-100	5.7	0.6	93.7	1.52	0.06	0.13	0.40
	average	**6.4**	**1.6**	**92.0**	**1.47**	**0.06**	**0.14**	**0.42**
Sandy loam	0-20	12.9	23.2	63.9	1.39	0.10	0.21	0.45
	20-40	12.6	23.5	63.9	1.41	0.10	0.21	0.44
	40-60	12.4	23.8	63.8	1.42	0.10	0.20	0.44
	60-80	12.1	24.0	63.9	1.43	0.10	0.20	0.43
	80-100	12.0	24.1	63.9	1.43	0.10	0.20	0.43
	average	**12.4**	**23.7**	**63.9**	**1.42**	**0.10**	**0.20**	**0.44**
Loam	0-20	10.9	48.0	41.1	1.40	0.10	0.25	0.49
	20-40	10.6	48.1	41.3	1.45	0.10	0.25	0.49
	40-60	10.3	48.3	41.4	1.49	0.09	0.25	0.49
	60-80	10.1	47.8	42.1	1.50	0.09	0.24	0.49
	80-100	9.6	46.1	44.3	1.49	0.09	0.24	0.48
	average	**10.3**	**47.7**	**42.0**	**1.47**	**0.09**	**0.24**	**0.48**
Silt loam	0-20	15.9	57.2	26.9	1.34	0.14	0.25	0.51
	20-40	16.8	58.7	24.5	1.43	0.13	0.23	0.40
	40-60	17.7	60.1	22.2	1.51	0.14	0.24	0.38
	60-80	13.6	55.6	30.8	1.42	0.10	0.23	0.36
	80-100	12.9	59.8	27.3	1.47	0.10	0.27	0.42
	average	**15.4**	**58.3**	**26.3**	**1.43**	**0.12**	**0.24**	**0.41**
Silt	0-20	15.5	80.0	4.5	1.33	0.11	0.30	0.47
	20-40	10.4	86.0	3.6	1.35	0.10	0.30	0.46
	40-60	8.8	88.0	3.2	1.35	0.10	0.31	0.46
	60-80	7.9	89.0	3.1	1.35	0.10	0.31	0.46
	80-100	12.2	84.6	3.2	1.37	0.10	0.30	0.46
	average	**11.0**	**85.5**	**3.5**	**1.35**	**0.10**	**0.30**	**0.46**

LL = lower limit of soil water; DUL = drained upper limit of available water; SAT = saturated limit of available soil water

Climate data

Weather data from 14 stations evenly distributed in the NCP were obtained from China Meteorological Administration (2007) (Fig. 1 B). Time-series for the different sites ranged from 10 to 30 years. The data included daily maximum and minimum temperature, rainfall, and sunshine duration. Sunshine duration was converted to solar radiation (MJ m^{-2} d^{-1}) by the Angström equation using the recommended default coefficients 0.25 and 0.50 (Allen et al., 1998). Information on chosen locations relative to identity, longitude, latitude, elevation and time-series is given in Table 1. The NCP is a vast expanse of flatland with a slight slope from southwest to northeast. The average elevation is less than 100 m (Yao, 1969), so it was hypothesized that the topography does not have any influence on the climate within the plain. Simulations were carried out with the weather data described for the 14 locations shown in Fig. 1 B and for the five soil texture classes sand, sandy loam, loam, silt loam, and silt (Table 5). The point data were interpolated to generate maps for the entire NCP. For interpolation the inverse distance weighting (IDW) method (Shepard, 1968) was used, which identified a neighborhood about the interpolated point. Afterwards a weighted average was taken for the observed values within this neighborhood. The weights are a decreasing function of distance (Fisher et al., 1987).

3. Results and Discussion

3.1. Model calibration and validation

From the calibration and validation results, the CERES-Maize model was found to simulated yields well (Table 6). The average RMSE between simulated and measured yield for summer maize was 316 kg ha^{-1} (calibration) and 356 kg ha^{-1} (validation). Similar results were obtained for spring maize with an average RMSE of 314 kg ha^{-1} (calibration) and 340 kg ha^{-1} (validation). Many researchers have demonstrated reasonably accurate simulations of grain yield because the CERES-Maize model has been in existence for many years and has been the subject of continuous evaluation. Liu et al. (1989) used the CERES-Maize model to simulate the growth and grain yield of a Brazilian maize hybrid in the years 1983-1987. Estimated yields were within 10 % error range except for one year. Another example is given by Mati (2000) who used the CERES-Maize model to simulate the crop response to changes in climate, management variables, soils and different CO_2 atmospheric levels in the semi-humid-semi-arid areas of Kenya. With an error of 5-10 % after calibration the model was found to simulate yields well within acceptable limits. The results of our simulations showed in general that the differences between the simulated and measured grain yields were within the range of differences reported in the literature. Thus, the model simulated grain yields adequately to proceed with simulating potential yield over regions of NCP.

Table 6. Average results of model calibration and validation for summer maize and spring maize.

Crop	**Process**	**Average grain yield** (kg ha^{-1})			**RMSE**
		measured	simulated	percent	
Summer maize	calibration	5610	5756	+ 2.6%	316
	validation	7562	7752	+ 2.5%	356
Spring maize	calibration	9712	9821	+ 1.1%	314
	validation	9337	9484	+ 1.6%	340

3.2. Spatial and temporal variability of climate

Spatial and temporal variability of precipitation, average daily temperature and average daily solar radiation in the NCP during the summer maize (June-September) and the spring maize grow season (April-September) were analyzed. Precipitation varied between 233 and 597 mm in the summer maize growing season and between 401 and 708 mm in the spring maize growing season. However, the average monthly perception for summer maize was higher than for spring maize, because the greatest amounts occurred during the summer months. Precipitation was higher in the south than in the north of the NCP and increased from west to east (Fig. 3 A). With a coefficient of variation between 0.28 (minimum) and 0.41 (maximum) for spring maize respectively 0.31 and 0.54 for summer maize precipitation indicated a high variability between years. This corresponds with results of Yao (1969) who reported an extremely high year to year variability of precipitation in the NCP. Average daily temperatures increased from north to south and decreased from west to east (Fig. 3 B). During the summer maize growing season average daily temperature varied between 23.2 and 26.3 °C and during the spring maize growing season between 20.4 and 23.8 °C. Average daily temperature showed a low variability between years, i.e. the coefficient of variation varied between 0.02 and 0.04 for spring as well as for summer maize.

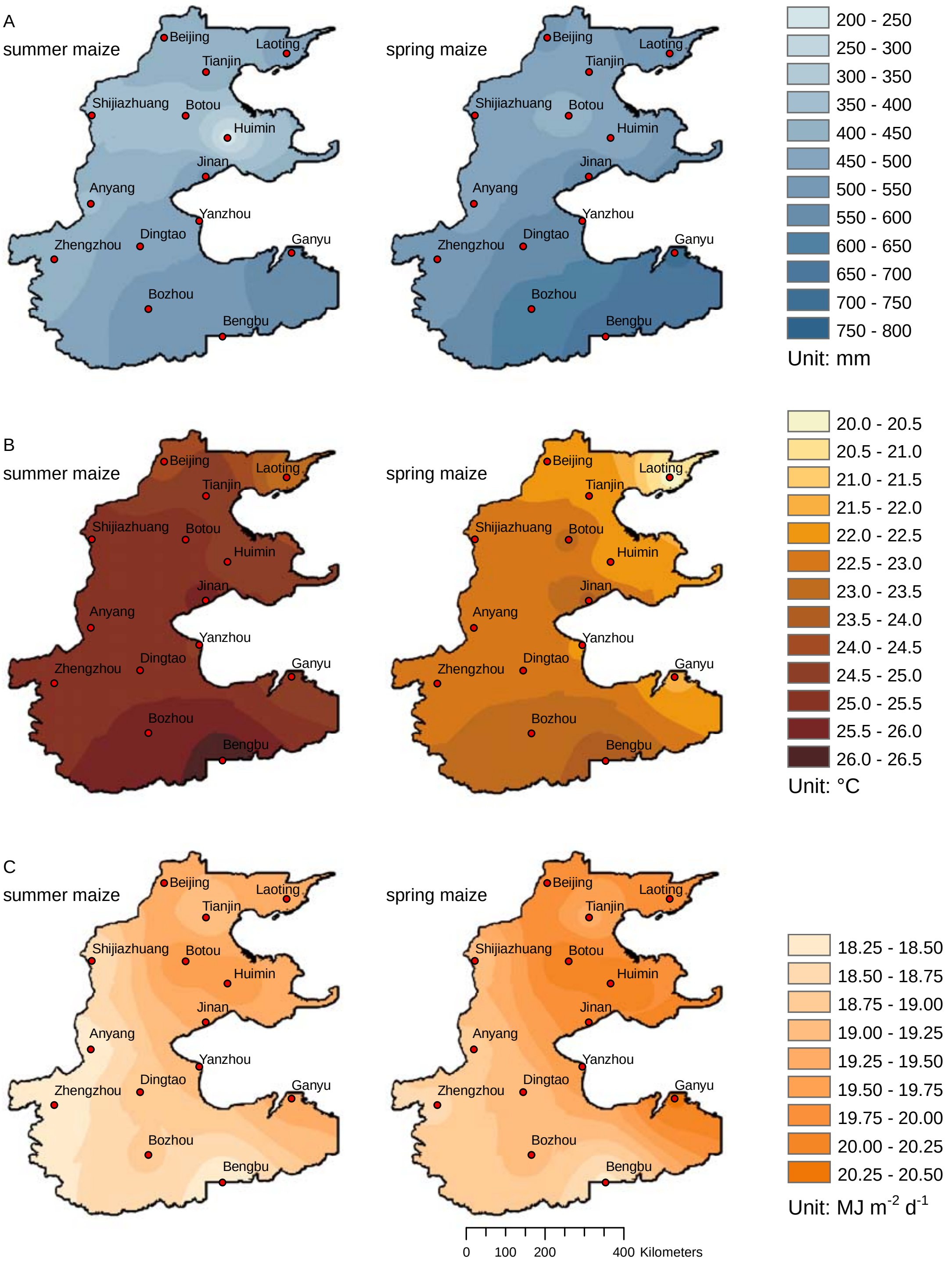

Fig. 3. Precipitation amount (mm) [A], daily average temperature (°C) [B], and average solar radiation (MJ m^{-2} d^{-1}) [C] during the spring maize (April-September) and summer maize (June-September) growing season.

Solar radiation varied between 18.3 and 19.7 MJ m^{-2} d^{-1} in the summer maize growing season and between 18.5 and 20.2 MJ m^{-2} d^{-1} in the spring maize growing season. Radiation increased from south to north due to lower rainfall and latitude, resulting in less cloudy days and more sunshine hours per day in the growing seasons (Fig. 3 C). The coefficient of variation between the years varied between 0.04 and 0.07 for spring maize and between 0.05 and 0.08 for summer maize.

