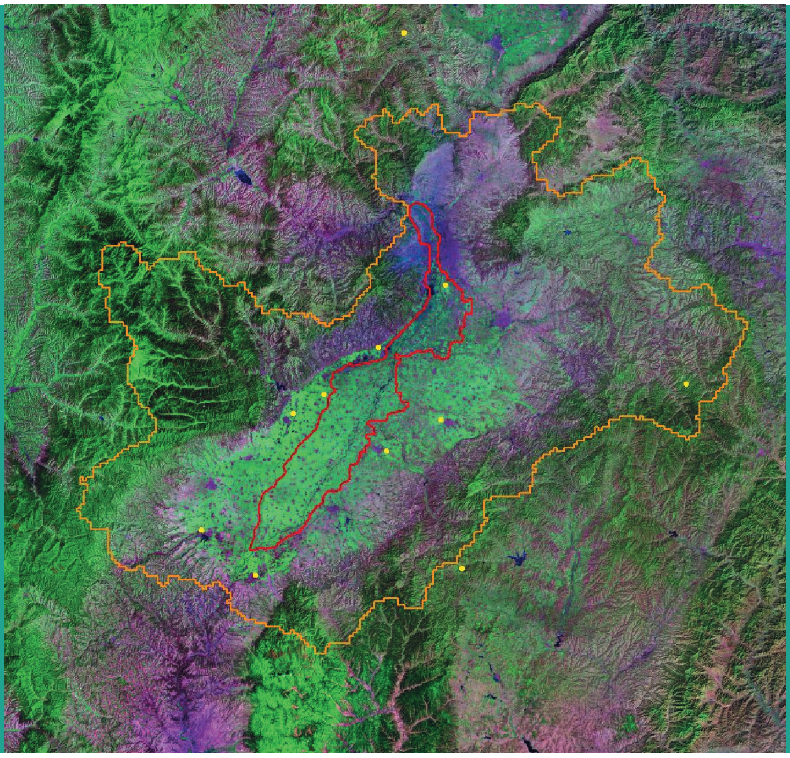
PLANT RESEARCH INTERNATIONAL
WAGENINGEN UR

Modelling Crop Production in Fenhe Irrigation District, Shanxi province, North China

B. Bake, H. van Keulen, A. Verhagen & D. Zheng



Note 419

PLANT RESEARCH INTERNATIONAL

WAGENINGEN UR

Modelling Crop Production in Fenhe Irrigation District, Shanxi province, North China

B. Bake[3], H. van Keulen[1,2], A. Verhagen[1] & D. Zheng[3]

[1] Plant Research International, Business Unit Agrosystems Research, P.O. Box 16, 6700 AA, Wageningen, the Netherlands
[2] Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, the Netherlands
[3] Research Center for Resource Utilization and Environment Management, China Agricultural University, 100094, Beijing, China

Plant Research International B.V., Wageningen
October 2006

Note 419

© 2006 Wageningen, Plant Research International B.V.
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of Plant Research International B.V.

Plant Research International B.V.

Address	:	Droevendaalsesteeg 1, Wageningen, The Netherlands
	:	P.O. Box 16, 6700 AA Wageningen, The Netherlands
Tel.	:	+31 317 47 70 00
Fax	:	+31 317 41 80 94
E-mail	:	info.pri@wur.nl
Internet	:	www.pri.wur.nl

Table of contents

Summary

Water scarcity is a very serious problem in Northern China (north of the Yangtze River). In Fenhe District, one of the largest irrigation schemes in Shanxi province, annual precipitation varies between 200-700 mm (453 mm on average); in dry years farmers can irrigate crops only once in conventional irrigation systems. To increase income, farmers increasingly grow vegetables that need more irrigation water. Despite the scarcity of water, waste in agriculture is widespread. In addition, the unreliability of water supply makes fertilizer management difficult. Hence, experiments related to irrigation and nutrient management and cropping pattern for the main field crops and vegetables were carried out in the Central Experimental Station (CES) since the 1990s. In this report, experiments from 1992 to 2004 are analyzed. Soil water dynamics, including soil surface evaporation under shallow water table depths are discussed and simulated. Irrigation management under different hydrological conditions and water table depths (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m) is discussed. Light-temperature characteristics of a new early maturing wheat variety were tested and possibilities for introducing this variety in the study area are discussed. Irrigation management experiments on vegetables were performed and effects of irrigation management and its economic benifits are anaysed.

The WOFOST crop growth simulation model is used to estimate potential, water-limited and nutrient-limited crop production for Fenhe Irrigation District (FID). To examine the spatial and temporal variability in crop production for Fenhe Irrigation District, weather data (1961-2002) for Taiyuan (north Fenhe), Jiexiu (south Fenhe) and the central meteorological stations were used to simulate potential and water-limited yields for winter wheat, spring maize and sunflower with the WOFOST simulation model.

Main results and conclusions from the study are:

1. The results show maximum grain yields of 5842, 9769 and 2231 kg $\cdot$ha^{-1}, under adequate nutrient supply for winter wheat, spring maize and sunflower, respectively. Highest observed water use efficiencies (WUE) under these conditions, based on grain yield and total water input (rainfall + irrigation) were 17.8, 25.2 and 8.8 kg ha^{-1} mm^{-1} for winter wheat, spring maize and sunflower, respectively. The relation between water consumption and grain yield under different fertilizer inputs could be expressed by a logarithmic curve; the relation between water consumption and WUE for winter wheat could be expressed by a negative logarithmic curve. As spring maize and sunflower are growing in the rainy season, the relations between water consumption and water use efficiency are hardly significant, but for sunflower, crop yield and water use efficiency starts to decrease at water consumption values exceeding 310 mm, hence supplementary irrigation is not needed in high rainfall years.
2. Root zone (0-100 cm) soil water dynamics are influenced by capillary rise under shallow water table depths, for both winter wheat and spring maize. Soil water content varies more strongly under shallower water table depths, which leads to more uptake from the groundwater and higher water use. Percolation after irrigation or rainfall started later under deeper water tables. The relation between rate of soil surface evaporation and water table depth can be expressed by an exponential curve, while the relation between cumulative soil surface evaporation over the crop growing season and water table depth for winter wheat and spring maize could also be expressed by an exponential curve. The effects of shallow water table depths on crop growth and yield were mainly mediated through more profuse tillering and higher spike densities, but not through individual grain weight. Crop yields and WUE were highest for water table depths of 1.0 and 1.5 m for spring maize and winter wheat, respectively. WUE for winter wheat attained the highest values at water table depths of 1.0 m and was lower at both shallower and greater depths. Crop water requirements, calculated by the FAO method, were 405 and 391 mm for winter wheat and spring maize, respectively. On this basis, irrigation requirements for winter wheat and spring maize, aimed at realizing high crop yields, were calculated for shallow water table depths under varying rainfall regimes.
3. The new photo-insensitive and early-maturing wheat variety, Dongzao 5 (DZ5), matured 4-5 days earlier and showed a 20% higher yield than Jingdong 8 (JD8). Moreover, DZ5 uses less thermal time for ear differentiation and does not need vernalization and can thus be sown either before or after winter. The temperature limit for 50% seedling mortality was -14.9 °C, 1.8 °C higher than that for JD8. It is expected to over-winter safely in Beijing and the southern part of North China.

4. Results of the vegetable experiments show that efficient water use and economic benefits are best combined by applying small irrigation doses, e.g. 20~40 mm per application (except for water melon). Recommended doses are: sweet potato: 200 mm irrigation (total water consumption 400 mm), jequirity: 100 mm (total water consumption 440 mm), sesame: 68 mm (total water consumption 350 mm), water melon/black bean: 188 mm (total water consumption 510 mm), muskmelon: 84 mm (total water consumption 270 mm), turnip: 250 mm (total water consumption 470 mm), sharo pepper: 110 mm (total water consumption 370 mm).
5. The WOFOST simulation model yielded an average total aboveground dry matter production under optimal conditions of 20 500 $kg \cdot ha^{-1}$ (10 500 $kg \cdot ha^{-1}$ in grain) for winter wheat, 27 110 $kg \cdot ha^{-1}$ (14 500 $kg \cdot ha^{-1}$ in grain) for spring maize and 11 650 $kg \cdot ha^{-1}$ (5 900 $kg \cdot ha^{-1}$ in grain) for sunflower. Potential production in Taiyuan was somewhat higher (winter wheat grain yield 1.6% higher, spring maize 3.4% higher, sunflower 2.3% higher) than in Jiexiu. Simulated grain yield under irrigated conditions was overestimated by 8.75% and 22.3% for spring maize and winter wheat, respectively, compared to measured yield. Simulated maximum leaf area indices and harvest indices were somewhat higher than observed value. Simulated grain yield and precipitation plus irrigation can be correlated by logarithmic curves for all three crops (correlation coefficients higher than 0.7). Crop production under water-limited (rainfed) conditions was low for all three crops, albeit acceptable for spring maize and sunflower, growing in the rainy season. For sunflower, simulated water-limited grain yields are logarithmically correlated to precipitation.
6. Anticipated developments in the agricultural sector will lead to a shift from cultivation of bulk products such as rice, wheat and maize, in view of the shift in consumer preferences and the continuing economic growth, to more remunerative high-value commodities, such as vegetables and fruits, and animal products, i.e. milk, meat, eggs, etc. As shown in the experiments reported in this report, vegetables (and the same holds for fruits), are high-intensity crops that require higher inputs, both in terms of water and in terms of nutrient elements.
7. The shift away from bulk products brings to the fore, the conflict between the dual objectives of the Chinese government of maintaining self-sufficiency in basic foodstuffs and reducing the income gap between the rural and the urban population. As China is now a full member of WTO, scope for policy measures is limited; it is doubtful therefore whether both objectives can be realized in the long run. In terms of water management this might mean that a choice will have to be made between the different water users in the Yellow river basin, i.e. agriculture, industrial and domestic. When industrial and domestic users will continue to receive priority, total agricultural production in Fenhe Irrigation District will decline.
8. As water availability from Fenhe reservoir is limited, farmer will increasingly resort to the use of groundwater for irrigation of the high-value commodities. Already there is a serious drop in groundwater table depths, and this will aggravate under the anticipated changes in structure of the agricultural sector. Whether this increased groundwater use can be restricted through economic measures such as water pricing is doubtful. The price of water required for full-cost recovery would be such that it would seriously affect the profitability of farm enterprises.
9. Expansion of the animal production sector which also will lead to high-intensity production activities involving import in the region of concentrate feed, to supplement the roughage that could be grown as an alternative to the current bulk food crops of low profitability, will lead to a surplus of nutrients, especially nitrogen and phosphorus. An active land use policy is then required to balance the intensity of the animal production systems and the associated manure production and the land area on which the manure can be applied as a fertilizer. Rules and regulations that would condition required licenses-to-produce for animals are the required.
10. In this report attention has focused on water use for agriculture. Increasingly, the requirements of water for ecosystem functions are stressed. In the Yellow river basin, including Fenhe River, these functions have largely been ignored in the past. More emphasis on this use is another serious threat to the agricultural sector, as it will reduce the availability of water for agricultural purposes.
11. There is therefore in Fenhe Irrigation District a need for formulation of water use plan, including the necessary enabling policy measures. This water use plan should not only take into account the bio-physical possibilities and constraints, but should also look at the (socio-)economic consequences. When agricultural water availability is seriously declining, the livelihoods of (many of) the small farmers now dependent on Fenhe reservoir will be under pressure. It will then be absolutely necessary to take measures creating alternative employment in the region.

Key Words: WOFOST simulation model; calibration; validation; winter wheat; spring maize; sunflower; vegetables; potential production; water-limited production; nutrient-limited production

Acknowledgements

During project implementation many people have assisted. Mr. Jia Yunmao, Mr. Meng Chong, Mr. Wang Zhansheng and Mr. Wu Chaobao from the Central Experimental Station helped in collecting experimental data and weather data and arranging accommodation; Mr. Duan Shuqiang, Mr. Zhao Yanfeng, Mrs. Yuexiang, Mrs. Zhixiang, Mr. Tuheti and Mr. Li Zhiqiang assisted in experimental observations. Special thanks are due to Mr. Niu Haozhen from Fenhe Irrigation Authority and Prof. Fan Guisheng from Taiyuan University for Technology for support in organizing the workshops during the project; Dr. Zhang Jianxin from Shanxi Meteorological Agency for providing climate data. In addition, Drs. Koen Roest and Robert Smit from Alterra, Wageningen, The Netherlands, gave comments on drafts of this report. Their contributions to the project are gratefully acknowledged.

1. Introduction

Crop models have proven to be useful tools in increasing quantitative understanding of the performance of cropping systems. Crop genetic properties and environmental conditions such as soil properties, weather conditions and management practices that interactively determine crop performance are represented in a simplified manner in crop growth models (van Keulen and Wolf, 1986). Crop production situations can schematically be classified into *potential* (determined only by radiation, temperature and crop genetic properties), *water-limited* (determined by availability of water), *nutrient-limited* (determined by availability of crop nutrients) and *actual* (effects of weeds, pests and diseases are taken into account).