Precipitation, temperature and solar radiation have direct effects on maize growth and yield. Precipitation provides soil water essential for emergence and plant establishment at sowing, for an adequate leaf area development and photosynthesis rate during the pre-flowering time, and for increasing ear and kernel set during the two weeks bracketing the flowering stage. Temperature also has a big effect on maize growth as maize is very sensitive to frost, particularly in the juvenile stage. Besides, increasing temperatures accelerates the plant development. Badu-Apraku et al. (1983) showed that increasing temperature cause decreased duration of grain filling resulting in lower grain yields. Further, growth of maize is very responsive to solar radiation, because radiation is the main source of energy for biomass synthesis (Idinoba et al., 2002). The dry matter produced is directly related to the amount of intercepted radiation. Muchow et al. (1990) showed that a low temperature and a high solar radiation results in high maize yields, because lower temperature increase the length of time that the crop can intercept radiation.

However maize varieties have a wide adaptability to different climate conditions (Shaw, 1988). Therefore the right choice of varieties with a length of growing period matching well with the length of the growing season is crucial for successful cultivation (Doorenbos and Kassam, 1979).

3.3. Spatial variation in potential yields of summer maize and spring maize.

According to the simulation analysis, long-term average potential yields of summer maize ranged from 3900 kg ha^{-1} on sand to 5800 kg ha^{-1} on silt loam (Table 7). The spring maize yields were lowest for sand and sandy loam (4800 kg ha^{-1}) and highest for silt loam (6600 kg ha^{-1}). The overall mean grain yields for the entire NCP were 4800 kg ha^{-1} for summer maize and 5700 kg ha^{-1} for spring maize. Average total biomass production for summer maize was 10700 kg ha^{-1} (8500-13500 kg ha^{-1}) and for spring maize 14200 kg ha^{-1} (12500-15900 kg ha^{-1}).

In general, yields decreased from north to south (Fig. 4 and 5) even if the potential growing season was longer in the south. This was due to the lower radiation and higher temperature in the south. Along the same latitude, yields increased with longitude from west to east, because lower temperatures at the coast extend the grain filling phase. The highest yields of summer maize and spring maize were realized at the most northeast meteorological station Laoting. The lowest summer maize as well as spring maize yields were obtained at Huimin station due to water shortage. As crop photosynthesis and hence biomass and grain yield production are directly associated with the light interception by the canopy (Muchow et al., 1990), yields increased in the direction from south-western to north-eastern.

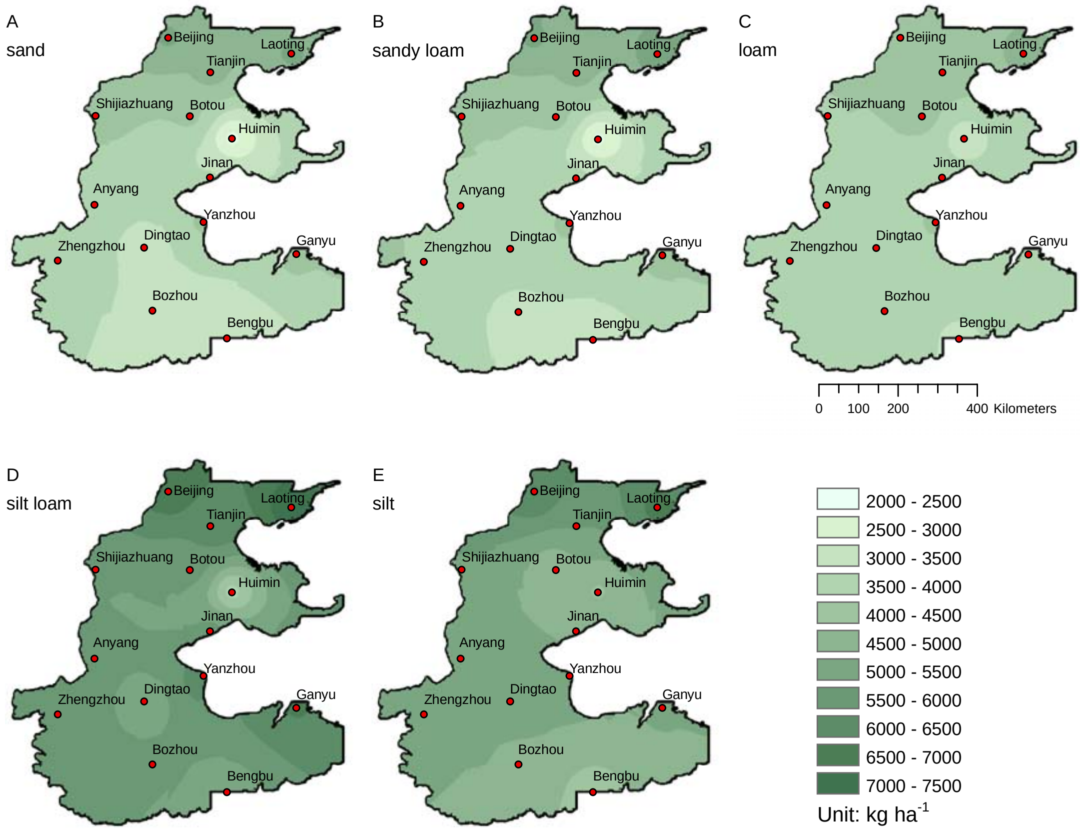

Fig. 4. Simulated potential yields (kg ha^{-1}) of summer maize for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

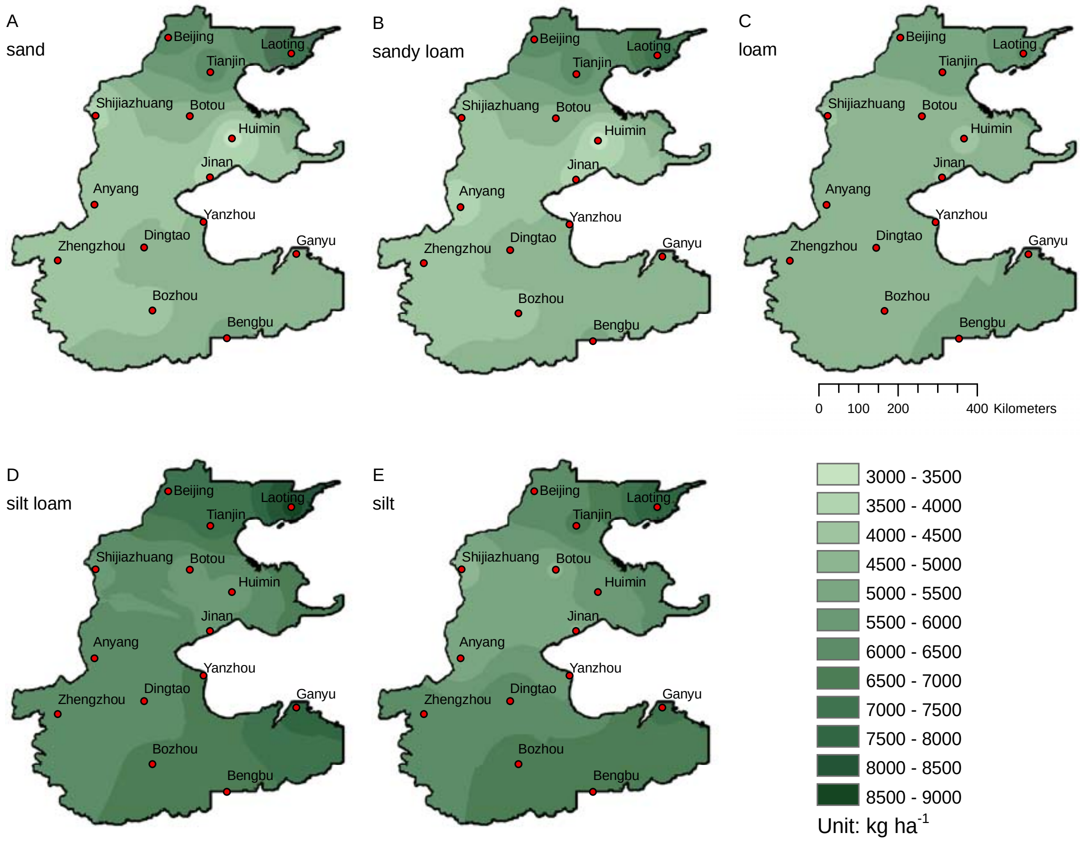

Fig. 5. Simulated potential yields (kg ha^{-1}) of spring maize for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

3.4. Yield distinction between summer and spring maize and possible developments

The yield difference between summer maize and spring maize varied from 810 kg ha^{-1} on silt loam to 1030 kg ha^{-1} on loam (Table 7). Due to lower temperatures interrelated with higher radiation and higher rainfall, yield distinction increased from west to east (Fig. 6). For the entire NCP the mean yield distinction was 900 kg ha^{-1}. However, considering the longer growing period of spring maize (165 days) in comparison to summer maize (110 days), differences in yield are quite small and sometimes negative. This is in agreement with results of Beck et al. (2002) who reported no major yield differences between summer maize and spring maize in the Loess Plateau.

Water stress and high temperatures during ear formation, reproduction and grain filling may be responsible for the

Table 7. Average summer maize and spring maize yields (kg ha^{-1}) and yield difference (kg ha^{-1}) for the tested soil texture classes.

Soil texture class	**Summer maize yield** (kg ha^{-1})	**Spring maize yield** (kg ha^{-1})	**Yield difference** (kg ha^{-1})
Sand	3900 (2400-5100)	4800 (3300-7200)	930 (-170-2100)
Sandy loam	4000 (2400-5300)	4800 (3300-7200)	860 (-150-1900)
Loam	4800 (3500-6300)	5800 (4800-8100)	1030 (-230-2200)
Silt loam	5800 (3900-7300)	6600 (5800-8600)	810 (140-1900)
Silt	5300 (4300-6600)	6200 (4500-8000)	890 (-610-2600)

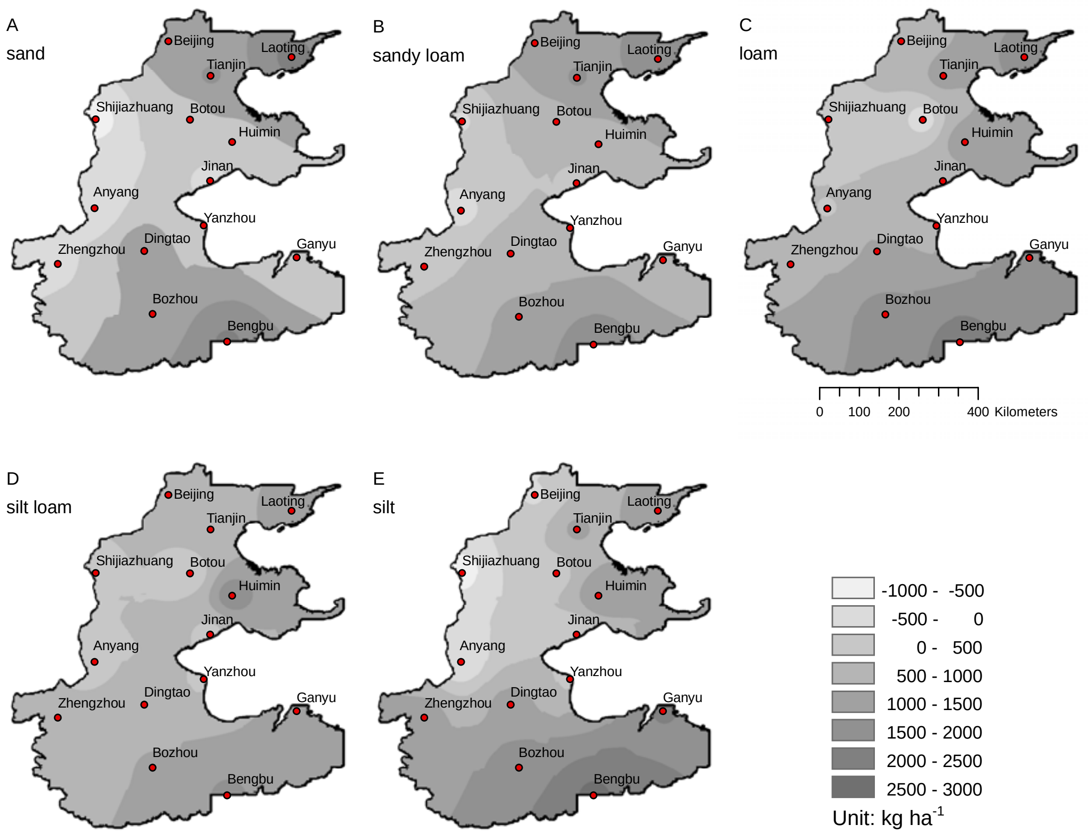

Fig. 6. Mean differences (kg ha^{-1}) between summer maize and spring maize yields for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

small differences in yield between summer maize and spring maize. Maize is highly sensitive to water deficit in specific growth stages. Sensitivity varies among different growth stages (Salter and Goode, 1967; Claassen and Shaw, 1970; Grant et al., 1989). Commonly grain crops are more sensitive to water stress during flowering and early seed formation than during vegetative or grain filling phases (Doorenbos and Kassam, 1979). This is in agreement with results of Denmead and Shaw (1960) and Grant et al. (1989) who found that maize water demand peaked in the period one week before until two weeks after flowering. Similarly Dale and Daniels (1992) reported a peak in water demand in the period four weeks prior to silking, ending about 20 days after silking. Drought at flowering often results in barrenness caused by a reduction in the flux of assimilates to the developing ear below some threshold level necessary to sustain grain formation and growth (Schussler and Westgate, 1995). According to Bänzinger et al. (2000), maize is more susceptible than other corps to water stress at flowering because of the large distance between male and female organs, exposing pollen and fragile stigmatic tissue to desiccating conditions during pollination.

In our study water stress at flowering was also detected as the major factor responsible for the small differences in yield between summer maize and spring maize. The CERES-Maize model considers stress related to water using water deficit factors. When the soils dry and the potential root water uptake decrease to a value lower than the potential transpiration rate, actual transpiration will be reduced by partially closed stomata to the potential root uptake rate. When this happens the potential biomass production rate is assumed to decline in the same proportion as the transpiration. The potential transpiration and biomass production rates are reduced by multiplying their potential rates by a soil water deficit factor calculated from the ratio of the potential uptake to the potential transpiration. This value is set to 1 when the ratio exceeds 1. A second water deficit factor is calculated to account for water deficit effects on phytophysiological processes that are more sensitive than the stomata controlled processes of transpiration and biomass reduction. Reduced turgor pressure in many crop plants will slow down processes such as leaf expansion, branching and tillering before stomata-controlled processes are reduced. Values for the second factor are assumed to fall below 1 when potential root uptake relative to potential transpiration falls below 1.5. They are assumed to be reduced linearly from 1 to 0 in proportion to this ratio (Ritchie, 1998). In our simulation the CERES-Maize model indicated average values at flowering of 0.13 for spring maize and 0.04 for summer maize. This corresponds to the differences in the amount of precipitation during the period from flowering initiation until the beginning of grain filling (spring maize: end of May until the beginning of July; summer maize: end of June until the beginning of August). On average, precipitation during this period amounted 207 mm for summer maize and 139 mm for spring maize. Taking into account an effective irrigation amount of 25 mm (irrigation efficiency was set to 0.50) for spring maize at the beginning of flowering, there is still a water deficit for spring maize of 43 mm less water compared to summer maize. However, there is a strong variation in the occurring water deficit between the single locations. In Yanzhou or Laoting for example the water deficit for spring maize during flowering period could almost be completely compensated by irrigation at flowering initiation. Therefore, spring maize outyielded summer maize at these two locations. On the other hand, there are also locations such as Anyang or Jinan where the water deficit could not be compensated by irrigation. As a consequence, spring maize yields there were rather low.

Timing and intensity of drought stress can be managed by irrigation. If water stress limits growth, irrigation at the most water-sensitive growth stages may result in higher yields per unit water compared to water applied during other growth stages (Stone and Schlegel, 2006). Therefore, a better irrigation management could help increase spring maize yields whereas for summer maize, no further yield increase can be expected. In our simulation two irrigations for spring maize (at sowing and 50 days after sowing) were applied. In wet years the first irrigation was not needed. However in dry season, it was needed to guarantee seedling emergence and establishment. The second irrigation took place in the water sensitive period reported by Dale and Daniels (1992). Therefore possibilities for improvements in irrigation scheduling can scarcely be proposed. A higher or an additional irrigation application seems also to be a problem because water in the NCP is scarce and its availability will be further reduced by the competition of non-agricultural users (Liu et al., 1998).

A further way to save water might be the adoption of advanced irrigation technologies and a better maintenance of irrigation infrastructure (Wolff, 1999).

Another management practice to reduce water stress is to reduce maize plant population in order to maintain the amount of available water per plant above a minimum. Some other agronomic practices such as mulching or reduced tillage might also help to improve the water conditions (Scopel et al., 2001) and there should be further tested.

Another alternative could be to use cultivars with higher water-use efficiency. In general, the available cultivars differ widely in agronomic characteristics, e.g. in the length of growing period. Longer growth duration is often associated with a higher yield potential (Olson and Sander, 1988). Consequently a delay in sowing especially when the moisture environment is sufficient leads to yield losses. However moisture environment is

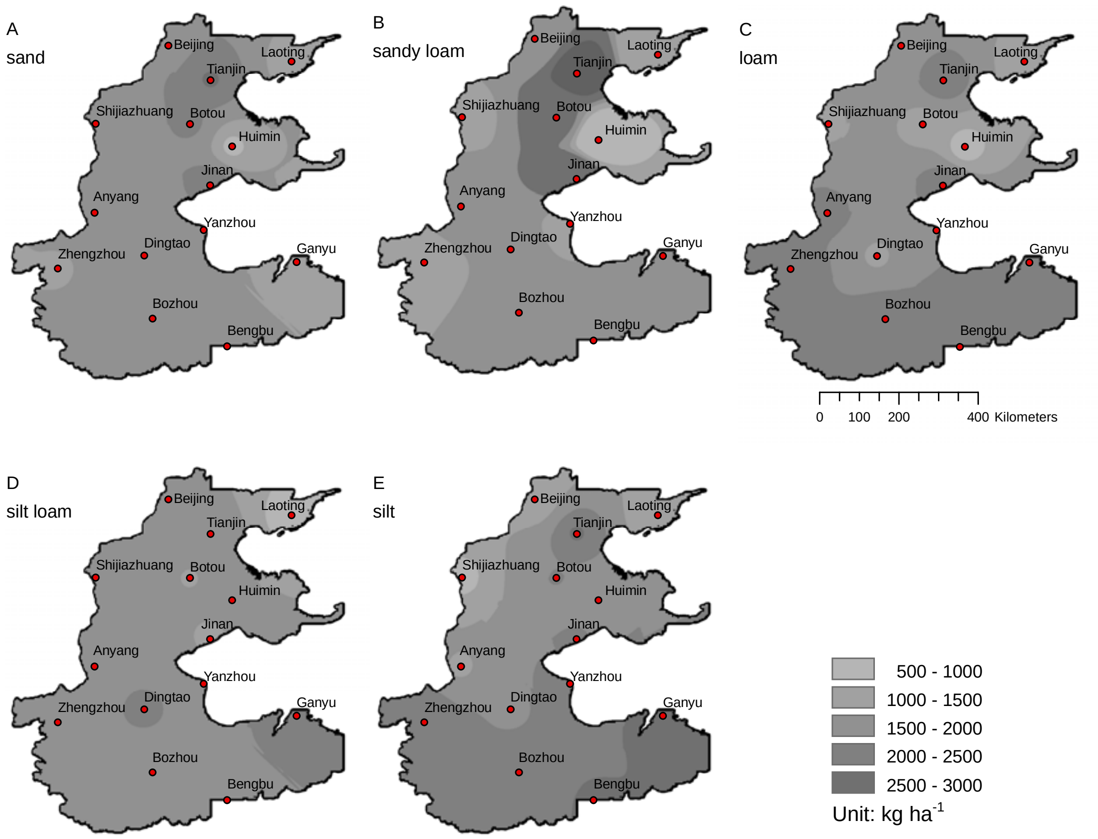

Fig. 7. Possible yield levels (kg ha^{-1}) of spring maize by a later sowing date for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

unpredictable and may vary to a large extent between years. Therefore, the object of agronomic practices must be to sow maize at a time when water deficit is least likely to occur during the late vegetative, flowering and grain filling stage. This could be reached by shifting the sowing date closer to the rainy season. In our simulations a delay in sowing of 30 days brought an average yield increase of 13 % (Fig. 7). However in some regions such as Laoting a yield decrease was ascertainable because the sowing date was already relatively late. Therefore a more site-specific variation in sowing seems to be required.

Another strategy to improve spring maize yields could be to find maize genotypes with appropriate phenology matching growth and developmental processes with environmental conditions. For environmental stress conditions cultivars diversification is based mainly on differential phenology, primarily flower-