Crop models offer a way to estimate the yield potential of a crop and yield levels under limiting conditions. Simulation, i.e. application of crop models, permits exploration of combinations of soil and crop properties for optimization of management strategies and, while such modeling experiments cannot substitute field experimentation, they enable preferred options to be identified (Karthikeyan *et al.*, 1996). Before formulating recommendations for improvements in crop management practices, it is useful to know the potential yield of a crop in the region of interest, as a yardstick for the 'ultimate' possibilities, to establish the gap between yield potential and current yields, and to identify the yield-limiting factors (Matthews, 2003). In crop models, the current state of knowledge of plant growth and development from various disciplines (such as crop physiology, agrometeorology, soil science and agronomy) is integrated in a consistent, quantitative and process-oriented manner (Jame and Cutforth, 1996). Yield gaps have been defined as the difference between an attainable yield level as obtained in well-kept trials and the actual yield (Pinnschmidt *et al.*, 1997). This yield gap can be the result of many factors, such as inadequate water supply, insufficient nutrient supply, weed competition, or incidence of diseases and pests. For example, Becker *et al.* (2003), analyzing rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa, reported yield gaps ranging from 3.2 to 5.9 Mg ha^{-1}. They concluded that improved management of fertilizer N would be most beneficial in reducing the gap in these savannah environments. Aggarwal and Kalra (1994) used a wheat growth model to quantify the gap between actual and potential yields. Simulated potential grain yields at New Delhi, determined by solar radiation and temperature, varied between 5.6 and 8.0 Mg ha^{-1}, depending on year. There was at least a 2.0 Mg ha^{-1} yield gap between climatic potential yield and actual yield. The gap appeared to be wide, and mainly dependent on two factors, i.e. crop variety and fertilization level. Yield gap analysis allows quantification of the likely benefits to be gained from improved crop management and identification of the factors on which research resources should be concentrated.

A crop model has been described as 'a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables' (Monteith, 1996). Many crop models have been developed for a variety of purposes. For example, SUCROS (Goudriaan *et al.*, 1997), a generic model that has been parameterized for various species, the ORYZA-family for rice, including ORYZA1 for potential production (Kropff *et al.*, 1993), ORYZA_W for water-limited production (Wopereis *et al.*, 1996), ORYZA_N for nitrogen-limited production (Drenth *et al.*, 1994) and ORYZA 2000 (Bouman *et al.*, 2001) an integrated version; and the CERES group (Jones *et al.*, 1984), including CERES-Rice (Alocilja & Ritchie, 1988), CERES-Maize (Jones and Kiniry, 1986) and CERES-Wheat (Ritchie and Otter, 1985), that have been widely applied (Mastrorilli *et al.*, 2003; Yun, 2003). WOFOST (Boogaard *et al.*, 1998) has been developed by the Centre for WOrld FOod STudies to explore the possibilities of increasing agricultural productivity at regional and national scales, in particular in developing countries. WOFOST has been applied in studies on quantitative land evaluation, regional yield forecasting, analysis of risk and inter-annual yield variation, and quantification of the effects of climate change and increased atmospheric CO_2 concentration (Roetter *et al.*, 1998; Wolf and Van Diepen, 1995; Wolf, 1993). WOFOST estimates potential, water- and nutrient-limited yields, taking into account the supply of water and nutrients from the soil and the crop's water and nutrient requirements. The model is particularly suited to quantify the combined effect of soil type, weather conditions and crop management on crop development, crop growth and production and water use, taking into account the interactions between factors. Foltescu (2000) used WOFOST to predict yields of spring barley, spring rape and winter wheat in Sweden, based on meso-scale meteorological information, and reported prediction errors of the order of 8 to 16%, with the smallest errors for winter wheat and spring barley.

In Fenhe Irrigation District (FID), one of the largest irrigation schemes in Shanxi province, Northern China, annual precipitation varies between 200-700 mm (453 mm on average); in dry years, farmers can irrigate crops only once in conventional irrigation systems. To supplement water supply from the irrigation system, water is pumped on an individual farm basis from the groundwater. Average annual net income per capita is about 130 U$ in the district. To increase income, farmers increasingly grow vegetables that need more irrigation water. Despite the scarcity of water, waste in agriculture is wide-spread. In addition, the unreliability of water supply makes fertilizer management difficult, leading to low (nitrogen) fertilizer use efficiencies (expressed as 'agronomic efficiency', i.e. increase in crop yield per unit fertilizer nutrient applied; Adhikari *et al.*, 1999; Witt *et al.*, 1999). Hence, lack of water increasingly constrains increases in agricultural production. Moreover, water scarcity, inappropriate use and mis-management of both surface- and groundwater resources have led to many environmental and ecological problems, such as land drops, land degradation, groundwater pollution, etc. In addition, drought injury may occur in early~mid June in FID (as in the whole of Northern China), coinciding with the late grain-filling period for winter wheat. Farmers always need supplementary irrigation to prevent yield reductions, which becomes increasingly difficult because of the lack of irrigation water. Research on early maturing wheat varieties has been carried out in attempts to avoid these late-season drought periods. Because of seasonal fluctuations in depth of the shallow water table, irrigation water management is becoming more difficult. Therefore, improvements in water management in crop production systems, among others through optimization of spatial and temporal water distribution at farm and regional level, modifications in cropping patterns and crop variety selection and precision irrigation management practices under shallow water tables, are urgently required in Fenhe Irrigation District.

In this report, experiments related to cropping pattern and irrigation and nutrient management for the main field crops and vegetables are analyzed.

The variation in potential and water-limited crop production for crop production systems in FID is analyzed for the period of 1961~2002, focusing on the main cereal crops winter wheat and spring maize and the oil crop sunflower. The WOFOST crop growth model has been applied to simulate potential and water-limited yields for these crops, and yield gaps due to unfavorable conditions are identified and analyzed.

2. Description of the region

2.1 General

Fenhe Irrigation District (FID), the study area (111°15' to 112°37' NL, 37°07' to 37°53' WL, see Figure 1) is located in the Taiyuan basin in North China (Figure 3), surrounded by Yunzhong Mountain (North), Taihang Mountain (East), Lüliang Mountain (West) and Taiyue Mountain (South). Its altitude ranges from 730 m above sea level in the south-west to 810 m in the northeast and its slope from 1/2500~1/3000 from north to south and from 1/1500~1/2000 from east to west. FID is the largest irrigation district of Shanxi province, with an irrigated area of 99 700 ha. Three dams and the Fenhe River divide the district into four irrigation schemes (Figure 1, right): First Dam Scheme (25 574 ha), Fenxi Scheme (34 800 ha), Fendong Scheme (21 033 ha) and Third Dam Scheme (23 293 ha).

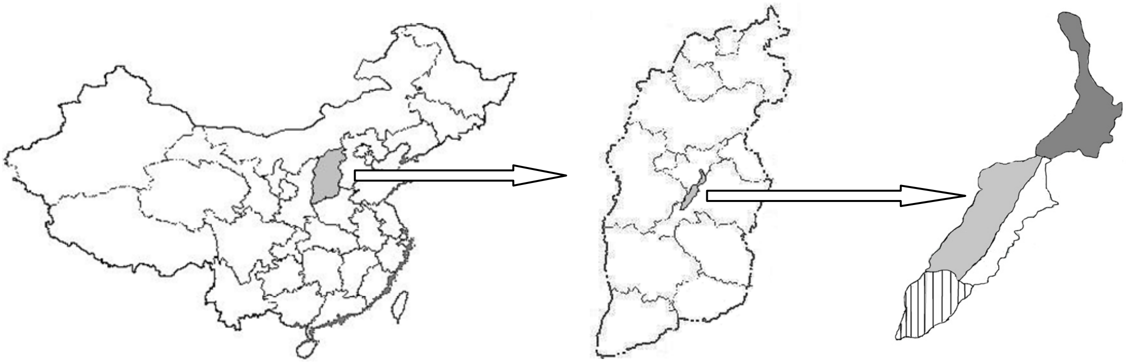


Figure 1. Location of (left) Shanxi province, (centre) Fenhe Irrigation District and (right) its sub-division in four irrigation schemes: First Dam Scheme (dark-grey), Fenxi Scheme (grey), Fendong Scheme (white) and Third Dam Scheme (hatched).

The study area is representative for the continental monsoon climatic region, with an annual average temperature of 9.5 °C and annual precipitation of 200-700 mm (453 mm on average for 1961~2002), concentrated in June, July and August, with strong year-to-year variability (Figure 2, right hand side). Annual average number of frost days is 177. Temperature and radiation are high in the wet season from May to September, and low in the dry season, especially in November, December and January (Figure 2, left hand side).

There are three main water sources: Fenhe reservoir, interzone water between the First Dam, Second Dam and Third Dam and groundwater. The major part of the surface water used for irrigation comes from Fenhe Reservoir, managed by the Fenhe Irrigation District Authority. Average annual discharge from the reservoir is 367.5 Mm^3 and exploitable groundwater resources amount to 93.5 Mm^3 annually. Higher water storage in Fenhe Reservoir In favorable rainfall years allows farmers to irrigate more frequently, resulting in higher crop production than in dry years (Figure 2, right hand side).

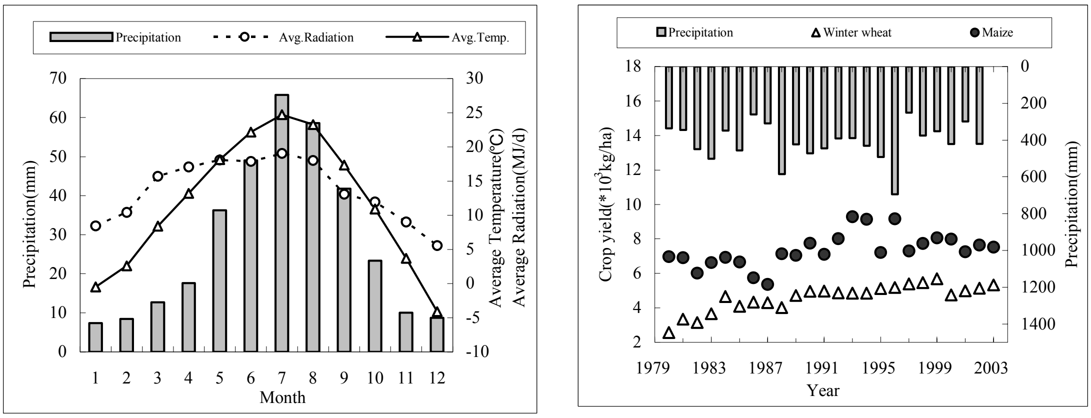


Figure 2. *Average weather conditions (left) and reported average crop yields for winter wheat and spring maize and precipitation during 1980~2003 (right) in Fenhe Irrigation District.*

Excessive water consumption and the consequent serious drop in groundwater table depth are the main problems in exploitation and utilization of water resources in FID. In the period 1965-1996, due to overexploitation of groundwater, the groundwater table has declined by 3.64 and 1.94 m/a in Taiyuan and Jiexiu, respectively (Wang and Cun, 2003). The shallow water table fluctuates seasonally between 0.5 and 9 m in FID. Because of spring irrigation and prevailing rainfall pattern, the shallow water table rises twice annually: in early spring and in mid-summer.

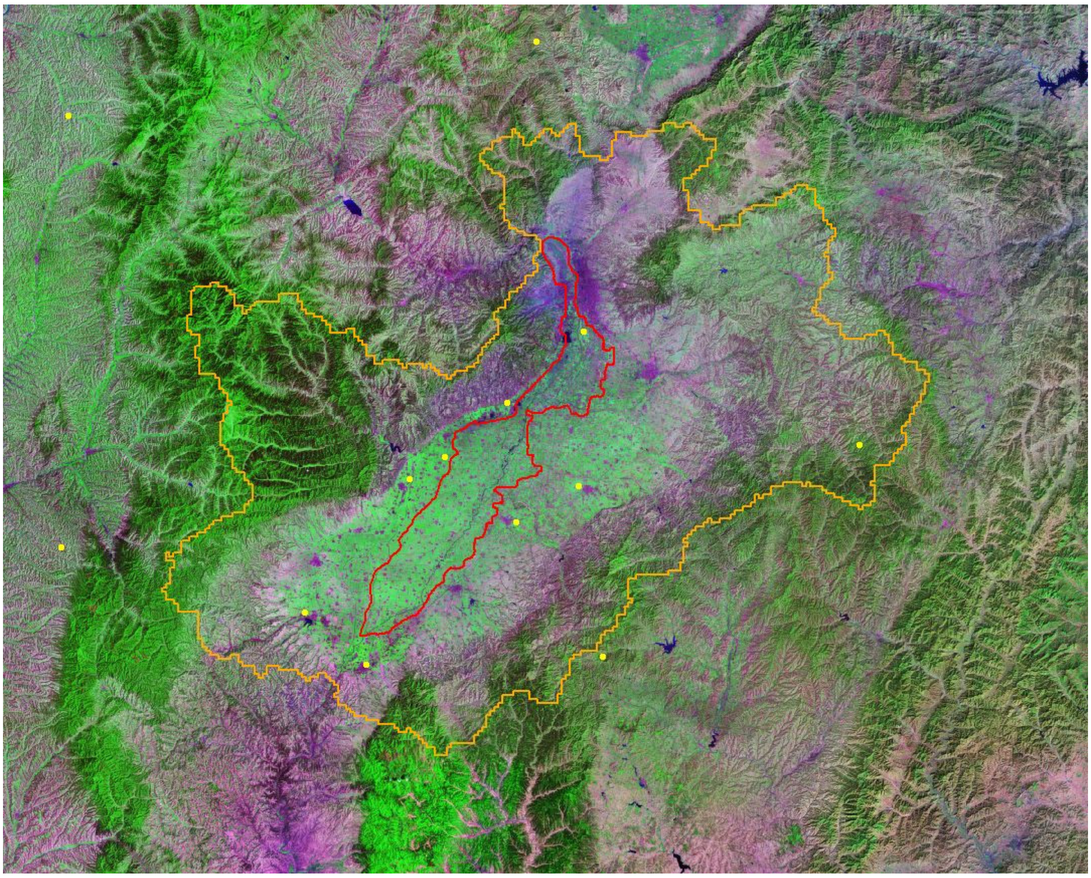


Figure 3. *Satellite image of Taiyuan Basin, the Fenhe Irrigation District (red line), hydrological border (yellow line) and the locations of weather stations (yellow points).*

Saline land occupies 6 667 ha (6.7% of the total area, 2000), of which 74.8% is slightly saline and the remainder moderately and heavily saline. The salt problem mainly occurs in the Fenxi, Fendong and Third Dam Schemes, being most serious in the Third Dam Scheme.