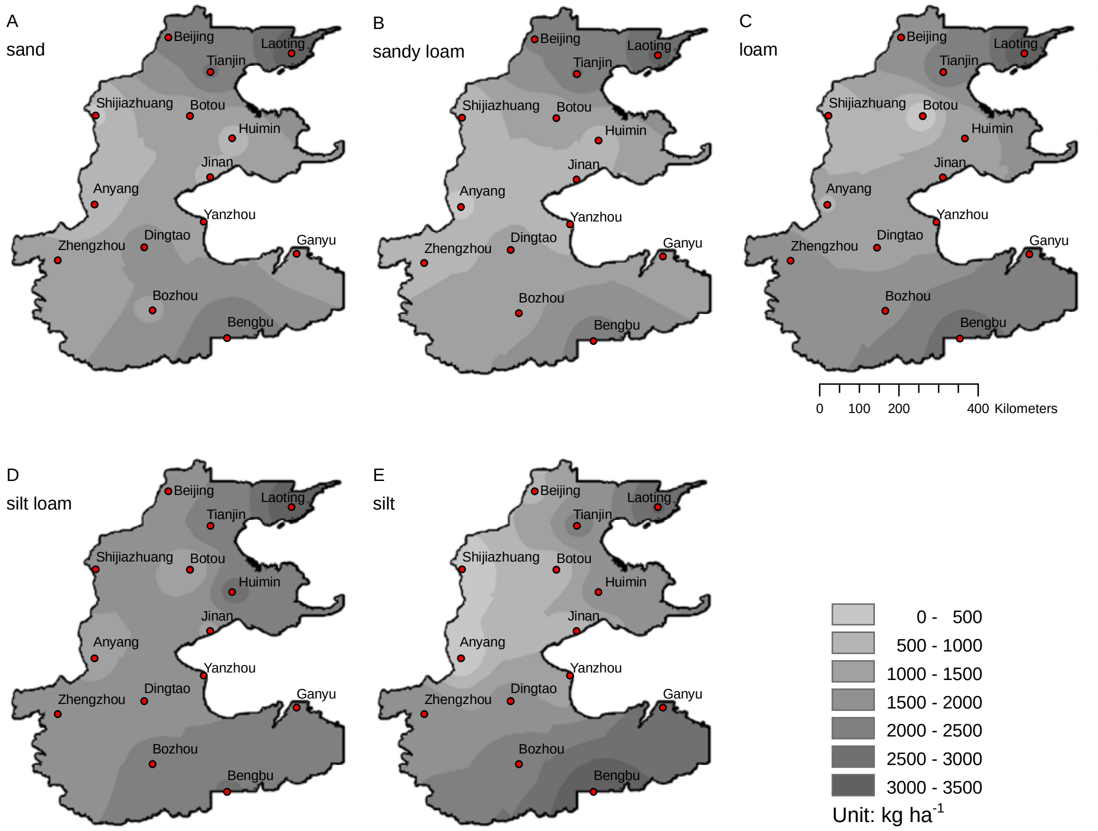

Fig. 8. Possible yield levels (kg ha^{-1}) of spring maize by the use of adapted cultivars for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

ing date. Maize is relatively insensitive to water stress during early vegetative growth stages because water demand is relatively low (Shaw, 1988). In our simulations the use of a cultivar with a later flowering date as a result of a longer vegetative growth led to an average increase in yield of 15 % (Fig. 8). Late flowering leads to a longer vegetative growing period that promotes the accumulation and allocation of more resources to seed production. Olson and Sander (1988) previously recommended the use of a cultivar that will not be in the critical flowering stage during the time when a stress period can be expected.

Combining both a delay in sowing and the use of a cultivar with a later flowering date led to an average increase in yield of 32 % (Fig 9).

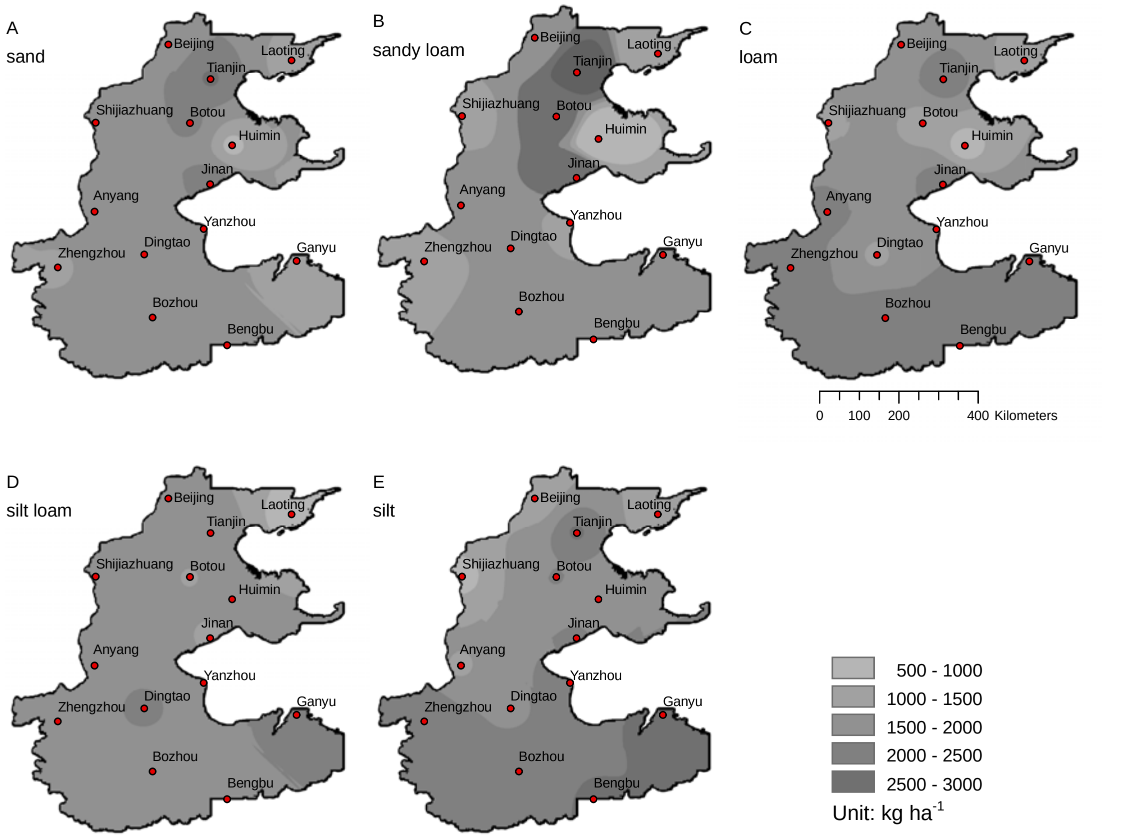

Fig. 9. Possible yield levels (kg ha^{-1}) of spring maize by a later sowing date in combination with the use of adapted cultivars for different soil texture classes (sand [A], sandy loam [B], loam [C], silt loam [D], silt [E]) in the North China Plain.

4. Conclusions

This paper presents a simulation approach to quantify the potential yields of spring maize and summer maize across the NCP. Climate-related temporal and spatial variability in yield performance were simulated using long-term daily weather data from various meteorological stations spread evenly throughout the NCP. Simulations were carried out for five different soil texture classes. Results of the simulations indicated that inspite of a longer growing season of spring maize the simulated yield difference in comparison to summer maize was relatively small, due to water stress during flowering. However, shifts in sowing dates to a later point in time and the use of late flowering varieties may facilitate an increase in spring maize yields.

Acknowledgement

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Results of the fifth article indicated that the average yields across the NCP were 4800 kg ha^{-1} for summer maize and 5700 kg ha^{-1} for spring maize. Furthermore, water shortage during spring maize flowering was detected as one of the major responsible factors for the partially very low yield distinction between summer maize and spring maize. However, a hypothetical delay in sowing and the use of a cultivar with a later flowering date helped to avoid the coincidence of the dry period with the sensitive flowering stage. Consequently spring maize yields increased.

9 GENERAL DISCUSSION

The general discussion of this study deals with different perspectives on the overall goal of this thesis to develop sustainable cropping systems in the NCP while reducing irrigation water supply. After a short introduction the main outcomes of the IRTG field experiments and modeling approaches are summarised and discussed. Afterwards complementary possibilities to counteract water scarcity and to reduce respectively to improve agricultural water use in the NCP are discussed. In the last section, future conditions as well as possible impacts on the cropping system and crop management in the NCP are presented.

Agriculture in China has to produce steadily more food for a still increasing population. However, the potential for expanding cultivated land is limited because China has only 7 % of the worlds arable land area (Jowett, 1985). Therefore, agricultural production became more intensive over the last decades (Mei, 1998), especially in the NCP, the granary of China. Farmers try to increase yields by increasing the input factors, mainly irrigation water and fertilization. However, besides the positive effects on yield, the increase of these input factors leads to many environmental problems and puts agriculture under great pressure (Chapter 4). Water, the most critical resource for agricultural production in China (Heilig, 1999) is becoming more and more scarce. In order to implement sustainable cropping systems and to meet the challenge of a stable food supply for a growing population it is essential to develop cropping strategies that will maintain high yields and minimize the needs for irrigation water.

9.1 Main outcomes

In the framework of the IRTG-project field experiments were established at three locations in the NCP since autumn 2004 (Chapter 2). The traditional cropping system, as it is practiced by the farmers in the NCP with a high input of irrigation water and fertilizer was compared with a system of reduced input. Different cropping systems were evaluated with special regard on grain yield and the demand of input factors.
Farmers in the NCP commonly operated a double cropping system which is largely based on winter wheat and summer maize (Zhao et al., 2006), both named after the

season in which they are grown. The major problem of the winter wheat - summer maize rotation is that about 50 to 75 % of the annual precipitation occurs during July to September, the growing season of maize. Precipitation during the winter wheat growing season is very low, wherefore a supplemental irrigation is required (Mc Vicar et al., 2000). Depending on the seasonal precipitation situation winter wheat is irrigated three to five times with a total amount of 200-300 mm (Zhang and You, 1996). For maize production however relative less irrigation is necessary, because the main part of the growing season coincides with the precipitation season (Chapter 4).

In a first approach we tried to reduce the total amount of irrigation water to winter wheat in the traditional double cropping system by adjusting the irrigation levels based on soil water measurements. Thresholds for irrigation application were set to 45-80 % field capacity. Independent of the location results of our study showed that there was a considerable potential for reducing the irrigation water supply to wheat. The average reduction over the three locations was 31 % resulting in an average decrease in yield of 5 %. A comparable experiment was implemented by Böning-Zilkens (2004) during 1999-2002 at Dongbeiwang site. Results were similar to our study and showed a possible reduction in irrigation water of up to 20 % without a significant decrease in yield. However, even if the results indicated a possible strong reduction in the irrigation water supply there is sill a high amount of irrigation water required for the double cropping of winter wheat and summer maize in the NCP. In our study an average irrigation amount of 356 mm for the traditional system and still 269 mm for the reduced system were required. Therefore, others or contemporary solutions have to be developed.

It was found that the water shortage problem in the NCP is mainly caused by over cropping winter wheat (Geng et al., 2001). Some studies suggested to reduce or even stop the wheat production to attenuate the water scarcity (Yang and Zehnder, 2001; Spyra and Jakob, 2004; Zhang et al., 2004). Hence, our second approach focused on the evaluation of different cropping systems where different rates of wheat in the rotation were tested (Chapter 4 and 7). The double cropping system was compared with a system of three harvests in two years (winter wheat and summer maize in the first year followed by spring maize in the second year) and the single cultivation of spring maize (one crop per year). In all three systems irrigation was based on measurements of soil water content. In the traditional double cropping system winter wheat is produced each year, in the system three harvests only every second year and it is never produced in the single cultivation of spring maize. Results of our study showed that with a decrease in the wheat cropped area respectively the cropping index, the demand of irrigation water could strongly be reduced. The average irrigation amount per year over the three locations for the double cropping system was 269 mm (100 %), for the system three harvests in two years 221 mm (82 %) and for the single cultivation of spring maize 112 mm (42 %). Besides the positive effect on water supply the changes in the cropping index resulted in lower yields. In comparison to the double cropping system (100 %) the average yield level of the system three harvests in two years was 81 % and for the single cultivation of spring maize only 64 %. The main reasons were low spring maize yields. Therefore, a better utilization of the available vegetation time for spring maize must be realised, as a later maturity leads to potentially higher yields (Schnell and Utz, 1981).

Besides empirical field experiments, the methodology of crop simulation modeling was used in our study to develop strategies for reducing the irrigation water supply (Chapter 5 and 6). Field studies are limited in extend and size and cannot be easily extrapolated (Jones et al., 2003; Pathak et al., 2004). Therefore modeling could play an elementary role for supporting the planning and testing of different irrigation practices as well as different cropping systems, as it allows the simulation of alternative practices (Pereira et al., 2000). However, studies which use crop models to evaluate crop production systems in the NCP are rare (Yu et al., 2006). Recently crop growth models are getting more and more used. Hu et al. (2006) e.g. used the RZWQM model to assess N-management in a double cropping system (winter wheat and summer maize) at Luancheng in the NCP. Results of the study indicated, that both, N and water could be reduced by about half of the typical application rates without a strong reduction in yield. Another example can be found in Yang et al. (2006) who used the CERES-Wheat and CERES-Maize model to estimate agricultural water use and its impact on ground water depletion in the piedmont region of the NCP. The results showed a strong correlation between the agricultural water use and the ground water depletion. The authors concluded that there is still a sustainable water use possible if water-saving technologies are applied. In the present thesis the CERES-Maize and CERES-Wheat models were used to quantify the effects of different irrigation management practices in the double cropping system of winter wheat and summer maize on crop growth, productivity and sustainability. Results indicated that there is a considerable potential for reducing the irrigation amount to winter wheat. Without a decrease in yield a theoretical reduction of up to 36 % and without a financial decrease a simulated reduction of up to 50 % in the irrigation amount was possible. This was reached by improving the irrigation schedule and by reducing the number of irrigation applications. However, the results also showed that a supplemental irrigation at critical growth stages seems to be essential to maintain high yields and to ensure an adequate gross margin (Chapter 5 and 6).

In further studies besides the irrigation management also the cropping system itself should play a major role as the right choice of crops respectively varieties or management decisions such as adoptions in sowing time or sowing density have a major influence on yield and the required irrigation amount. Thereby modeling could be a useful tool because after proper calibration and validation simulations of different management practices and cropping systems are possible.

The collection and editing of the input data for crop growth models for a large number of locations is generally complex and difficult (Liu et al., 2007). Modeling in combination with a GIS can be a useful tool to extrapolate data on a large scale. As maize becomes more and more important in the NCP, not as food but as feed grain, the CERES-Maize model was used to simulate the yield of summer maize and spring maize for 14 locations evenly distributed across the NCP. Simulations were carried out for five different soil texture classes (sand, sandy loam, loam, silt loam and silt). To provide the model results on a large geographical scale the results were extrapolated by using a GIS (Chapter 8). Results showed that maize yields in the NCP decreased from north to south and increased from west to east. The overall mean grain yield for the entire NCP achieved 4800 kg ha^{-1} for summer maize and 5700 kg ha^{-1} for spring maize. Besides, the results indicated that the yield distinction between summer maize and spring maize was partially very low as a result of water shortage at flowering stage. A delay in sowing and the use of adapted cultivars with a later flowering date could help to increase spring maize yields.

Overall the conducted simulation studies indicated that crop models are valuable tools for e.g. irrigation planning or the evaluation of different cropping designs in the NCP. However crop models can only be properly used as decision support tool when they are calibrated and validated using field data. Besides, the accuracy of the model output largely depends on the quality of the input data. Although CERES-Maize and CERES-Wheat were able to simulate maize respectively wheat production reasonably well in the present studies, a further evaluation and improvement with detailed field databases is desirable for agricultural systems in NCP. Further, the proposed model-based strategies for improvements in irrigation management and the cropping system still have to be evaluated in the field.

The DSSAT model, as all models contains a number of assumptions and limitations. DSSAT grew out of previous single-crop models including the CERES and crop growth (CROPGRO) families and others. Altogether models of 16 different crops (barley, maize, sorghum, millet, rice, wheat, dry bean, soybean, peanut, chickpea, cassava, potato, sugarcane, tomato, sunflower, pasture) are incorporated (Jones et al., 2003). According to Jones et al. (1998) the main limitations of DSSAT are related to the included crop models. The models do not respond to all environmental and management factors. They are most useful where weather, water and nitrogen are the factors that affect crop performance. However, components to predict the effects of tillage, pests and intercropping are still missing (Ines et al., 2001). Besides, the models do not simulate extreme soil conditions e.g. salinity or extreme weather events such as floods or hurricanes (Hoogenboom et al., 1995). In wet years e.g. yields in CERES-Maize are overestimated even if excess water hinders plant growth (Wu et al., 1989). Under very poorly drained conditions oxygen stress will affect crop growth. Ritchie (1998) recommended the need for a better simulation of the water balance in badly drained soils. For improving DSSAT Ines et al. (2001) recommend to take the interaction of the soil water balance model with the groundwater into account. Furthermore, the definition of water, oxygen and salt stress should be done in a more generic way. Besides, DSSAT should consider lateral drainage routines. Concerning the use of DSSAT in China improvements regarding salinity, excess water as well as the adoption of further relevant crops are desirable.

9.2 Activities to counteract water scarcity

In the NCP multitudes of activities to counteract water scarcity and to improve respectively reduce agricultural water use are more or less implemented. In the following chapter, some examples and possibilities to attenuate the water problem in the NCP are discussed.

In terms of water resources China can be divided into two parts, North China and South China. The southern part is water abundant whereas North China is water scarce (Jin and Young, 2001). The distribution of the water resources does not match with the amount of arable land and the predominant production intensity in various regions (Li, 2006x). The NCP for example has approximately 40 % of the nation's crop land, but only 6 % of the total water resources (Smit and Yunlong, 1996). Therefore, regional water shortage is very serious (Li, 2006x). To overcome the perceived handicap the Chinese government has decided to construct aqueducts to transport water from the south to the north. The planned **Grand South to North Water Diversion Project** diverts up to 16000 million m³ water from south to north (Jin and Young, 2001). Even if the project may help to partly solve the water problem, it is costly and entails many negative ecological impacts (Wang and Ma, 1999). Zhu et al. (1983) concluded in their study that with a south to north water transfer there is still not enough water to solve China's overall water crisis.

Due to **improper technological irrigation equipment**, up to now only 50 % of the delivered water in China has reached agricultural fields (Jin and Young, 2001). Canal lining or water pipes may help to increase the water delivery (Gu, 2001). If the water is delivered to the fields the use of water-saving irrigation techniques, such as drip or sprinkler irrigation may help to save water as these techniques are more than 50 % efficient in comparison to flood irrigation (Wolff, 1999). Flood irrigation is currently predominant as the low water prices do not provide any incentive to the farmers to adapt new irrigation techniques (Jin and Young, 2001).

Winter wheat is with about 80 % of the total agricultural water consumption the most irrigated crop in China (Li, 1993). The high amount of irrigation water required for wheat production is due to the limited precipitation amount during the main growing season of winter wheat (see also chapter 4). Hence, the **improvement of irrigation management** to wheat may be one of the most important tools for saving water (Shin, 1999). In order to reduce irrigation amounts, knowledge on crop responses to water stress during different growth stages is important (English and Nakamura, 1989; Ghahraman and Sepask, 1997; Zhang et al., 1999). Using irrigation timing at critical growth stages, irrigation water can be conserved while maintaining at the same time high yields. The sensitivity of wheat to water stress is small at seedling stage, higher at the stages from stem elongation to milking and becomes rather low after milking (Table 6) (Zhang et al., 1999).

Table 6. Sensitivity index of wheat to water stress during different growing periods (0 = not sensitive; 1 = highly sensitive) (Source: Zhang et al. 1999, adapted and modified).

Location	**Sensitivity index**					
	Sowing - winter freezing	Winter freezing - regreening	Regreening - stem elongation	Stem elongation - heading	Heading - milking	Milking - maturity
Luancheng (114.4° N, 37.5° E)	0.0800	0.0100	0.0830	0.1827	0.1264	0.0093

The variation in sensitivity to water stress has an important implication for the irrigation schedule. Farmers in the NCP traditionally irrigated winter wheat before the over-wintering period (Zhang et al., 2003). As winter wheat is not sensitive to water stress during the seedling stage respectively the over-wintering period, the application amount can be reduced to an amount just ensuring germination. Complementary results of Zhang et al. (2003) showed that irrigation before winter could be omitted due to its loss to soil evaporation and its effects on increasing the non-effective tillers in spring.

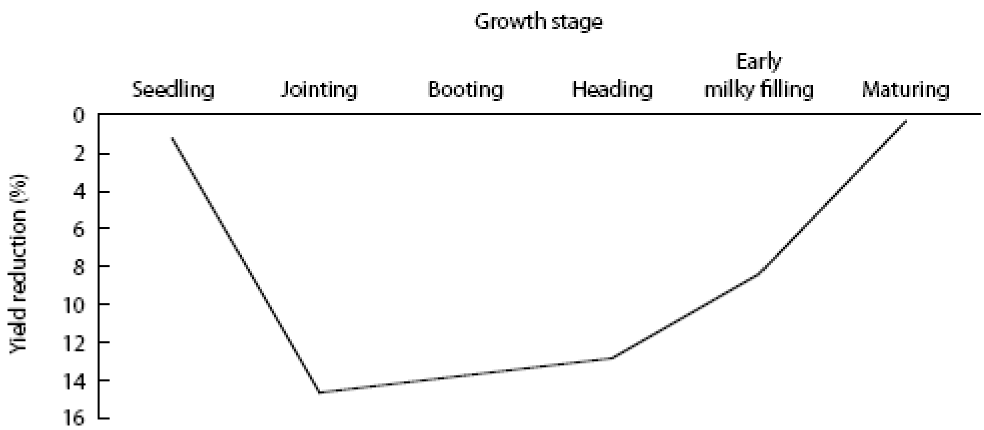

Fig. 8. Yield reduction of winter wheat at different growth stages by water deficit at Luancheng during the growing season 1996/1997 (Source: Zhang 2002, adapted and modified).

With increasing temperatures and a growing leaf area, crop water demand significantly increases from the start of vegetation to stem elongation and heading. If water-stress is limiting growth, irrigation at the most water-sensitive growth stages may result in higher yields per unit water compared to water applied during other growth stages (Stone and Schlegel, 2006). In conclusion an irrigation application around stem elongation (jointing) to heading may have the greatest influence on grain yield and would be advisable especially in areas where water resources are limited such as the NCP (Fig. 8).

The **selection of the crop** is the most important management decision (Tanwar, 2003) because it specifies the environmental requirements such as the water demand, the growth duration and with it the compatibility of crop rotations. Furthermore, with the selection of crops the potential yield as well as the crop quality and consequently the economic value are determined. Besides the crop selection the right use of varieties affects the environmental requirements as well as the economical outcome.

Plant breeding efforts can attribute to increase water productivity (Molden, 2007) and enhance crop tolerance for abiotic stress. Over the last century breeding has indirectly increased the productivity of water by increasing yields without increasing the crop water demand (IWMI, 2003). Recently plant breeders have realised the importance of crop productivity in relation to water consumption (Bennett, 2003). More attention is paid to breeding crops that can yield more with less water, withstand water scarce conditions and thrive on low quality water (IWMI, 2003).