2.2 Soil texture and cropping pattern

Soils in FID are pre-dominantly sandy loams and loams, with some fine sandy and clay soils. Sandy loam and a mixture of sand and clay constitute the upper soil layer in FID. A typical profile consists of an upper layer of some 0.8 m, underlain by 0.2 m fine sand, followed by alternating layers of sand and clay. Close to the river, the texture is sandy loam up to some 1/3 of the length of the main laterals. The remaining part is clay and sand.

Table 1. Main crops, planted area and average yields in Fenhe Irrigation District, North China (2002).

Crop	First Dam Scheme 25 574 ha		Fenxi Scheme 34 800 ha		Fendong Scheme 21 033 ha		Third Dam Scheme 23 293 ha		FID Total 99 700	
	Planted area (%)	Crop yield ($kg \cdot ha^{-1}$)	Planted area (%)	Crop yield ($kg \cdot ha^{-1}$)	Planted area (%)	Crop yield ($kg \cdot ha^{-1}$)	Planted area (%)	Crop yield ($kg \cdot ha^{-1}$)	Planted area (%)	Crop yield ($kg \cdot ha^{-1}$)
Winter wheat	28.9	4950	25.1	4320	29.0	5230	11.7	3000	23.1	4500
Maize+ sorghum+ millet	57.1	6165	66.9	6450	52.7	6840	58.9	4800	60.8	6120
Rice	5.5	6975	0	0	0	0	0	0	1.3	6975
Cotton	0	0	2.2	450	8.2	900	2.2	585	2.8	720
Oil crops	0	0	3.3	2310	7.6	2175	20.1	2220	7.3	2235
Vegetables	8.5	40425	2.5	25125	2.5	52920	7.1	26445	4.7	33750
Multiple cropping	0	0	3.9	2730	21.3	1965	2.7	1680	5.9	2115

As rainfall is low and evaporative demand high, agricultural production is low without irrigation. Irrigated crop yields are moderate in FID, e.g. wheat (winter) and corn yields are 4500 and 6100 $kg \cdot ha^{-1}$ on average, respectively. Winter wheat, corn, sorghum, millet, oil crops and vegetables are the main crops in FID (Table 1, Figure 4). Annually, only one crop can be planted or three crops in two years: winter wheat or autumn crops; maize-winter wheat-sunflower or vegetables. During the winter season no crops can be grown, because of low temperatures.

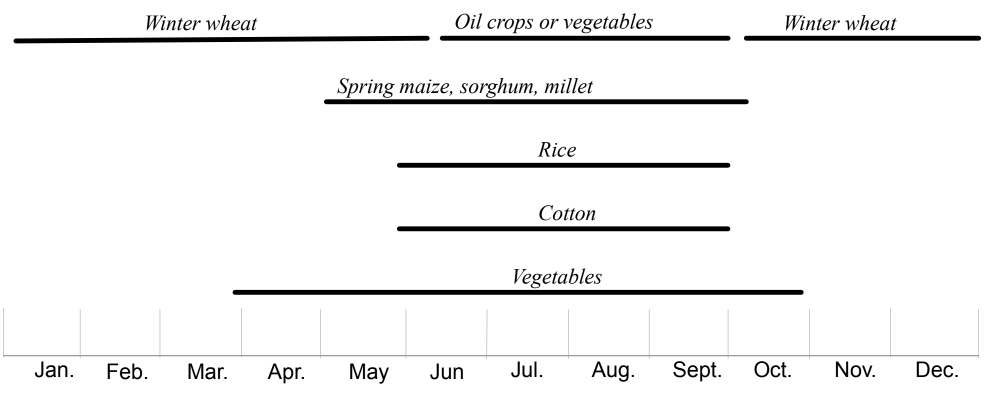


Figure 4. Cropping calendars of the main crop rotations in Fenhe Irrigation District, North China.

Spring maize is cultivated on the largest area (56.1% of the total area in 2002), followed by winter wheat (23.1% of total area in 2002). More and more farmers plant vegetables, because of the higher revenues. Rice is grown on a small area beyond the Fenhe riverbank and the cotton area has decreased since 1995.

Cereal crops, cash crops, fruit trees and vegetable occupied 86%, 11.3%, 1.05% and 0.75% of the irrigated land, respectively (2002).

2.3 Social and economic conditions

FID is the largest irrigation district in Shanxi province, North China, accounting for 10% of the total irrigated area in the province. Located near the political, economic and cultural centre, Taiyuan city, it is the basis for the production of the main food crops and vegetables. Agricultural production constitutes 70.3% of the total production value in Shanxi. Dunhua Scheme (located to the east of FID in Figure 1) has been added to FID (administrative change) in 2000. The total population in FID is 1.02 million (2000), of which 92% is occupied in agriculture; there are 12 006 agricultural machines. Average GDP is RMB 5000 per capita (SBSP, 2002)[1] and average annual income RMB 1085 (130 US$). More detailed information at irrigation scheme level is given in Table 2.

Table 2. Social and economic conditions in Fenhe Irrigation District, North China (2000).

Irrigation Scheme	Villages	Population ($*10^6$)	Agricultural population ($*10^6$)	Labor force ($*10^6$)	Agricultural machines	Annual income per capita (RMB)	GDP (in 2001) per capita (RMB)
First Dam Scheme	209	0.351	0.303	0.119	4807	1329	7050
Fenxi Scheme	79	0.132	0.131	0.057	1817	1692	3500
Fendong Scheme	136	0.289	0.286	0.124	2128	855	4050
Third Dam Scheme	98	0.178	0.166	0.079	2254	944	6000
Dunhua Scheme	36	0.065	0.059	-	-	-	-

1 1US$ equal to 8.27 RMB

3. Description of the experiments in the region

3.1 Experimental Site

Because of the increasing pressure on water resources in agriculture (Rijsberman, 2004), during the past decades experiments on irrigation management have been carried out in FID, with the aim of designing precision water management schemes. These experiments on winter wheat, spring maize, sunflower and some vegetables, carried out in the Central Experimental Station (CES) since the 1990s, mainly focused on irrigation scheduling.

CES (112°12' NL,37°17' EL) is located in Hulan town, Taiyuan Basin, at an altitude of 749 m asl; annual radiation is 54.5-56.5 MJ m^{-2}, average annual temperature 9.4 °C, annual precipitation 450 mm and potential evaporation 1565 mm. The soil profile consists of three layers in CES. The first layer, 0~32 cm, is loamy (sand 12%, clay 23%), bulk density 1.0~1.32 g·cm^{-3}; the second layer, 32~77 cm, is clay (sand 7%, clay 37%), bulk density 1.39 g cm^{-3}; the third layer, 77~150 cm, is fine sand (sand 44%, clay 10%). For the soil layer 0~1 m, average bulk density is 1.38 g cm^{-3}, field capacity is 27.7% (by weight), salinity 0.3%, organic matter 1.3%, total nitrogen is 0.8%, available potassium is 20 ppm (2001). Crops are irrigated using deep groundwater (well). Shallow groundwater table depth fluctuates between 1.5 and 3.5 m, under the influence of spring irrigation and summer rainfall (Figure 5).

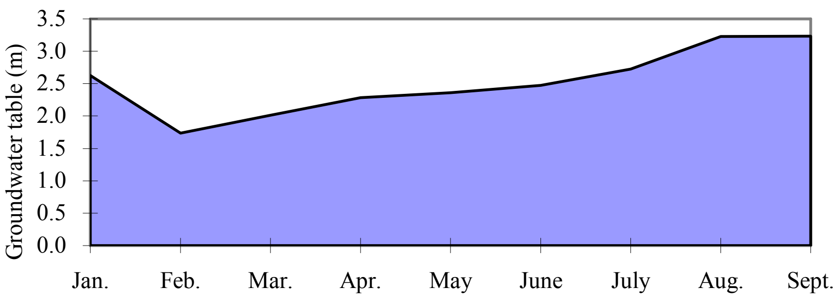


Figure 5. Annual fluctuation in shallow groundwater table depth in the Central Experimantal Station, Shanxi Province, North China

3.2 Materials and methods

3.2.1 Irrigation and nutrient management

Winter wheat

Experiments on irrigation management were carried out in the periods 1992–1996 and 2001-2004. Table 3 shows the experimental design for winter wheat crop under irrigated condition. These experiments were done in 2 m × 2 m plot with three replicates (Figure 6). Winter wheat variety was Jingdong 8. Sowing date varied between 25th September and 10th October, depending on weather conditions and the crop matured mid to end of June.

The crop was irrigated twice after re-greening. Irrigation dates were determined on the basis of soil moisture content (Table 3). Before jointing, irrigation was generally delayed to prevent excessive vegetative growth before anthesis. Fertilizer applied with high level in two doses (sufficient supply) from 1992 till 2002: before sowing 750kg·ha^{-1} basic multi-fertilizer (8% nitrogen, 12% phosphorus, 5% potassium) and before jointing, i.e. top application, 375 kg·ha^{-1} urea ($CO(NH_2)_2$, 46% nitrogen). Birds (e.g. sparrow) are considered the main yield- reducing factor before harvest. Hence, sparrow nets have been used to protect grains from birds.

Figure 6. Experimental plots used for irrigation and nutrient management in the Central Experimental Station, Shanxi Province, North China.

Table 3. Irrigation management for winter wheat experiments in the Central Experimental Station in Shanxi province, North China.

Year and treatment		Before jointing		Before grain filling		Effective precipitation during growing season (mm)
		Date	Irrigation volume (mm)	Date	Irrigation volume (mm)	
1992		24th March	120	16th May	65	120.4
1993		24th March	120	16th May	60	117.4
1994		22nd April	100	19th May	100	167.7
1995		30th March	90	13th May	78	125.4
1996		24th March	70	16th May	60	110.9
2001		24th March	100	19th May	100	182.0
2002	1	25th March	140	29th April	140	115.8
	2	25th March	100	19th May	100	115.8
2003a	1	15th April	150	27th May	105	165.0
	2	15th April	120	27th May	90	165.0
	3	15th April	90	27th May	75	165.0
	4	15th April	60	27th May	60	165.0
	5	15th April	30	27th May	45	165.0
	6	-	0	-	0	165.0
2004	1	21st April	150	19th May	105	123.0
	2	21st April	120	19th May	90	123.0
	3	21st April	90	19th May	75	123.0
	4	21st April	60	19th May	60	123.0
	5	21st April	30	19th May	45	123.0
	6	-	0	-	0	123.0

Soil physical and chemical characteristics were observed before sowing and after harvesting. Soil water content distributions were measured with neutron probes (CPN503, CPN Company, USA), from the surface to the depth 2.5 m with neutron probe, at 10 day intervals and in 20 cm increments. In the case of rainfall or irrigation observation intervals are shortened (e.g. add observation just before and after rainfall or irrigation). Crop phonology and crop yield have been observed.

In 2003 and 2004, three levels of nutrient supply (high, medium and low) were combined with six irrigation management schemes (Tables 3 and 4). Soil nutrient and salinity conditions before sowing and after harvesting were observed. Leaf area development and mean culm height were measured every 15 days.

Table 4. Nutrient management (application rate in kg ha^{-1}) for winter wheat experiments in the Central Experimental Station in Shanxi province, North China (2003-2004).

Fertilizer treatment	2003				2004	
	Basal		After re-greening		Basal	After re-greening
	NH_4HCO_3 (17% N)	$Ca(H_2PO_4)_2H_20$ (14% P_2O_5)	K_2SO_4 (33% K_2O)	NH_4NO_3 (35% N)	Compound fertilizer (8%N, 12% P, 5% K)	$CO(NH_2)_2$ (46% N)
High	750	750	150	600	750	375
Medium	500	500	100	400	500	280
Low	250	250	50	200	250	185

An additional experiment on irrigation management was conducted in 2003 (Table 5). The winter wheat variety was Jing 9428 (similar to Jingdong 8) sown on 13th October 2002 in 6.67 × 3 m plots and harvested on 23rd June, 2003. Fertilizer was applied in two splits: A basal dressing before sowing of 125 kg·ha^{-1} diammonium phosphate ($(NH_4)_2HPO_4$, 18% N, 46% P_2O_5) and a topdressing before jointing of 225 kg·ha^{-1} urea ($CO(NH_2)_2$, 46% N). Total precipitation during crop growth was 182.4 mm (effective precipitation was 165.0 mm). Soil moisture was measured with a neutron probe (CPN503, CPN Company, USA) in 20 cm increments to a depth of 2.0 m, at 5-day intervals. In the case of rainfall or irrigation, the observation interval was shortened (e.g. observations were added just before and after rainfall or irrigation). Crop phenology and dry matter dynamics were monitored. Groundwater table depth was fixed at 8.0 m through installation of a drain pipe.

Table 5. Irrigation schedule for the winter wheat experiment in the Central Experimental Station in Shanxi province, North China in 2003b.

Treatment	Jointing 10th April (mm)	Heading 25th April (mm)	Grain filling 27th May (mm)	Total irrigation (mm)
1	75.0	75.0	75.0	225.0
2	60.0	0	45.0	105.0
3	0	45.0	0	45.0
4	45.0	0	0	45.0
5	0	0	0	0

Spring maize

Experiments were conducted in 1992, 1993, 1994, 1995, 2001 and 2002 (Table 6) in 2 × 2 m plots with three replicates. The maize variety Tunyü 2 was sown in mid- or late April and harvested end of September. Fertilizer was applied at a high level in a single dressing before sowing. Soil physical and chemical characteristics were monitored before sowing and after harvesting. Soil moisture was monitored with a neutron probe (CPN503, CPN Company, USA) in 20 cm increments to 1.5 m depth, at 10-day intervals. In the case of rainfall or irrigation, the observation interval was shortened (e.g. observations were added just before and after rainfall or irrigation). Crop phenology and crop yield were monitored.

Table 6. Irrigation and fertilizer management for spring maize in the Central Experimental Station in Shanxi province, North China.

Year	Irrigation		Effective precipitation during growing season	Fertilizer	
	Date	Irrigation volume (mm)	(mm)	$Ca(H_2PO_4)_2H_20$ (14% P_2O_5) ($kg{\cdot}ha^{-1}$)	$CO(NH_2)_2$ (46% N) ($kg{\cdot}ha^{-1}$)
1992	5th June	95	173.0	750	375
1993	16th June	40	251.0	750	375
1994	21st June	43	258.9	750	375
1995	24th June	100	368.7	750	375
2001	26th May	60	248.2	750	375
2002	15th May	98	232.1	750	375

Sunflower

Sunflower is planted after harvesting of winter wheat. Experimental data are available for 2002 and 2003. Irrigation management comprised the main treatment in 6.67 × 3 m plots. Fertilizer was applied at a high level as a single dressing before sowing (Table 7). Sunflower variety was KWS203. Fertilizer ammonium bicarbonate NH_4HCO_3 (17% N) was applied with amount of 750 $kg{\cdot}ha^{-1}$. Soil water content distributions were measured with neutron probes (CPN503, CPN Company, USA), from the surface to the depth 2.0 m with neutron probe, at 15 day intervals and in 20 cm increments. In the case of rainfall or irrigation observation intervals are shortened (e.g. add observation just before and after rainfall or irrigation). Crop phonology and crop yield have been observed.

Table 7. Irrigation and fertilizer management for sunflower in the Central Experimental Station in Shanxi province, North China.

Irrigation	2002			2003	
	Irrigation		Fertilizer	Irrigation	Fertilizer
	5th July (mm)	30th July (mm)	NH_4HCO_3 (17%N) (kg ha^{-1})	30th July (mm)	NH_4HCO_3 (17%N) (kg ha^{-1})
1	146.0	146.0	750	120.0	750
2	120.0	120.0	750	93.0	750
3	93.0	93.0	750	66.0	750
4	66.0	66.0	750	45.0	750
5	45.0	45.0	750	0	750
Ck	0	0	750	-	-

Water use efficiency (WUE in kg ha^{-1} mm^{-1}) was calculated as grain yield divided by total water consumption:

WUE= $Y/(I + P_e + S_g - D + \Delta W)$

Where, I is irrigation, P_e is effective precipitation, S_g is capillary contribution from the groundwater table to the crop root-zone (only included if observed), D is downward drainage from the crop root-zone to the groundwater (only included if observed), ΔW is change in soil water storage (0-150 cm) and Y is grain yield (14% water content).

3.2.2 Groundwater table management

Experimental design

Seasonal fluctuations in depth of the shallow water table make water management difficult. Therefore, experiments have been carried out on water table management schemes in CES for winter wheat (Babijiang *et al.*, 2004a) and spring maize (Babijiang *et al.*, 2004b).

A Mariotte bottle system (RWCMWR, 1994) was used to control the water table depth and to provide an estimate of the amount of water required to maintain a static groundwater level. The columns were closed at the bottom and connected to the Mariotte bottle via flexible PVC tubes (Figure 7). Six constant water table depths, i.e. 0.5 m ($WT_{0.5}$), 1.0 m ($WT_{1.0}$), 1.5 m ($WT_{1.5}$), 2.0 m ($WT_{2.0}$), 2.5 m ($WT_{2.5}$) and 3.0 m ($WT_{3.0}$) were maintained, 3 replicates for each depth and the natural variation in water table depth (WT_{ck},) as control. Plot area was 2 × 2 m and the top of each plot was about 10 cm above ground surface. The columns were packed to a bulk density of 1.38 g cm^{-3} with a sandy loam soil, with the 0–32 cm, 32–77 cm and deeper than 77 cm layers returned in the proper sequence, to reconstruct the original soil profile collected from the experimental station.

Each plot was connected with a pipe to a Mariotte bottle in a centrally located underground laboratory. Water was supplied to each plot from the Mariotte bottle and recorded twice a day (0800 hours and 2000 hours). Downward drainage from the crop root-zone to the groundwater was collected and recorded daily. Soil water content was measured with a neutron probe (CPN503, CPN Company, USA), in 10-cm increments from the surface to the water table depths (0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m) at 10-day intervals.

Actual evapotranspiration (ET_c) from each plot between successive soil moisture content measurements was estimated using the water balance equation:

$$ET_c = I + P_e + S_g - D - R_f + \Delta W \qquad (1)$$

where, I is irrigation, P_e is effective rainfall, S_g is capillary contribution from the groundwater table to the crop root-zone, D is downward drainage from the crop root-zone to the groundwater, R_f is surface runoff, and ΔW is change in soil water storage.

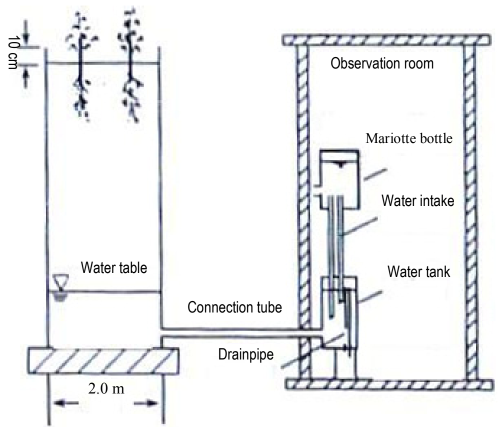


Figure 7. Schematic representation of the groundwater table control facility in the Central Experimental Station, Shanxi Province, North China.

Evaporation under controlled water table depth (E_t) is estimated from the empirical relation:

$$E_t/E_{20} = a\, e^{-b\,H}$$

where, E_{20} is potential evaporation (mm) from a 20 cm evaporation dish (obtained from the weather station), H is groundwater table depth (m), a and b are empirical constants.

Winter wheat

Experiments were conducted from 1992 till 1996 and in 2001 and 2002. The winter wheat variety was Jingdong 8, sown between 25th September and 10th October, depending on weather conditions and the crop matured mid- to end June. Irrigation rates were determined on the basis of soil moisture content, with the aim to maintain soil moisture content at 60-80% of field capacity. Fertilizer was applied at high doses in two splits, before sowing and before jointing (Table 8). Before jointing, irrigation was generally delayed to prevent excessive vegetative growth before anthesis. Crop phenology and yield were monitored.

Table 8. Dates and amounts of irrigation for winter wheat under different water table management regimes in the Central Experimental Station in Shanxi province, North China (2002).

Water table treatment	Irrigation		Fertilizer	
	Before jointing 25th March (mm)	Before grain filling 29th April (mm)	Basal (compound fertilizer) (8% N, 12% P , 5% K) (kg ha^{-1})	Topdressing ($CO(NH_2)_2$) (46% N) (kg ha^{-1})
WT_{ck}	149.0	102.5	750	375
$WT_{0.5}$	0.0	22.5	750	375
$WT_{1.0}$	8.3	47.5	750	375
$WT_{1.5}$	58.0	85.0	750	375
$WT_{2.0}$	127.0	120.0	750	375
$WT_{2.5}$	128.3	125.0	750	375
$WT_{3.0}$	142.3	135.0	750	375

Table 9. Irrigation applications to spring maize under different water table management regimes in the Central Experimental Station in Shanxi province, North China (2002).

Water table	Irrigation management	Precipitation in growing season	Fertilizer	
	15th April (mm)	Total/effective (mm)	$Ca(H_2PO_4)_2H_20$ (14% P_2O_5) (kg ha^{-1})	$CO(NH_2)_2$ (46% N) (kg ha^{-1})
WT_{ck}	98	285/232	750	375
$WT_{0.5}$	7.5	285/232	750	375
$WT_{1.0}$	0	285/232	750	375
$WT_{1.5}$	18	285/232	750	375
$WT_{2.0}$	60	285/232	750	375
$WT_{2.5}$	50	285/232	750	375
$WT_{3.0}$	60	285/232	750	375

Spring maize

Experiments were performed in 1992, 1993, 1994, 1996, 2001 and 2002 (Table 9) with maize variety Tunyü 2. Fertilizer was applied at a high level as a basal dressing before sowing. Irrigation rates were determined on the basis of soil moisture contents, with the aim to maintain soil moisture content at 60-80% of field capacity. Total precipitation was 285 mm with 232 mm of effective precipitation in 2002.

3.2.3 Experiments on sowing date and early maturing wheat

This experiment was carried out in the experimental field of China Agricultural University (CAU) in Beijing in 2000-2001. CAU (116°18' NL, 37°57' EL) is located in the Northwest of Beijing; average annual temperature is 11.5 °C, annual precipitation 595 mm, depth of the shallow water table 14 m. The 0-100 cm soil profile consists of light clay and clay, organic matter is 1.258%, total nitrogen is 0.068%, and available potassium 20 ppm (2000). Crops are irrigated using deep groundwater (well).

Two varieties of winter wheat, Jingdong 8 (JD8) and Dongzao 5 (DZ5), were used to study the effects of sowing date and variety on growth and yield. DZ5 is a new photo-insensitive and early maturing variety, developed at the Beijing Academy of Agricultural and Forestry Sciences. With JD8 as reference, this experiment focused on the effects of day length and temperature and frost hardiness on DZ5, as a basis for its characterization as a photo-insensitive, winter-hardy and early maturing variety.

Five sowing dates in autumn (20th Sept., 27th Sept., 4th Oct., 11th Oct., 10th Nov. 2000) and three in (early) spring (1st March, 15th March, 1st April 2001) were included in 4 × 5 m plots with 3 replicates. Before sowing, 750 $kg \cdot ha^{-1}$ basal compound fertilizer (8% N, 12% P, 5% K) and after re-greening a topdressing of 225 $kg \cdot ha^{-1}$ urea ($CO(NH_2)_2$, 46% N), were supplied. Soil moisture contents were measured in 20 cm increments to a depth of 1.0 m, at the main development stages.

The main phenological development stages were recorded, in addition to leaf number on the main culms, LAI and aboveground dry matter at ten-day intervals from mid-October till flowering for each sowing date. Detailed phenological development stages, based on ear differentiation, were recorded at five-day intervals from early March till flowering. Storage organ weight was measured at five-day intervals from flowering till maturity and crop yield was recorded at maturity.

Table 10. Locations and soil conditions of experimental sites in Shanxi Province, North China (2002).

Experimental site	Coordinates (NL; EL)	Altitude (m asl)	Soil characteristics			Soil Fertility			Groundwater table depth (m)
			Field capacity (% by weight)	Bulk density (g/m^3)	Porosity (% by weight)	Organic matter (%)	Available N (%)	Available P (ppm)	
Yu he	113° 20′; 40° 06′	1052	22.5	1.5	49	1.3	0.06	4.9	6
Xiaohe	112° 36′; 37° 22′	787	27.1	1.4	46	1.34	-	-	8
CES	112° 02′; 37° 04′	749	27.7	1.4	48	1.26	0.08	20	1-3
Zhen Ziliang	113° 11′; 39° 33′	1005	24.3	1.46	45	-	-	-	1-3
Shenxi	113° 41′, 39° 43′	1075	27.2	1.42	48	0.72	-	-	7
Zhang Bei	113° 23′; 36° 31′	753	23.5	1.38	47	1.23	0.76	20.0	30

Table 11. Experimental site, species and growth period, and weather conditions during the growing period for vegetable experiments (2002).

Experimental site	Vegetable species	Duration		Weather conditions	
		Sowing date	Harvesting date	Effective precipitation (mm)	Potential evaporation (mm)
Yu he	Sweet potato	30th April	5th Sept.	154.5	962.8
Xiaohe	Jequirity[2]	20th May	30th Sept.	338.9	737.6
CES	Sesame	28th May	17th Sept.	226.2	665.8
Zheng Ziliang	Water melon/black bean	11th May	1st Sept.	170.6	732.6
Shenxi	Musk melon	21st April	25th July	142.0	827.8
	Turnip	10th June	20th Sept.	219.0	921.8
Zhang Bei	Chilli pepper	21st May	20th Oct.	281.0	977.4

Table 12. Water management treatments for vegetables in Shanxi Province, North China (2002).