Varying the **sowing date** modifies the environmental conditions (radiation, thermal and water conditions) during the growing period (Cirilo and Andrade, 1994). Commonly grain crops are more sensitive to water stress during flowering and early seed formation than during vegetative or ripening phases (Doorenbos and Kassam, 1979). Therefore, for reducing the irrigation water demand, the object of agronomic practices must be to sow the individual crops respectively varieties at a time when water deficit is least likely to occur during the late vegetative, flowering and grain filling stage (see also irrigation management). Additionally, adoptions in the cropping system such as shortening the period between harvests of winter wheat and sowing of summer maize in the double cropping system by e.g. direct drilling methods or transplanting maize can improve water use significantly (Böning-Zilkens, 2004). Relay intercropping, i.e. the sowing of maize into the winter wheat shortly before harvest, enables an increase of maize yield due to an extension of the maize growing season. In experiments of Böning-Zilkens (2004) no decrease in wheat yield was detected resulting in a higher WUE. Besides sowing time **sowing density** is an important cultural practice determining crop water use. A high plant population has a negative effect on the yield per plant due to the effects of interplant competition for water, light, nutrients and other growth factors (Modarres et al., 1998). Hence an increasing sowing density increases water use and thereby generally increases plant stress if not enough water is available (Shaw, 1988). Therefore, the sowing density should not be too high in order to maintain the amount of available water per plant above a certain minimum (Sangoi, 2000).

Changing the balance between evaporation and transpiration could help to increase WUE under water limited conditions (Cooper et al., 1987). In wheat production evaporation is about 30-60 % of the evapotranspiration (Amir et al., 1991). Due to the fact that the evaporation is little conductive to the crop productivity a decrease in evaporation and an increase in transpiration may help to increase WUE (Xie et al., 2005). Covering the surface with **mulch** or any kind of crop residue reduces radiation and wind speed and hence decreases evaporation. However, due to lower soil temperatures, as an effect of shading the soil surface, the plant development is partly delayed. **Reduced tillage** also helps to decrease evaporation as the surface cover is maintained and soil surface is undistributed (Aase and Pikul, 1995). Besides reduced tillage leads to an increased infiltration rate of precipitation, enhanced earthworm activity, decreased soil erosion and a high amount of organic matter. An increase in soil organic matter results in a positive impact on soil water holding capacity and an increase in water availability (Hudson, 1994). According to Hatfield et al. (2001) it is possible to increase WUE by 25-40 % through the soil management.

Due to water shortage the importance of **fertilizer application** to maintain respectively increase the productivity level seems to be limited (Li et al., 2004). However fertilization in combination with irrigation could stimulate deeper rooting thus a greater quantity of stored soil water is available to the plant (Brown, 1971; Nielsen and

Halvorson, 1991). If enough soil water is available, the deeper rooting system could help to mitigate water stress. Besides the positive effect on root growth an increased fertilization stimulates also the growth of the above ground biomass resulting in a higher transpiration of the canopy (Ritchie and Johnson, 1990). Therefore, if not sufficient soil water is available a high fertilization leads to a greater water stress resulting in lower yield, WUE and lower economical returns (Frederick and Camberato, 1994; Huang et al., 2003).

Water pricing seems by many as an adequate tool for increasing WUE and promoting water savings (Zhang and Zhang, 1995; Nyberg and Rozelle, 1999; Ward, 2000). The government of China is currently updating the water price structure in China (Ehrensperger, 2004). Up to now, the water prices show a large variation across the country because they take the water scarcity and the ability to pay into account. The prices are increasing in provinces where water is becoming more and more scarce. However, agricultural users pay a lower price than domestic users, who pay less than industrial users (Lohmar et al., 2003). Overall the water prices are very low and do not provide any incentive for efficient use or water conservation. Agricultural water prices are not sufficient to cover the costs of water supply (Ehrensperger, 2004). Any increase in water prices for agriculture would force the farmers to irrigate more efficiently (Löw, 2003). According to Bannayan et al. (2003) maximizing yield and gross margin as a function of inputs and production costs is one of the main goals when making management decisions such as irrigation applications (Fig. 9). The classic production function exhibits stages of increasing, diminishing and negative returns (Roy et al., 2006).

Figure 9 indicates that changes in the quantity of variable inputs will cause a variation in the quantity of outputs produced e.g. varying amounts of irrigation water affect grain yield as well as gross margin. At the starting point a quantity of output is reached as growing of e.g. wheat in the NCP is possible without irrigation. However, due to the dry conditions yields as well as gross margin are low (Chapter 6). Therefore, a supplemental irrigation is required (Wang et al., 2001). With an increasing quantity of irrigation water, yield as well as gross margin increase. However, as one increases an input, a point is reached at which the additional output produced by adding another unit of input begins to get smaller and smaller, ultimately leading to a decline in the total output produced.

For example, as more and more water is added to a crop, keeping all other inputs constant the field will eventually become waterlogged and yields will decline. This corresponds with findings of Zhang et al. (2005) which originated that winter wheat could attain its maximum yield with less than full application of the current irrigation practice in the NCP. Similar winter wheat experiments of Zhang et al. (2002x) at Luancheng and Hengshui in the central part of the NCP showed that wheat yield initially rose with an increased water supply, but decreased beyond a certain irrigation level. Farmers in the NCP generally irrigate for maximizing grain yield (Zhang et al., 2002x). However, the highest yield is not always connected with the highest gross margin (Fig. 9). Analyzing the economics of irrigation, the principle considerations are that the production increase is attributed to irrigation and the relationship between the cost of irrigation water and the price for its production (Roy et al., 2006). The farmers objective is to obtain the economic optimal value from the use of irrigation water while the yield obtained from a unit of irrigation water is increasing but at a decreasing rate. The exact cut-off point would be the last mm of water that paid for itself. Due to low water prices in China the highest gross margin is often connected with the highest yield (Chapter 6). However, with an increasing water shortage irrigation water prices may rise (Zhang et al., 2002x).

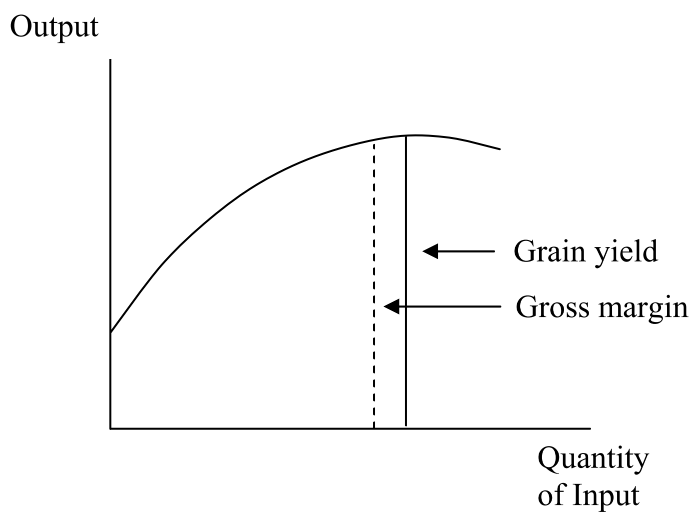

Fig. 9. Effect of input quantity on grain yield and gross margin (Roy et al. 2006, adapted and modified).

Prices will help to determine which crops become more profitable (Lohmar and Wang, 2002). Changes in input costs e.g. by increasing water prices, and output prices affect the financial profitability of all crops and affect the farmers production decisions. For example if water prices increase, farmers may move out of irrigated wheat production and produce alternative crops with a lower water demand or a higher economical value. Winter wheat is the crop affected most as wheat yields are low without irrigation (Chapter 5 and 6). Therefore a decline in wheat production is expected. The cultivation of a full season of maize to achieve high yields could be a possible adoption (Chapter 4). However, with changing cropping patterns it will be hard to achieve the governmental goal of self-sufficiency (Huang, 1998). As a consequence China has to increase its imports. According to Yang and Zehnder (2001) it would be wise to increase grain imports, not only because the imports can ease water stress, but this would also conform to the general idea of an open economy. Since China has a limited arable area but a large population, it does not have a comparative advantage in land-intensive crops like grain, but it does have a comparative advantage in labour-intensive crops such as vegetables (Lin, 2000).

9.3 Future conditions and reactions

9.3.1 Water competition

Water in China is supplied to three main sectors: agriculture, industry and the domestic part (Jin and Young, 2001). Up to now agriculture is with about 80 % of the total water consumption the largest water user (Hubacek and Sun, 2005). However, a continuing population growth connected with higher living standards and rapid economic developments has led to an increasing demand for water by non-agricultural users. Therefore, it is estimated that the agricultural share will be reduced by 16 % up to 2050 (Jin and Young, 2001). The economics of water use between agriculture and industry is also not of in favour for agriculture in the competition for water. To produce one ton of wheat grain thousand tons of water are required, worth around U$ 200. In industry the same water amount will expand an output of U$ 14000 (Kim, 2003). Besides, the political value of water for urban domestic use is much higher than that for irrigation (Jin and Young, 2001). Overall future water availability for agriculture will be further reduced by the competition of non-agricultural users (Liu et al., 1998).

9.3.2 Rainfed cultivation

If water is becoming more scarce and the competition for water is high, it is conceivable to stop irrigation cultivation altogether. Currently rainfed cultivation makes up about 57 % of the total farmland in China but the production from this land is less than 30 %. However in future, rainfed cultivation will play a more important role for sustainable water supply (Li, 2006x). If no irrigation water is available the cropping pattern must be readjusted so that the crop development coincides with the rainfall distribution (Shangguan et al., 2001). For example in the NCP spring crop growing must be reduced by enlarging autumn crop growing. Besides the cropping pattern also the right use of crops suitable for rainfed cultivation is important because the drought resistance is different for different crops. The major drought enduring crops grown in the dry land farming areas of China are millet, sorghum, beans, tuber crops and naked oats (Shangguan et al., 2001). Rainfed cultivation implies an effective utilization of precipitation base on three basic principles (Fageria, 2001). First, the surface runoff of precipitation should be minimized by avoiding surface seals, improving infiltration rate, increasing surface retention capacity and decreasing run-off rate. This is possible e.g. by mulching (Li, 1998; Mellouli et al., 2000; Chen et al., 2002), reduced tillage (Aase and Pikul, 1995) or cover crops (Azevedo et al., 1999; Benites and Castellanos, 2003). The second principle is that the precipitation has to be absorbed by or infiltrated into the soil. This necessitates, that the soil and crops are managed in a way that the water is covered in the root zone and crop water use is increased. One possibility to accomplish this second principle is to cover the soil surface with mulch because mulching can reduce soil evaporation, alleviate the threat of drought and improve the WUE (Li, 1998; Mellouli et al., 2000; Chen et al., 2002) (see chapter 4). The third principle of a successful water use is that any surplus of precipitation or runoff is stored. Water harvesting, defined as the collection of water for productive use is a technique that was in use more than 4000 years ago in China (SIWI, 2001) owing to the temporal and spatial variability of precipitation. However, a growing awareness of the potential of water harvesting to supply drinking water and improving crop production arose with the widespread droughts in the 1980s (Li, 2003). Up to now 17 provinces in China have adopted techniques for water harvesting. The total water capacity of the 5.6 million implemented tanks is around 1.8 billion m^3, supplying drinking water for approximately 15 million people and supplemental irrigation for 1.2 million ha of land (GDRC, 2007). Water harvesting is becoming a living, sustainable entity and has a great potential to achieve sustainable agriculture in semiarid regions in China (Li, 2003).