Experimental site	Vegetable species	Treatment 1 Irrigation dose	Treatment 1 Irrigation date	Treatment 2 Irrigation dose	Treatment 2 Irrigation date	Treatment 3 Irrigation dose	Treatment 3 Irrigation date	Treatment 4 Irrigation dose	Treatment 4 Irrigation date	Treatment 5 Irrigation dose	Treatment 5 Irrigation date	Treatment 6 Irrigation dose	Treatment 6 Irrigation date
Yu he	Sweet	59 mm	7th June	59 mm	7th June	59 mm	7th June	-		-		0 mm	
	potato	74 mm	8th July	74 mm	8th July	85 mm	23rd July	-		-			
		72 mm	23rd July	55 mm	22nd Aug.	-		-		-			
		52 mm	22nd Aug.			-		-		-			
Xiaohe	Jequirity	150 mm	12th Aug.	-		-		-		-		0 mm	
CES	Sesame	216 mm in 2 doses		126 mm in 2 doses		120 mm in one dose		76 mm in one dose		62 mm in one dose		0 mm	
Zheng	Water melon	195 mm	7th June	150 mm	7th June	105 mm	7th June	60 mm	7th June	-		0 mm	
Ziliang	Black bean	195 mm	18th July	150 mm	18th July	105 mm	18th July	60 mm	18th July	-			
Shenxi	Musk melon	61 mm	5th June	63 mm	5th June	-		-		-		0 mm	
		59 mm	25th June					-		-			
	Turnip	31 mm	10th June	33 mm	10th June	35 mm	10th June	33 mm	10th June	32 mm	10th June		
		33 mm	15th June	31 mm	15th June	31 mm	15th June	32 mm	15th June	34 mm	15th June		
		33 mm	25th June	32 mm	25th June	31 mm	25th June	34 mm	25th June	30 mm	25th June		
		28 mm	10th July	35 mm	10th July	34 mm	10th July	28 mm	10th July	25 mm	20th July		
		33 mm	20th July	31 mm	10th Aug.	28 mm	30h July	30 mm	30th July	31 mm	20th Aug.		
		33 mm	10th Aug.	27 mm	20th Aug.	29 mm	10th Aug.	33 mm	20th Aug.	-			
		33 mm	20th Aug.	33 mm	30th Aug.	31 mm	20th Aug.	-		-			
		32 mm	1st Sept.	32 mm	10th Sept.	-		-		-			
		30 mm	10th Sept.	-		-		-		-			
Zhang Bei	Chilli pepper	111 mm	21st May	90 mm	21st May	63 mm	21st May	90 mm	21st May	-		0 mm	
		101 mm	16th June	90 mm	16th June	62 mm	16th June	-		-			

2 Jequirity (*Abrus precatorius*), is also called Black-eyed Susan, Rosary Pea or Indian Licorice

3.2.4 Vegetables and other crops

Various vegetable species have been tested at different experimental sites throughout Shanxi Province (Table 10). Experiments were performed on sweet potato, jequirity (*Ormosia*), black bean, sesame (gingili), water melon, musk melon, chilli pepper, turnip, etc., in 2002 (Table 11). These experiments dealt mainly with irrigation management (irrigation amounts and timing). Development stages and soil moisture contents at main development stages were monitored. Few nutrient management data are available. However, data are available for summary economic analyses. Table 12 shows detailed irrigation management practices for each vegetable.

4. Results of the experiments

4.1 Effects of irrigation and nutrient management

Winter wheat

Results for different irrigation management regimes for winter wheat are given in Table 13 (1992-1996, 2001-2003). Total water consumption of winter wheat varied between 220 mm (no irrigation) and 390 mm and grain yield between 1300 and 5800 kg ha^{-1}. Highest crop yield, 5842 kg ha^{-1}, was observed under the high irrigation regime in 2002 (280 mm; water consumption 393.3 mm) with WUE 14.9 kg $ha^{-1} \cdot mm^{-1}$; lowest crop yield, 2250 kg ha^{-1}, was observed without irrigation in 2003 (water consumption 219.1 mm) with WUE 10.3 kg ha^{-1} mm^{-1}.

Table 13. Winter wheat terms of the water balance, grain yield and water use efficiency under different irrigation regimes in the Central Experimental Station in Shanxi province, North China (1992-1996, 2001-2003).

Year Treatment	Change in soil moisture (mm)	Irrigation (mm)	Effective precipitation (mm)	Water consumption (mm)	Grain yield ($kg \cdot ha^{-1}$)	Water use efficiency ($kg \cdot ha^{-1} \cdot mm^{-1}$)
1992	54.3	185	120.4	359.7	4 396	12.2
1993	37.2	180	117.4	334.6	4 140	12.4
1994	4.2	200	167.7	371.9	2 713	7.3
1995	56.0	168	125.4	349.4	4 605	13.2
1996	30.6	210	110.9	351.5	4 542	12.9
2001	42.0	200	144.4	386.4	4 812	12.5
2002 1	- 2.5	280	115.8	393.3	5 842	14.9
2002 2	19.0	200	115.8	334.8	5 520	16.5
2003b 1	-35.9	225.0	165.0	354.1	5 431	15.3
2	10.1	93.3	165.0	268.4	4 275	15.9
3	56.4	45.0	165.0	266.4	3 960	14.9
4	53.4	45.0	165.0	263.4	3 600	13.7
5	54.1	0	165.0	219.1	2 250	10.3

In 1994, effective precipitation was relatively high (167.7 mm), and with 200 mm irrigation, grain yield was only 2713 kg ha^{-1}, leading to a low WUE of 7.3 kg ha^{-1} mm^{-1}, as a result of unfavorable distribution of precipitation and loss of grain through predation by birds.

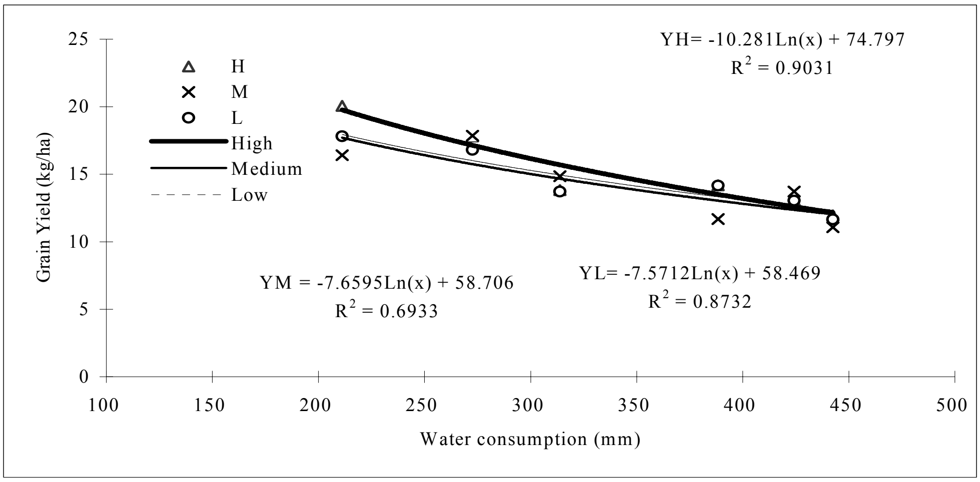


Figure 8. The relation between water consumption and grain yield of winter wheat under high (H, triangles), medium (M, crosses) and low nutrient supply (L, circles) in CES, North China (2003).

Table 14. Terms of the water balance, grain yield (air-dry) and water use efficiency for different irrigation and fertilizer management regimes in winter wheat in the Central Experimental Station in Shanxi province, North China (2003 and 2004).

Irrigation treatment	Change in SM (mm)	I[a] (mm)	P_{ef} (mm)	TWC (mm)	High nutrient supply		Medium nutrient supply		Low nutrient supply	
					Grain Yield ($kg \cdot ha^{-1}$)	WUE ($kg \cdot ha^{-1}$ mm^{-1})	Grain yield ($kg \cdot ha^{-1}$)	WUE ($kg \cdot ha^{-1}$ mm^{-1})	Grain yield ($kg \cdot ha^{-1}$)	WUE ($kg \cdot ha^{-1}$ mm^{-1})
2003a 1	22.5	255.0	165.0	442.5	5286	11.9	4901	11.1	5162	11.7
2	49.2	210.0	165.0	424.2	5542	13.1	5819	13.7	5535	13.0
3	58.3	165.0	165.0	388.3	5504	14.2	4532	11.7	5502	14.2
4	28.8	120.0	165.0	313.8	4341	13.8	4658	14.8	4307	13.7
5	32.6	75.0	165.0	272.6	4851	17.8	4866	17.9	4581	16.8
6	46.2	0.0	165.0	211.2	4237	20.1	3467	16.4	3763	17.8
2004 1	46.1	255	123.0	424.1	5237	12.3	4477	10.6	4303	10.1
2	61.3	210	123.0	394.3	4497	11.4	4736	12.0	4577	11.6
3	54.9	165	123.0	342.9	4104	12.0	3427	10.0	3287	9.6
4	50.5	120	123.0	293.5	3190	10.9	3225	11.0	2763	9.4
5	52.4	75	123.0	250.4	2776	11.1	2852	11.4	1777	7.1
6	16.8	0	123.0	139.8	1889	13.5	1292	9.2	1207	8.6

[a]I = irrigation; $P_{ef.}$= effective precipitation; TWC = total water consumption; WUE = water use efficiency

For the experiment conducted in 2003a (Table 14), grain yield and total water consumption showed a negative logarithmic relation; for the high fertilizer supply (Figure 8) a correlation coefficient of 0.9, a slope of -10.281 and an intercept of 74.797 was established. Highest WUE was observed in the no irrigation treatment.

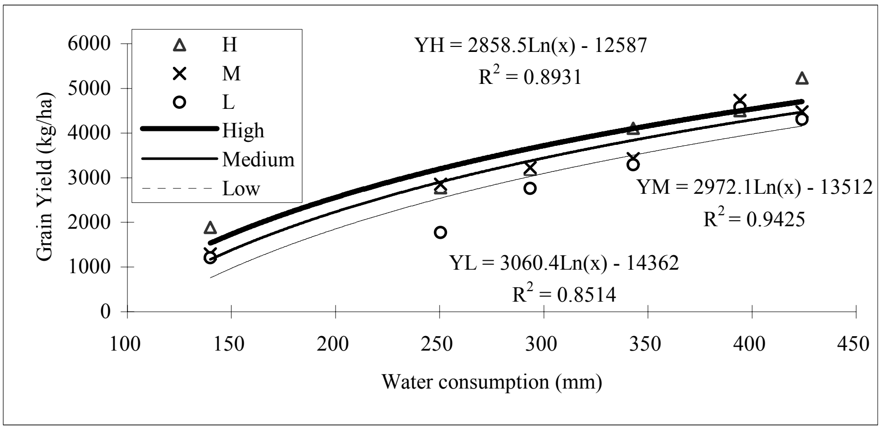


Figure 9. The relation between water consumption and grain yield under high (H, triangles), medium (M, crosses) and low nutrient supply (L, circles) for winter wheat in CES, North China (2004).

In the experiment in 2004, the highest grain yield of 5237 kg·ha^{-1} was observed under the high water and high fertilizer input, and the highest WUE of 13.5 kg ha^{-1} mm^{-1} in the no irrigation treatment (total water consumption 139.8 mm).

Water consumption and grain yield under different fertilizer input levels in this year showed a logarithmic relation. For the high fertilizer input, the correlation coefficient is 0.9, the slope 2858.5 and the intercept -12 587 (Figure 9).

4.1.2 Spring maize

Spring maize is grown in the rainy season, and because of strong variation in total precipitation (effective precipitation varied between 173 and 368 mm for the 6 years illustrated in Table 15) and its distribution, grain yield fluctuates substantially over the years, even with supplementary irrigation. Total water consumption for spring maize over the 6 years varied between 350 mm and 480 mm.

Water use efficiency also fluctuates strongly, and two of the lowest values coincide with relatively low total water consumption, but the highest value coincides with one but the lowest total water use. This could suggest that not so much total water availability, but rather its distribution is the major factor in yield formation. Without additional information, however, this conclusion can not be substantiated.

Table 15. Terms of the water balance, grain yield (air-dry) and water use efficiency for different spring maize experiments in the Central Experimental Station in Shanxi province, North China (1992-1995, 2001-2002).

Year Treatment	Change in soil moisture (mm)	Irrigation (mm)	Effective precipitation (mm)	Total water consumption (mm)	Grain yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
1992	132.8	95	173	400.8	9 159	22.85
1993	99.9	40	251	390.9	4 636	11.86
1994	147.5	43	258.9	449.4	9 769	21.74
1995	9.9	100	368.7	478.6	9 417	19.68
2001	37.5	60	248.2	345.7	5 661	16.38
2002	37.2	98	232.1	367.3	9 250	25.18

4.1.3 Sunflower

Water consumption varied between 114 and 376 mm in the sunflower growing season in 2002 and grain yield was between 200 and 2270 kg ha^{-1}. Under very low water input, i.e. 90 mm irrigation and no irrigation, because of water deficiency, grain set in sunflower was negatively affected (Table 16), which led to sink-limited grain yields and thus to very low water use efficiencies.

Table 16. Terms of the water balance, grain yield (air-dry) and WUE for sunflower under different irrigation treatments in the Central Experimental Station in Shanxi province, North China (2002-2003).

Treatment	Total Irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Total water consumption (mm)	Grain yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
2002 1	292	-9.2	123.2	376	2175	5.79
2	240	-46.2	123.2	320	2268	7.09
3	186	-17.2	123.2	275	2231	8.11
4	132	-34.2	123.2	238	2100	8.82
5	90	-43.2	123.2	167	1305	7.80
Ck	0	-39.2	123.2	114	198	1.74
2003 1	120.0	-	417.6	-	866	-
2	93.0	-	417.6	-	855	-
3	66.0	-	417.6	-	627	-
4	45.0	-	417.6	-	606	-
Ck	0	-	417.6	-	459	-

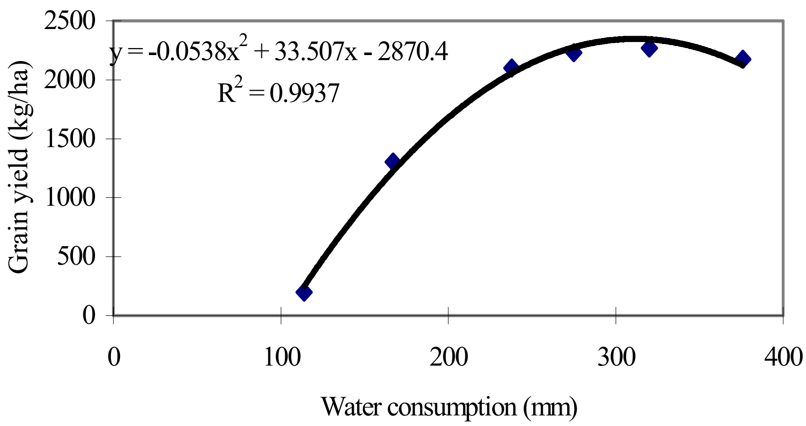


Figure 10. The relation between water consumption and grain yield for sunflower in CES, North China (2002).

The relation between water consumption and grain yield can be described by a parabolic curve, with a correlation coefficient of 0.9 (Figure 10).