9.3.3 Climate change

Future changes in climate will greatly affect agricultural production (Erda, 1996). Over the last 50 years total precipitation has decreased substantially in China (Zhai et al., 1999) whereas annual temperature has increased by 0.5-0.7 °C (Wang et al., 2004). In addition due to an increase in atmospheric CO_2 and other greenhouse gases it is projected that during the period of 1999 to 2100 the global surface air temperature will increase by 1.4 to 5.8 °C (IPCC, 2001). Higher temperatures and a less increase of precipitation may lead to increased evaporation and transpiration levels. This will lead to an increase in soil salinization because salinity follows the movement of water and so evaporation leaves an accumulation of salt on the surface (Zhu et al., 1983). Furthermore, the change in climate may lead to a reduction of the available water for crop growth and make the water stress stronger which results in a reduction of crop yield (Wang and Wang, 1998). Besides, increasing temperatures shorten the growing duration of grain crops, resulting in a shorter grain filling period. Consequently plants produce smaller and lighter grains, resulting in lower yields (Wolfe, 1995; Adams et al., 1998). New varieties that are more heat and drought tolerant and do not mature too quickly are needed. However it is difficult to quantify the impacts of future climate changes on agriculture. There are also some facts which may lead to a more positive judgment. The CO_2 enrichment e.g. may lead to a production increase (Smit and Yunlong, 1996) through the stimulation of photosynthesis and the reduction of transpiration (Rosenberg et al., 1990). C_3 plants (e.g. wheat, soybean, citrus) and C_4 plants (e.g. maize, sorghum, millet) will be affected differently by an increased CO_2 level because the pathway for photosynthetic fixation of CO_2 is different (Rosenzweig and Hillel, 1998). C_3 plants are more responsive to an increased CO_2 concentration as up to half of the photosynthate is normally lost and returned to the air by photorespiration. Further, higher CO_2 levels also reduce the dark respiration in C_3 plants. In comparison C_4 plants are less responsive to a higher CO_2 concentration because the photorespiration in C_4 plants is smaller than in C_3 plants. Instead, the largest benefit C_4 plants receive from higher CO_2 levels comes from a reduced water loss. Loss of water through transpiration declines by about one third in C_4 plants with a doubling of the CO_2 concentration from the current atmospheric level (Wittwer, 1992). However, most of the experiments with CO_2 enrichment were done in greenhouses. Therefore, it is still uncertain whether CO_2 fertilization will be as strong in agricultural fields as suggested under controlled experiments. Besides, the effects of CO_2 enrichment on plants depend on soil water availability, and plants may benefit more from CO_2 increase when enough water is available (Wu et al., 2004). However climate in the NCP generally will become warmer and drier. As a consequence the arid period will be prolonged (Schäfer, 2001) and therefore water will become more and more scarce.

9.4 Synopsis

Water scarcity is viewed as a major problem for Chinas agricultural sector. The rapid economic development and population growth as well as changes in climate are accentuating the water problem. Therefore first and foremost policy reforms and measures dealing with water scarcity are needed (Fig. 10).

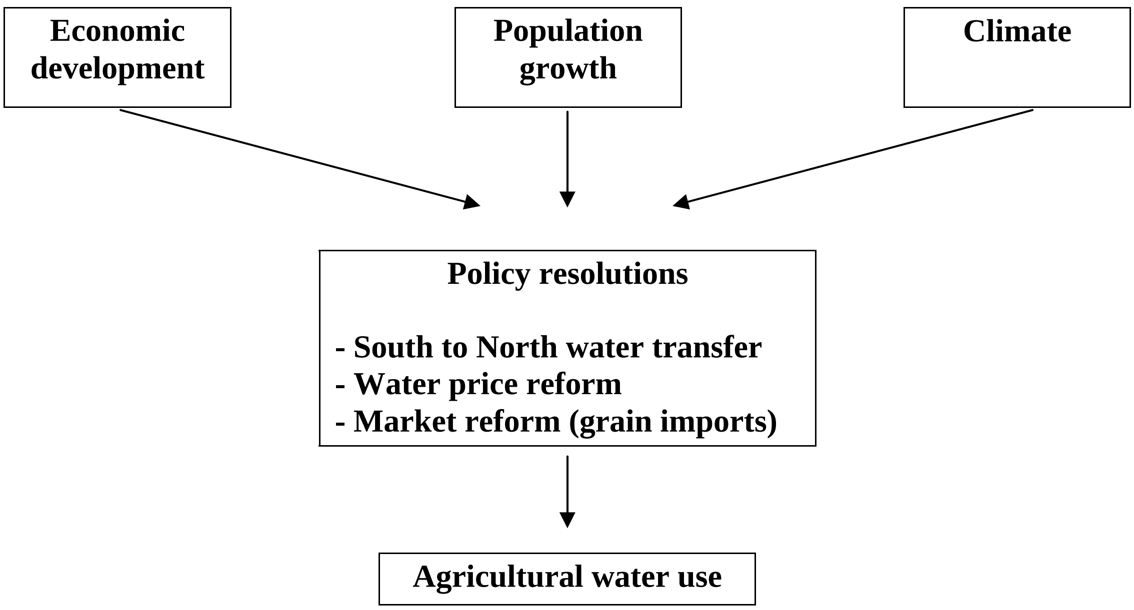

Fig. 10. Factors affecting agricultural water use.

With the Grand South to North Water Diversion Project a first approach to improve the water supply in the water scarce north was undertaken. However besides a guarantee on the supply side also measures regarding the minimization of the overall water consumption are needed. Reforms of the water prices as well as a justification of the governmental goal of grain self sufficiency may help to improve respectively reduce agricultural water use.

Up to now many possibilities are presented to reduce agricultural water use, but they must be implemented in the production systems (Fig. 11).

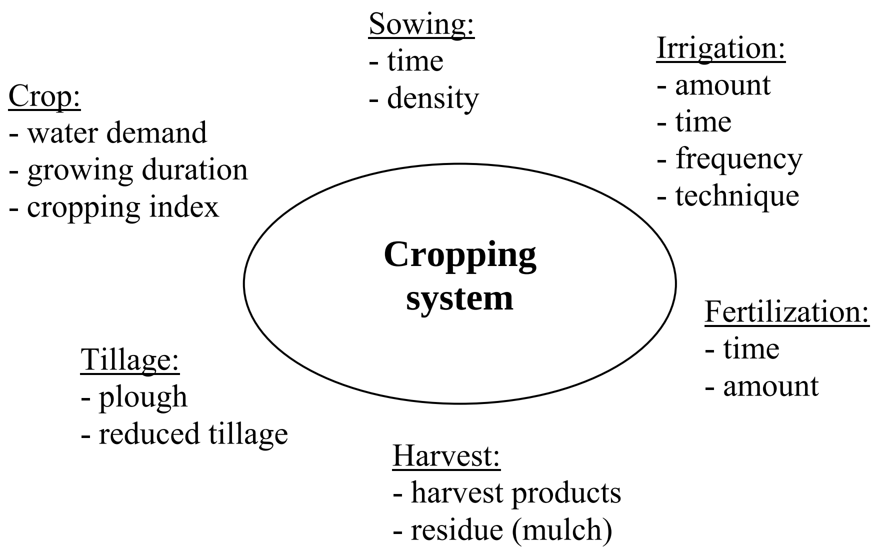

Fig. 11. Factors which impinge on the goal of a sustainable cropping system regarding water use in the North China Plain.

The selection of the crop is the most important management decision because it specifies the environmental requirements especially in the water demand. Further, the cultivated crops differ widely in agronomic characteristics, e.g. in the length of growing period. The object of agronomic practices must be to sow the individual crop at a time when water deficit is least likely to occur at sensitive stages. To maintain the amount of available water per plant above a minimum the sowing density should not be too high.

Improving irrigation management is one of the most important tools for saving water. In order to reduce irrigation amounts, knowledge about crop responses to water stress in different growth stages is required. Besides the irrigation management the use of water-saving irrigation techniques, such as drip or sprinkler irrigation, could help to save water. Fertilization measures in combination with irrigation could stimulate deeper rooting so that a greater quantity of stored soil water is available to the plant. Furthermore, mulching and reduced tillage may help to avoid surface seals, improving infiltration rates, increasing surface retention capacity and decreasing the run-off rate. Besides, they can reduce soil evaporation, alleviate the threat of drought and improve WUE. However cropping systems and their environments are complex. Therefore, the main difficulty will be to select and combine the available possibilities for reducing respectively improving agricultural water use to form a sustainable cropping system for the NCP.

10 SUMMARY

The topic of this study was "Reducing Irrigation Water Supply to Accomplish the Goal of Designing Sustainable Cropping Systems in the North China Plain". The background of the investigation can be seen in facing the problem of producing more food for a still rising population connected with a limited land area and water scarcity in China. The dissertation was embedded in the context of the International Research Training Group (IRTG) of the University of Hohenheim and the China Agricultural University, entitled "Modeling Material Flows and Production Systems for Sustainable Resource Use in the North China Plain". The major hypothesis of the IRTG was "that adjustments in cropping systems and management practices provided potential for sustainable resource protection on a high yield level" in the North China Plain (NCP). The main objectives of the present study were to:

- analyze the changes in yield performance of the two main crops winter wheat and summer maize in the NCP over the last 20 years (Chapter 4).
- assess the actual cropping system and the trend towards new cropping systems in the NCP (Chapter 4 and 7).
- evaluate CERES-Wheat and CERES-Maize for their ability to simulate wheat respectively maize growth and yield under the conditions of the NCP and demonstrate the potential of using models to improve sustainability related to water use in the NCP (Chapter 5, 6 and 8).
- determine the production potential of summer maize and spring maize in the NCP by using a Geographic Information System (GIS) to regionalize obtained results over the whole NCP (Chapter 8).

The research programme was conducted in one of the most important economic and agricultural regions in China, the NCP. Winter wheat and summer maize are currently the main cultivated crops. Both crops are combined in a single-year rotation also referred to as a double cropping system. The results of the study showed that over the last two decades yields of wheat and maize increased by more than 20 % which had mainly been achieved by augmenting the amount of irrigation water and fertilizer. Besides the positive effects on yield an increasing amount of this input factors lead to many environmental problems (Chapter 4).

Field experiments were set up on three locations in the NCP to compare different cropping systems and to evaluate altered input scenarios. In the field experiments two respectively three different treatments were tested within the double cropping system to find out whether it is possible to reduce the input factors irrigation water and N-fertilizer by maintaining high yields. In the traditional treatment irrigation and fertilization was carried out according to farmer's practice, with the input being very high. In the treatment reduced input, irrigation was based on measurements of the soil water content aiming to keep the available field capacity between 45-80 %. The N-fertilization was based on N_{min}-measurements and target yield. Results indicated that through a more scientific based use a strong reduction of the input factors is possible without a strong decrease in yield.
Besides input optimizations within the double cropping system, alternative cropping systems were tested. Currently the double cropping of winter wheat and summer maize is the common cultivation system in the NCP and consists of growing two crops in one year. Winter wheat is sown in mid October and harvested in mid June. Afterwards summer maize is sown directly and harvested at the beginning of October. The winter wheat production depends on a supplemental irrigation, because rainfall is concentrated in the summer months during the maize growing season. An alternative to the intensive double cropping system could be the single cultivation of spring maize as a monoculture. Spring maize is sown in the middle of April and harvested at the end of September. The remaining time of the year is fallow. The rainy season coincides with the main part of the maize growing season. Therefore relative less irrigation water is required for spring maize production. Due to the longer growing season spring maize normally realises higher yields in comparison to summer maize. However, the total yield of double cropping wheat and maize is higher. The system three harvests in two years forms a balance between the double cropping of winter wheat and summer maize and the single cropping of spring maize. In the first year the double cropping system with growing winter wheat from October until June followed by summer maize from June until September is practiced. Afterwards a fallow period follows. Spring maize is cultivated in the second year from April until September before the rotation starts again with winter wheat. Due to the fact that three crops are grown in two years total yield is higher in comparison to single cropping of spring maize (two harvests in two years) but lower in comparison to the traditional double cropping system (four harvests in two years).