4.2 Soil moisture dynamics under shallow groundwater table depths

Figure 11 shows the dynamics of soil moisture contents in the 0-20 and 0-60 cm soil layers for spring maize and winter wheat in the course of the growing season for different water table depths. Total soil moisture in both layers strongly reacts to precipitation (irrigation included in precipitation). For both crops, soil water contents are higher for shallower groundwater depths, but the dynamics show similar trends.

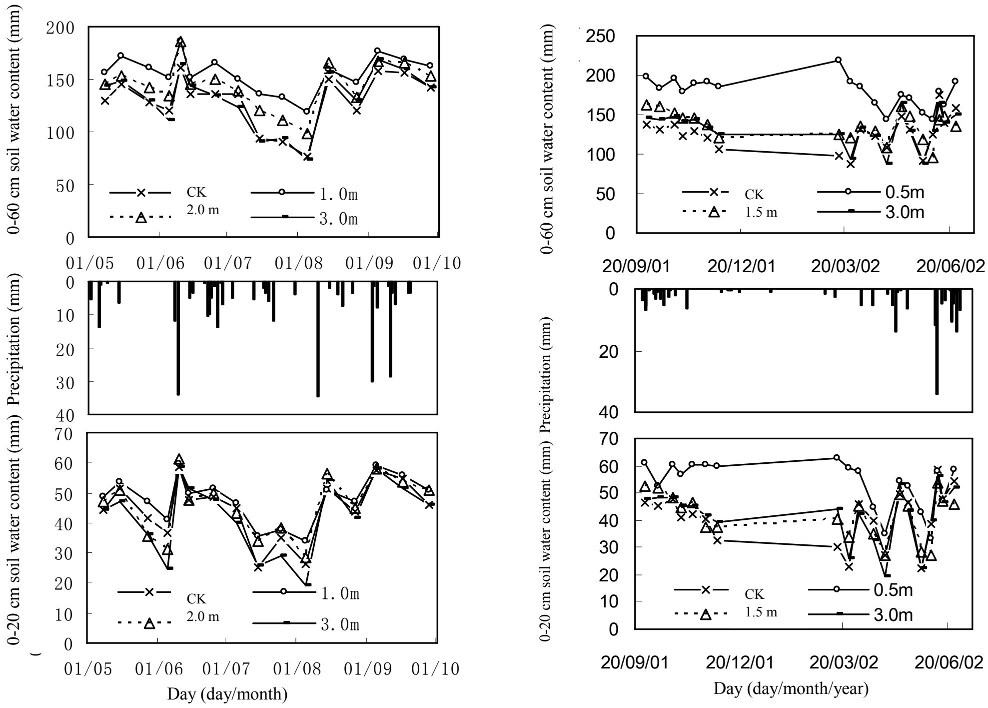


Figure 11. Soil moisture contents in the 0-20 cm and 0-60 cm soil layers for spring maize (left) and winter wheat (right) at different water table depths in the Central Experimental Station in Shanxi province, North China.

In spring maize, crop water consumption after the jointing stage increases, as a result of higher temperatures and lower humidity, which leads to increased soil surface evaporation. Precipitation during August and September maintains soil moisture content at a relatively high level.

In winter wheat soil moisture dynamics can be divided in 3 periods. In the first period (from Sept. till Nov.), temperature gradually decreases, precipitation is relatively low, and soil moisture decreases due to evapo-transpiration loss from the soil and the crop. Soil moisture content in the 0.5 m water table is substantially higher than in the other treatments (Figure 11). In the second period, 'the winter', with frost, soil water content changes not much. Only under the 0.5 m water table soil moisture content slightly increases due to capillary rise. In the third period, from April till end of June, soil moisture content strongly fluctuates, under the influence of evapotranspiration and precipitation/irrigation, with only small differences among the different water table depths.

Soil water contents before and after irrigation on March 25th (Figure 12A) and precipitation on June 9th (Figure 12B) show that in the top layers soil moisture contents increase substantially, and the deeper the water table, the lower soil moisture for a given soil depth. In the 1.0 m water table treatment, irrigation was restricted to 8.3 mm, because soil moisture was above the limiting value. Irrigation or precipitation reduces the differences in soil moisture content among the water table depths. Soil water contents below 100 cm are similar for all water table depths. Under shallow water tables, water is transported from the groundwater to the root zone (capillary rise), and evaporation from the soil surface is higher than under deeper water tables.

The effect of crop water consumption on soil moisture dynamics, in the absence of irrigation and precipitation (from 8th till 27th May) is illustrated in Figure 13.

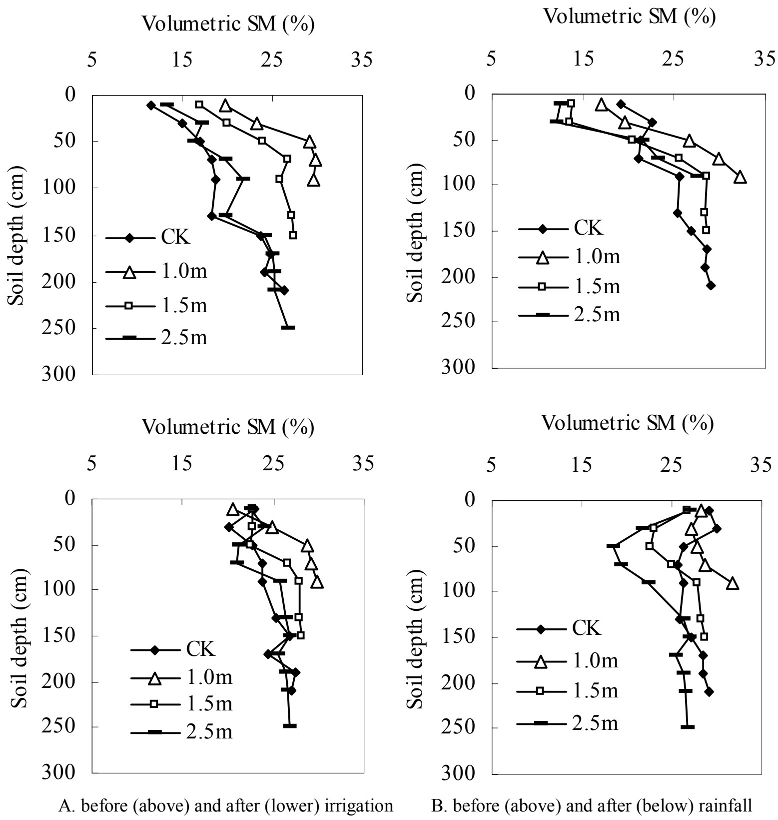


Figure 12. *Volumetric soil moisture content variations before and after rainfall and irrigation in the water table depth experiment in the Central Experimental.*

Under the 1.0 m table depth, water content changes in the upper layers (0-70 cm) only; under the 3.0 m table depth, water content changes over the full profile depth (till 100 cm). As irrigation and precipitation were absent during this period and the crop has attained full cover, the difference in soil moisture dynamics can only be explained by capillary rise. Under the shallow water table, more water is transported from the groundwater to the root zone. During this period the water table depth in the control was about 2.4 m; the soil moisture distribution in the profile in this treatment is consequently between those for the treatments with water table depths of 2.0 m and 3.0 m.

For spring maize, t soil water dynamics are almost identical. The only difference is that soil moisture extraction is restricted to a shallower depth because of the shallower rooting system of maize.

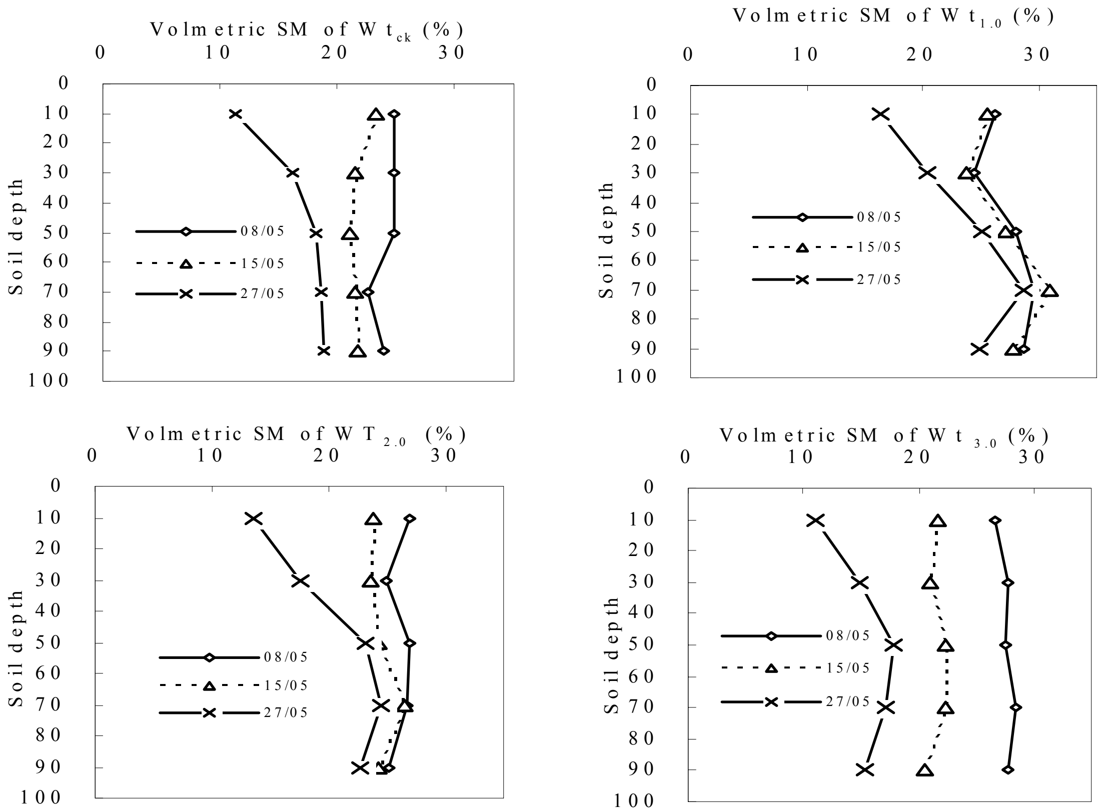


Figure 13. Volumetric soil moisture contents under different water table depths (WT, depth in m.; ck = control) in the water table management experiment in the the Central Experimental Station in North China.

Cumulative drainage and cumulative capillary rise from the groundwater in spring maize show remarkable differences among the groundwater treatments (Figure 14). High rainfall or irrigation lead to higher drainage rates, that cease after a relatively short time. Under deeper water tables, drainage is lower and starts later than under shallower water tables. For example, precipitation on June 8th/9th was 46 mm. Drainage from water table treatments 0.5 m, 1.0 m, 1.5 m and 2.0 m was 10.8, 8.7, 8.3 and 5.8 mm, respectively. Under the water table treatment of 0.5 m, drainage started on 10th June, under the 2.0 m treatment on 12th June. Drainage ceased under the 0.5 m. treatment on 13th June, for the 2.0 m on 18th June. In the groundwater treatments of 2.5 and 3.0 m. no drainage was observed throughout the growing season.

Total seasonal capillary rise m was 40.9, 33.4, 20.1 and 19.6mm, respectively in the water table treatments 0.5 m, 1.0 m, 1.5 m and 2.0 m. The dynamics of capillary rise from the groundwater to the root zone of spring maize can be sub-divided into four stages for all groundwater treatments. In the first stage (from sowing till jointing), there is a slow but constant rate. Transpiration is negligible, as the crop is in the seedling stage; hence water loss is mainly from soil surface evaporation. In the second stage, capillary rise is absent, as the large amount of rainfall on June 8th and 9th brought the root zone to field capacity. In the third stage (i.e. jointing to grain filling), capillary rise is substantial again, as high rates of evapo-transpiration remove large amounts of water from the root zone, even though that is partially replenished by rainfall. In the forth stage (i.e. grain filling to maturity), the rate is stable but low again, as precipitation supplies most of the water for crop transpiration and surface evaporation (Figure 14).

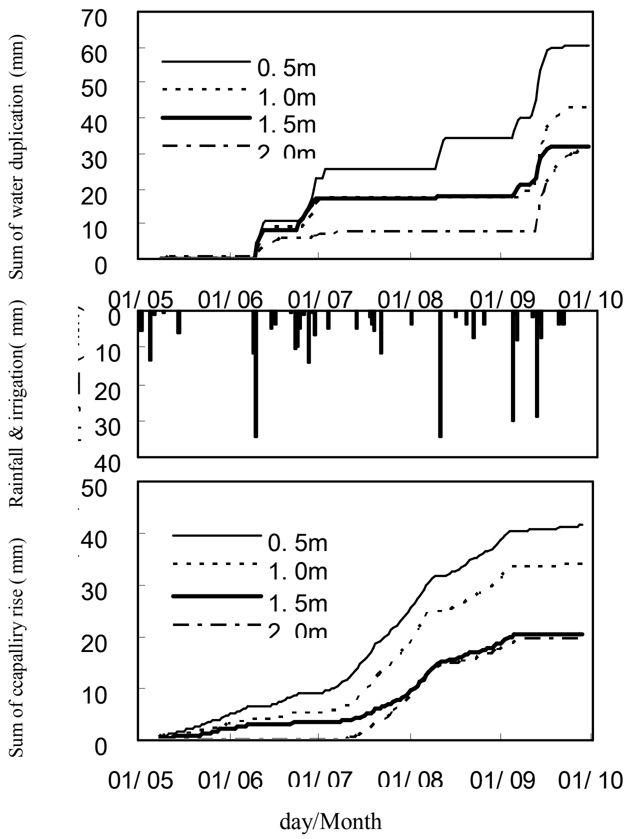


Figure 14. Cumulative draianage (top) and cumulative capillary rise (bottom) and rainfall/irrigation (middle) for the groundwater table experiment depth experiment Transformation of groundwater-soil water under different water table in the Central Experimental Station, North China.