However the lower cropping index in contrast to the double cropping of wheat and maize results in a lower demand of the input factors irrigation water and N-fertilizer whereas in comparison to the single cropping of spring maize a higher amount of input factor is required (Chapter 4 and 7).

Besides the field experiments the CERES-Maize and CERES-Wheat models were used to quantify the effects of different irrigation management practices on crop growth, productivity and sustainability of agricultural production. Results indicated that there is a considerable potential for reducing the irrigation amount. However, the results also showed that a supplemental irrigation at critical growth stages seems to be essential to maintain high yields and to ensure an adequate gross margin (Chapter 5 and 6).

In a more complex approach the CERES-Maize model was used to simulate the yield of summer maize and spring maize across the NCP. The spatial and temporal climate variability was taken into account by using up to 30 years of weather data from 14 meteorological stations. Simulations were carried out for five different soil texture classes (sand, sandy loam, loam, silt loam and silt). The simulated results were linked to a GIS. Results indicated that the yield distinction between summer maize and spring maize was partially very low as a result of water shortage at flowering stage. A delay in sowing and the use of a cultivar with a later flowering date could help to increase spring maize yields (Chapter 8).

Summarizing, the overall results of this study indicated that water is one of the most limiting factors for crop production in the NCP. Further, the reduction of total water consumption will become more and more important with water becoming increasingly scarce and thus costly. Consequently agriculture has to undergo and is already undergoing dramatic changes. The results of this study indicated that there are several possibilities to optimize cropping systems in the NCP, focussing on a more sustainable use of water while maintaining high yields. In this context, crop models are valuable tools for e.g. irrigation planning or evaluating different cropping designs in the NCP.

11 ZUSAMMENFASSUNG

Die vorliegende Arbeit stand unter dem Titel "Reducing Irrigation Water Supply to Accomplish the Goal of Designing Sustainable Cropping Systems in the North China Plain". Hintergrund der Untersuchung war eine Erhöhung der Nahrungsmittel-produktion für eine stetig wachsende Bevölkerung in China, verbunden mit einer begrenzt landwirtschaftlich nutzbaren Fläche, sowie einer zunehmenden Wasserknappheit. Die vorliegende Dissertation wurde im Rahmen der International Research Training Group (IRTG) der Universität Hohenheim und der China Agricultural University mit dem Titel "Modeling Material Flows and Production Systems for Sustainable Resource Use in the North China Plain" erstellt. Die Haupthypothese des Projekts war, dass in der Nordchinesischen Tiefebene (NCP) „durch eine Anpassung der Produktionssysteme sowie der Produktionspraktiken Potenziale für einen nachhaltigen Ressourcenschutz bei gleitzeitig hohen Erträgen existieren". Folgende Teilaspekte wurden in der Dissertation bearbeitet:

- Untersuchung der beiden Hauptkulturen Winterweizen und Sommermais in der NCP hinsichtlich ihrer Ertragsentwicklung in den letzten 20 Jahren (Kapitel 4).
- Bewertung des gegenwärtigen Double Cropping Systems, sowie alternativer Anbausysteme (Kapitel 4 und 7).
- Evaluation von CERES-Wheat und CERES-Maize hinsichtlich ihres Einsatzes für die Simulation des Weizen- bzw. Maiswachstums und -ertrags in der NCP, sowie die Demonstration, wie Modelle zu einem nachhaltigeren Wassereinsatz in der NCP beitragen können (Kapitel 5, 6 und 8).
- Bestimmung des Produktionspotenzials von Sommermais und Frühjahrsmais in der NCP, sowie die Regionalisierung der Ergebnisse mit Hilfe eines Geographischen Informationssystems (GIS) (Kapitel 8).

Die Untersuchungen wurden in der NCP, einer der wichtigsten Wirtschafts- und Agrarregionen Chinas, durchgeführt. Winterweizen und Sommermais sind gegenwärtig die am häufigsten angebauten Kulturen. Beide werden in einer einjährigen Rotation, einem so genannten Double Cropping System angebaut. Während der letzten beiden Jahrzehnte stiegen die Erträge für Weizen und Mais um über 20 % an, was vor allem durch eine Ausdehnung der Bewässerung, sowie der Düngung ermöglicht wurde. Neben einem Ertragsanstieg führte der gesteigert Produktionsmitteleinsatz jedoch auch zu vielen Umweltproblemen (Kapitel 4).

An drei verschiedenen Standorten in der NCP wurden Feldversuche angelegt, um verschiedene Anbausysteme, sowie im Produktionsmitteleinsatz variierte Varianten zu vergleichen. In den Feldversuchen wurden zwei bzw. drei verschiedene Versuchsvarianten bezüglich dem Double Cropping System getestet, um herauszufinden, inwieweit der Einsatz von Bewässerungswasser und N-Dünger ohne starke Ertragseinbußen reduziert werden kann. Die Bewässerung und Düngung in der traditionellen Versuchsvariante wurde wie bei den ansässigen Landwirten ausgeführt, wobei der Einsatz sehr hoch war. In der reduzierten Versuchsvariante basierte die Bewässerung auf Messungen des Bodenwassergehaltes mit der Zielsetzung die nutzbare Feldkapazität zwischen 45 und 80 % zuhalten. Die N-Düngung basierte auf N_{min}-Untersuchungen sowie Daten hinsichtlich der Ertragserwartung. Die Versuchsergebnisse zeigten, dass durch einen optimierten Einsatz die Produktionsfaktoren erheblich reduziert werden konnten, ohne dass die Erträge stark absanken.

Neben den Versuchen innerhalb des Double Cropping Systems wurden auch alternative Anbausysteme getestet. Gegenwärtig ist das Double Cropping von Winterweizen und Sommermais das am häufigsten praktizierte Anbausystem in der NCP, wobei beide Kulturen im gleichen Jahr angebaut werden. Die Winterweizenaussaat erfolgt Mitte Oktober, die Ernte Mitte Juni. Anschließend erfolgt direkt die Aussaat von Sommermais, der Anfang Oktober geerntet wird. Aufgrund der Niederschlagskonzentration in den Sommermonaten, während der Maisvegetation, ist eine ergänzende Bewässerung zu Winterweizen erforderlich. Eine Alternative zu dem intensiven Double Cropping System könnte der alleinige Anbau von Frühjahrsmais als Monokultur sein. Die Frühjahrsmaisaussaat erfolgt Mitte April, die Ernte Ende September. Die restliche Zeit des Jahrs liegt das Feld brach. Der überwiegende Teil der Maisvegetationsperiode fällt mit der Regenzeit zusammen. Daher ist relativ wenig Bewässerungswasser für den Anbau von Frühjahrsmais erforderlich. Aufgrund der längeren Vegetationsperiode erzielt Frühjahrsmais im Vergleich zu Sommermais meist höhere Erträge. Dennoch ist der Gesamtertrag beim Double Cropping von Weizen und Mais höher. Einen Kompromiss zwischen dem Double Cropping von Winterweizen und Sommermais und dem alleinigen Anbau von Frühjahrsmais bildet das System drei Ernten in zwei Jahren.

Im ersten Jahr wird das Double Cropping System praktiziert wobei Winterweizen von Oktober bis Juni, gefolgt von Sommermais von Juni bis September angebaut wird. Anschließend folgt eine Brache. Frühjahrsmais wird im zweiten Jahr im Zeitraum April bis September angebaut, bevor die Rotation wieder mit Winterweizen startet. Da drei Kulturen in zwei Jahren angebaut werden, ist der Gesamtertrag im Vergleich zum alleinigen Anbau von Frühjahrsmais (zwei Ernten in zwei Jahren) höher, im Vergleich zum traditionellen Double Cropping System (vier Ernten in zwei Jahren) jedoch geringer. Der niedrigere Anbauindex, im Vergleich zum Double Cropping von Weizen und Mais, führt jedoch auch zu einem geringern Bedarf an Bewässerungswasser und N-Dünger. Im Vergleich zum alleinigen Anbau von Frühjahrsmais ist dennoch ein höherer Produktionsmitteleinsatz erforderlich (Kapitel 4 und 7).

Neben den Feldversuchen wurden die Modelle CERES-Maize und CERES-Wheat zur Bewertung verschiedener Bewässerungsmanagementpraktiken und deren Auswirkung auf das Pflanzenwachstum, sowie die Produktivität und Nachhaltigkeit der landwirtschaftlichen Produktion verwendet. Die Ergebnisse zeigten ein beträchtliches Einsparungspotenzial an Bewässerungswasser. Daneben zeigten die Ergebnisse jedoch auch, dass für den Erhalt hoher Erträge sowie die Erzielung ausreichender Deckungsbeiträge eine ergänzende Bewässerung zu kritischen Wachstumsstadien erforderlich ist (Kapitel 5 und 6).

In einem umfassenderen Ansatz wurde das Model CERES-Maize zur Simulation des Ertragspotenzials von Sommer- und Frühjahrsmais über die gesamte NCP genutzt. Die räumliche und zeitliche Variabilität des Klimas wurde durch die Verwendung von bis zu 30 Jahren an Wetterdaten von 14 Wetterstationen berücksichtigt. Die Simulationen erfolgten für fünf verschiedene Bodenarten (Sand, sandiger Lehm, Lehm, lehmiger Schluff und Schluff). Die Simulationsergebnisse wurden in einem GIS verknüpft. Aufgrund von Wassermangel während der Blüte waren die Ertragsunterschiede zwischen Sommer- und Frühjahrsmais lokal sehr gering. Eine Erhöhung der Frühjahrsmaiserträge konnte durch eine spätere Aussaat sowie durch die Verwendung spät blühender Sorten erreicht werden (Kapitel 8).

Zusammenfassend zeigen die Ergebnisse dieser Studie, dass Wasser eines der am stärksten limitierenden Faktoren für die Pflanzenproduktion in der NCP ist. Mit einer zunehmenden Verknappung sowie steigenden Wertschätzung des Wassers wird eine Reduzierung des Verbrauchs immer wichtiger. Daher sind und werden noch weitere tief greifende Änderungen in der Landwirtschaft erfolgen. Die Ergebnisse dieser Studie zeigten jedoch auch, dass verschiedenste Möglichkeiten vorhanden sind, bei gleich bleibend hohen Erträgen die Anbausysteme in der NCP hinsichtlich ihres Wassereinsatzes nachhaltiger zu gestalten. Pflanzenwachstumsmodelle stellen diesbezüglich ein nützliches Instrument dar z.B. für die Planung der Bewässerung oder die Bewertung verschiedener Anbausysteme.

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