The exchange of water between the groundwater and the root zone for winter wheat is similar to that for spring maize. Total seasonal capillary rise from water table depths of 0.5, 1.0, 1.5 and 2.0 m is 66.3, 54.5, 25.6 and 16.1 mm, respectively. High rainfall or irrigation leads to drainage that ceases after a few days, and decreases with increasing groundwater depth and does not play a role for the groundwater treatments of 2.5 and 3.0 m.

4.3 Simulation of E_t, the contribution from the water table to evapotranspiration under different water table depths

Analysis of the contribution from the water table to evapotranspiration under different water table depths shows (Figure 15) that the contribution was much smaller for the bare soil than for the crop field. Crop roots reduce the distance of movement of phreatic water compared to bare soil. The contribution from groundwater decreases with increasing groundwater depth. The difference between winter wheat and maize may be explained by the difference in growing period (winter for winter wheat; summer for spring maize).

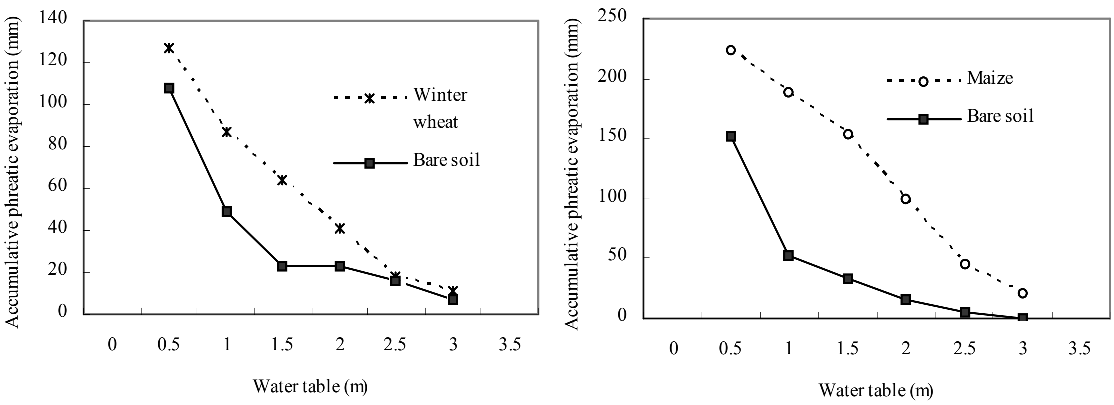


Figure 15. *Contribution from the groundwater to evapotranspiration at different water table depths in winter wheat (Oct. 1991 till March 1992) and spring maize (July till September 1992) in the Central Experimental Station, North China.*

The phreatic efficiency *C* is defined as the ratio of the contribution from the groundwater to evapotranspiration and potential evapotranspiration, and is calculated as:

$$C = E_t/E_{20} \quad (1)$$

where, E_t is contribution from the groundwater (mm) in a period, E_{20} is potential evaporation (mm) from a 20 cm evaporating dish (observed at weather stations). The relation between the contribution of the groundwater table and water table depth, H, could be expressed by:

$$C = a\, e^{-b H} \quad (2)$$

where, *a* and *b* are empirical constants.

Statistical analyses were carried out on the relation between the contribution from the groundwater to evapotranspiration and water table depth, using the observed data from 1992. The exponential curve yielded a coefficient of 0.9923.

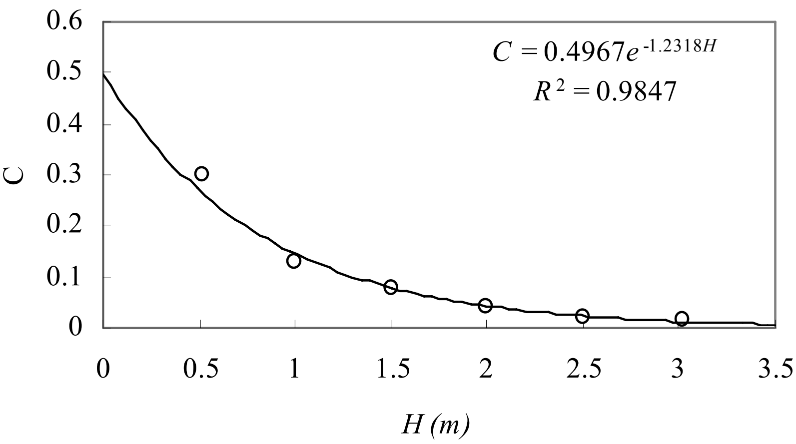


Figure 16. *Fitted curve for the relation of the contribution from the groundwater table to evapotranspiration, C and water table depth H for a bare soil in the Central Experimental Station, North China (1992).*

Statistic analyses have been carried out on the relation between the cumulative contribution from the groundwater to evapotranspiration over the whole crop growing season E_t (observed) and water table depth H. The results show an exponential relation for both, winter wheat and spring maize (Table 17).

Table 17. The relation between the cumulative contribution from the groundwater to evapotranspiration E_t and water table depth H, for winter wheat and spring maize.

Year	Winter wheat		Spring maize	
	Formula	R^2	Formula	R^2
1991	$E_t = 494.81\ e^{-1.1925H}$	0.9801	$E_t = 854.76\ e^{-1.3722H}$	0.9578
1992	$E_t = 579.56\ e^{-1.1464H}$	0.9884	$E_t = 635.84\ e^{-1.0396H}$	0.9737
1993	$E_t = 303.25\ e^{-0.8990H}$	0.9511	$E_t = 323.59\ e^{-1.3898H}$	0.9849
1994	$E_t = 400.45\ e^{-1.2594H}$	0.9766	$E_t = 863.96\ e^{-1.8475H}$	0.9861
1995	$E_t = 756.84\ e^{-1.7434H}$	0.9919	$E_t = 588.68\ e^{-2.0749H}$	0.9964
1996	$E_t = 709.15\ e^{-1.6984H}$	0.9847	$E_t = 382.79\ e^{-1.4979H}$	0.9803

The relations between potential evaporation E_{20}, the contribution from the groundwater to evapotranspiration, E_t and water table depth H for the period 1991-1996 are given in Table 18 for winter wheat and spring maize for the whole growing season. The results indicate that other factors, in addition to potential evaporation and water table depth, such as precipitation and irrigation, influence the relation.

Table 18. The relation between potential evaporation E_{20}, the cumulative contribution from the groundwater to evapotranspiration Et and water table depth H, for winter wheat and spring maize.

Year	Winter wheat		Spring maize	
	Formula	R^2	Formula	R^2
1991	$E_t/E_{20} = 0.5855\ e^{-1.1925H}$	0.9801	$E_t/E_{20} = 0.9372\ e^{-1.3722H}$	0.9578
1992	$E_t/E_{20} = 0.5796\ e^{-1.1464H}$	0.9884	$E_t/E_{20} = 0.7003\ e^{-1.0396H}$	0.9737
1993	$E_t/E_{20} = 0.3808\ e^{-0.8990H}$	0.9511	$E_t/E_{20} = 0.3902\ e^{-1.3898H}$	0.9849
1994	$E_t/E_{20} = 0.4353\ e^{-1.2594H}$	0.9766	$E_t/E_{20} = 0.9095\ e^{-1.8475H}$	0.9861
1995	$E_t/E_{20} = 0.7884\ e^{-1.7434H}$	0.9919	$E_t/E_{20} = 0.6832\ e^{-2.0749H}$	0.9964
1996	$E_t/E_{20} = 0.8082\ e^{-1.6984H}$	0.9847	$E_t/E_{20} = 0.5266\ e^{-1.4979H}$	0.9803

This analysis indicates that the relation between the cumulative contribution from the groundwater to evapotranspiration and groundwater depth is characterized by different empirical constants, a and b, for different years. It is recommended that the simulation interval should be shortened To restrict errors, average monthy values have been used in the calculations. The values of the empirical constants a and b for the various months, calculated from regression analysis for bare soil, winter wheat and spring maize are given in Tables 19, 20 and 21.

Table 19. Values of the empirical constants a and b for calculation of the contribution from the groundwater to evapotranspiration from bare soil in the Central Experimental Station, North China (1991-1992).

Constant	Oct.	Nov.	Dec.	Jan.	Feb.	March	April-June	July	August	Sept.
a	0.3945	0.6649	0.9742	0.9368	0.4562	0.2534	-	0.7642	0.5010	0.6596
b	0.4848	0.6342	0.4930	0.6325	0.5523	0.5154	-	1.2288	1.2485	1.7605
R^2	0.9142	0.8743	0.8570	0.8814	0.9290	0.9792	-	0.9936	0.9878	0.9936

Table 20. Values of the empirical constants a and b for calculation of the contribution from the groundwater to evapotranspiration for winter wheat in the Central Experimental Station, North China (1991-1992).

Constant	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June
a	0.6627	0.9378	1.0721	1.0833	0.2192	0.0604	0.8761	3.2111	1.1441
b	0.8318	1.0198	0.9386	0.9088	0.6884	0.5259	2.6804	2.7703	2.1320
R^2	0.9299	0.9806	0.9801	0.9868	0.9504	0.9863	0.9635	0.9635	0.9094

Table 21. Values of the empirical constants a and b for calculation of the contribution from the groundwater to evapotranspiration for spring maize in the Central Experimental Station, North China (1991-1992).

Constant	April	May	June	July	August	Sept.
a	1.2063	0.4087	2.7949	1.2955	0.9903	1.2063
b	2.2063	2.6427	0.2.6638	0.9790	0.9433	2.2063
R^2	0.9898	0.9210	0.9651	0.9753	0.9386	0.9898

Experimental data from 1993-1994 were used for validation of the empirical model for winter wheat. The results show reasonable agreement between simulated and observed values (Figure 17) for the various water table depths. The relative error varied between 4.4 and 12.6%.

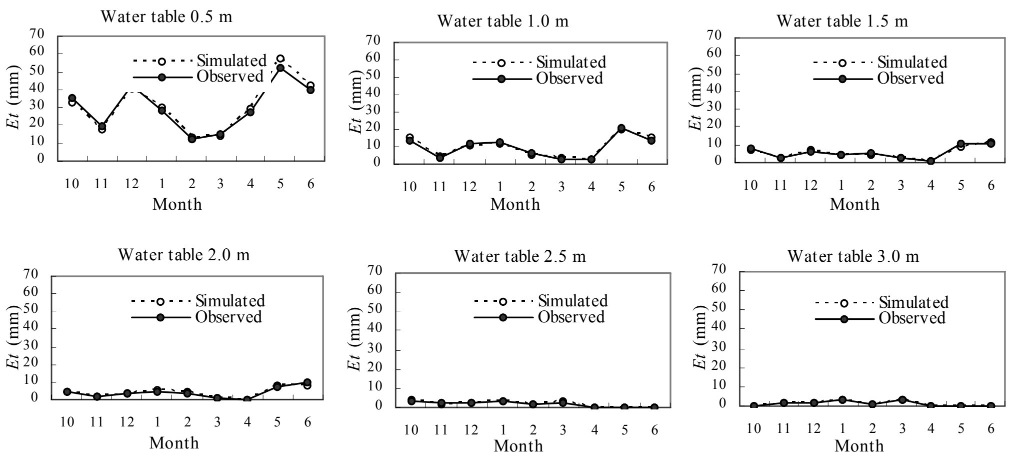


Figure 17. Simulated and observed values for the contribution from the groundwater to evapotranspiration for winter wheat in the 1993-1994 growing season under different groundwater table depths in the Central Experimental Station, North China.

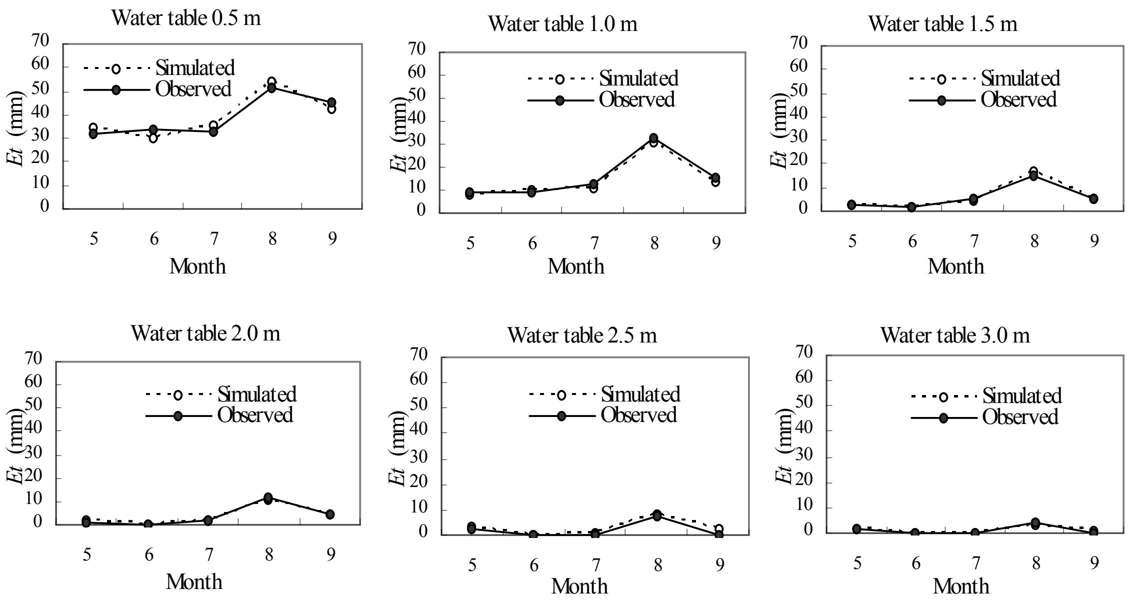


Figure 18. *Simulated and observed values for the contribution from the groundwater to evapotranspiration for spring maize in the 1993 growing season under different groundwater table depths in the Central Experimental Station, North China (1993).*

Experimental data from 1993 were used for validation of the empirical model for spring maize. The results show reasonable agreement between simulated and observed values (Figure 18). The relative error varied between 5.6 and 13.3%. The relative error for spring maize exceeds that for winter wheat, probably because of higher rainfall during the maize growing season.

Comparison of simulated and observed E_t-values for winter wheat (1993-1994) and spring maize (1993) during the whole growing season (Figure 19) under all water table depths shows satisfactory agreement for both crops. For winter wheat, simulated values are linearly correlated to observed values with a slope of 0.97 and an intercept of 0.1583. For spring maize, simulated values are linearly correlated to observed values with a slope of 0.9963 and an intercept of 0.0004. Correlation coefficients for the relation between measured and simulated E_t are above 0.99 for both winter wheat and spring maize.

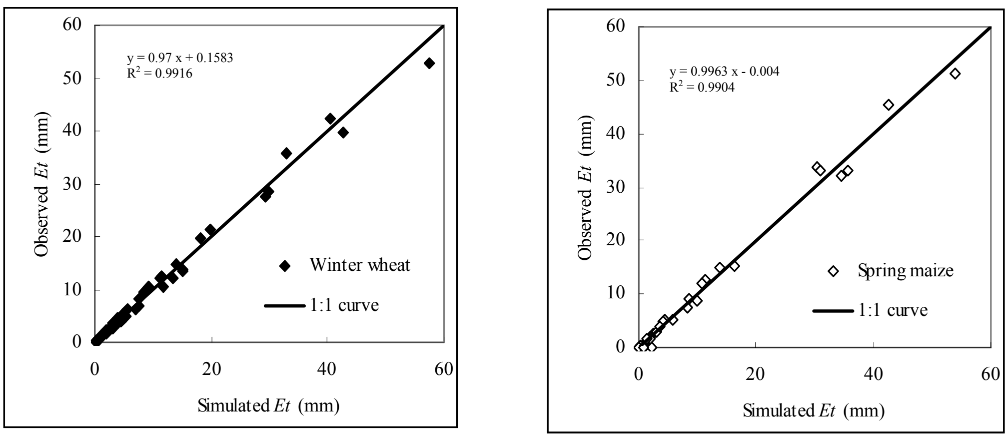


Figure 19. *Comparison of simulated and observed value for the contribution from the groundwater to evapotranspiration for winter wheat (1993-1994) and spring maize (1993) in the Central Experimental Station, North China.*

4.4 Impacts of water table on crop yield and WUE

Yield and yield component data are given in Table 22 for further analysis of the influence of water table depth on yield formation. At water table depths of 0.5 and 1.0 m, seedling density, tiller density, ear density and total aboveground dry matter were lower than at greated water table depths. This might be because of unfavorable soil aeration under the shallow water tables. In addition, strong evaporation may have led to salinity problems in the surface layer.

Table 22. Crop yield and yield components under different water table depths for winter wheat in the Central Experimental Station, North China (1996).

Water table depth (m)	Seedling density (10^4 ha^{-1})	Tiller density (10^4 ha^{-1}) Before wintering	Jointing	Ear density (10^4ha^{-1})	Grains per spike	Thousand grain weight (g)	Total aboveground dry matter (kg·ha^{-1})
0.5	375.0	399.0	138.0	85.5	24.2	40.2	3 499.5
1.0	418.5	490.5	399.0	238.5	22.4	41.6	3 639.0
1.5	496.5	606.0	790.5	445.5	27.7	40.3	8 667.0
2.0	546.0	642.0	724.5	426.0	30.6	42.4	8 041.5
2.5	501.0	570.0	684.0	450.0	30.0	38.8	8 958.0
3.0	496.5	534.0	738.0	450.0	31.3	42.7	10 126.5

During the spring maize growing season, high temperatures in summer lead to high evapotranspiration rates, soil water fluctuation maintain rooting depth soil water, air, heat movement in favorable level. In 1992, i.e. the first year experiment, crop growth is not much different under different water table depths (Table 23). The situation changed dramatically after 1992, as illustrated for 1993. Because of saline water, crop growth was negatively influenced under the shallow water tables, as evaporation leads to salinization in the rooting zone. Under the water table depths of 0.5 m and 1.0 m in 1993, plant density, plant height, cob height and cob weight were lower than under the deeper water tables. These results were confirmed in 1994, 1995 and 1996.

Table 23. Yield components under different water table depths for spring maize in the Central Experimental Station, North China (1992-1993).

Water table depth (m)	1992					1993				
	Plant density (10^3 ha^{-1})	Plant height (cm)	Cob height (cm)	Cob weight per plant (g)	Hundred grain weight (g)	Plant density (10^3 ha^{-1})	Plant height (cm)	Cob height (cm)	Cob weight per plant (g)	Hundred grain weight (g)
0.5	49.9	270.0	115.0	233.5	36.57	34.9	233.7	101.7	203.5	35.38
1.0	49.9	258.0	110.0	245.1	36.82	46.7	255.3	111.0	190.9	34.29
1.5	49.9	227.0	88.0	219.7	36.77	50.0	275.7	115.5	220.7	35.26
2.0	49.9	232.0	102.0	201.4	36.82	49.1	273.3	118.3	219.8	24.98
2.5	49.9	223.0	100.0	204.9	37.09	50.0	276.0	114.6	213.5	34.37
3.0	49.9	215.0	91.0	198.9	37.22	50.0	279.0	123.0	233.0	37.20

In FID, the climate conditions during the spring maize and winter wheat growing seasons are different. As a single crop is growth annually, the soil remains bare after crop harvest. After maize harvest, rainfall is less than following harvest of wheat. Soil water evaporation exceeds infiltration during the period of bare soil after maize harvest, bringing salt to the upper soil layers. At sowing of the next maize crop, the surface soil has accumulated considerable amounts of salt. Young seedlings of maize suffered from these salinity problems. For winter wheat the situation is not the same. During the rainy season, following harvest of wheat, there is net downward movement of water so that the surface soil is leached and soil salinity is reduced to a low level. Hence,the initial situation is much more favourable for winter wheat than for spring maize.

Crop yield and soil water balance in winter wheat field are given in Table 24 for 2001-2002. The soil water balance, has been calculated for the soil layer till the water table level. Effective precipitation during the crop growing season was 115.8 mm. Under the water table depths of 0.5 and 1.0 m, crop water consumption is less than under the other treatments. Crop water use under the 0.5 m water table depth is 9.9 mm higher than under the 1.0 m water table depth, though irrigation was lower, due to more capillary rise. The highest crop yield of 5842 kg ha^{-1} was observed at 1.5 m water table depth. Under the 0.5 m treatment, crop yield might have been negatively influenced by salinity problems if groundwater has a high salt concentration. The highest WUE of 20.23 kg ha^{-1} mm^{-1} (kg grain per hectare per mm water input) occurred at a water table depth of 1.0 m.

Table 24. Water consumption, crop yield and WUE under different water table depths for winter wheat in the Central Experimental Station, North China (2001-2002).

Water table depth (m)	Change in soil moisture (mm)	Irrigation (mm)	Capillary rise (mm)	drainage (mm)	Effective precipitation (mm)	Water consumption (mm)	Crop yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
Ck	19	251.5	-	-	115.8	348.3	5203	14.94
0.5	-7.8	22.5	66.3	20.1	115.8	232.5	4399	18.92
1.0	34	55.8	54.5	30.5	115.8	222.6	4480	20.13
1.5	-37	143.0	25.6	5.9	115.8	327.3	5842	17.85
2.0	-15	247.0	16.1	21.5	115.8	415.4	5520	13.29
2.5	-8	253.3	0.0	0.0	115.8	377.1	5314	14.09
3.0	7	277.3	0.0	0.0	115.8	386.1	4403	11.40

Effective precipitation in the spring maize growing season was 232.1 mm. At a water table depth of 1.0 m, crop water consumption is higher than under the other treatments (Table 25) due to higher drainage. temperature lead to As evapotranspiration is high during summer, crop water use is 45.8 mm higher at 0.5 m water table depth than 1.0 m water table depth, due to more capillary rise. The highest crop yield of 10 250 kg ha^{-1} is observed at the water table depth of 1.0 m. The highest WUE of 32.60 kg ha^{-1} mm^{-1} (kg grain per hectare per mm water input) was observed at 2.5 m water table depth, but the differences among the treatments are small.

Table 25. Water consumption, crop yield and WUE under different water table for spring maize in the Central Experimental Station, North China (2002).

Water table	Change in soil moisture (mm)	Irrigation (mm)	Capillary rise (mm)	drainage (mm)	Effective precipitation (mm)	Water consumption (mm)	Crop yield ($kg\cdot ha^{-1}$)	Water use efficiency ($kg\ ha^{-1}\ mm^{-1}$)
Ck	37.2	98	ignore	ignore	232.1	292.9	8750	29.87
0.5m	12.4	7.5	40.9	32.0	232.1	300.1	9250	30.82
1.0m	-20.2	0	33.4	60.2	232.1	345.9	10250	29.63
1.5m	8.6	18	20.1	42.8	232.1	304.4	8750	28.75
2.0m	26.8	60	19.6	30.4	232.1	315.3	9625	30.53
2.5m	-1.6	50	0.0	0.0	232.1	283.7	9250	32.60
3.0m	19	60	0.0	0.0	232.1	273.1	8250	30.21

4.5 Irrigation management aimed on high crop yield and limited irrigation under shallow water table

The crop coefficient K_c under standard conditions (Table 26) was calculated according to the FAO method (Allen *et al.*, 1998). Crop water requirements were subsequently calculated on the basis of potential evaporation data. Crop water requirements amount to 405 mm under optimal moisture conditions (high crop yield).

Table 26. Crop coefficients for different growth stages of winter wheat in the Central Experimental Station, North China.

Growing stage	Date (day month)	Duration (days)	K_c	Potential evaporation (mm)	Crop water requirements (mm)
Whole season	22nd Sept.~29th June	280		1172.2	405.0
Sowing ~ wintering	22nd Sept.~20th Nov.	59	0.433	193.6	83.8
Wintering ~ re-greening	21st Nov.~10th March	110	0.285	199.2	56.8
re-greening ~ jointing	11th March~20th April	41	0.304	226.7	68.9
Jointing ~ heading	21st April~13th May	23	0.321	174.2	55.9
Heading ~ grain filling	14th May~1st June	19	0.481	151.3	72.8
Grain filling ~ maturity	2nd June~29th June	28	0.294	227.2	66.8

A statistical analysis of long-term average precipitation is given in Table 27 for the winter wheat whole growing season. Precipitation events less than 2 mm are considered non-effective and precipitation exceeding the storage capacity at field capacity for the rooting depth of 0-80 cm is considered drainage.

Table 27. Long-term average precipitation and its distribution during the winter wheat growing season in the Central Experimental Station, North China (1961-2002).

Precipitation	Probability 25% (mm)	Probability 50% (mm)	Probability 75% (mm)	Probability 95% (mm)
Total precipitation	301.4	240.4	202.9	130.2
Precipitation less than 2 mm	36.5	11.5	6.7	4.3
Effective precipitation	264.9	228.9	196.2	125.7
Sowing + seedling stage	95.3	69.3	41.2	17.0
Wintering ~ re-greening	24.0	15.8	11.0	19.4
Re-greening ~ jointing	33.6	21.6	5.3	7.3
Jointing ~ heading	39.3	61.2	48.6	0.0
Heading ~ maturity	72.7	61.0	90.1	82.0

Average available soil water for crop use for winter wheat in 1993-1996 before sowing has been calculated by taking into account the water above wilting point and below field capacity under different water table depths (Table 28). Irrigation was calculated as:

$IR = 10 * H * (\theta_f - \theta_o)$

Where IR is total irrigation; H is thickness of soil layer; θ_f and θ_o are field capacity and wilting point (volumetric %), respectively. Irrigation demands have been calculated for different rainfall years. The results indicate that no irrigation is needed for water table depths above 1.0 mm, even in very dry years.

Table 28. Soil water balance and irrigation demand before sowing for winter wheat under water table in the Central Experimental Station, North China (1993-1996).

Water table depth (m)	Thickness of soil layer (cm)	Available soil water before sowing (mm)	Total capillary rise (mm)	Irrigation demand in different rainfall years			
				25% (mm)	50% (mm)	75% (mm)	95% (mm)
0.5	50	60.5	264.4	0	0	0	0
1.0	80	84.8	100.7	0	0	0	0
1.5	80	57.3	53.4	30	75	100	175
2.0	80	44.3	36.5	85	120	150	220
2.5	80	41.6	9.2	90	135	160	230
3.0	80	29.6	4.3	90	135	165	230

The calculated irrigation demands for different growth stages for winter wheat (Table 29) show that irrigation is needed twice at a water table depth of 1.5 m in dry years (95%) and once in other years. For water table depths below 2.0 m, irrigation is needed three times in dry years (95%), twice in moderately rainy years (50% and 75%) and once in rainy years (25%).

Table 29. Average available soil water before sowing and Irrigation demands for different growth stages for winter wheat under different water table depths in the Central Experimental Station, North China (1993-1996).

Rainfall year	Water table depth (m)	Sowing and Seedling stage (mm)	re-greening (mm)	Jointing (mm)	Heading (mm)	Grain filling (mm)
	1.5	-	-	30	-	-
Probability 25%	2.0	-	-	85	-	-
	2.5	-	-	90	-	-
	3.0	-	-	90	-	-
	1.5	-	-	75	-	-
	2.0	-	60	60	-	-
Probability 50%	2.5	-	75	-	-	-
	3.0	-	60	75	-	-
	1.5	-	-	100	-	-
	2.0	75	-	75	-	-
Probability 75%	2.5	80	-	80	-	60
	3.0	-	-	85	-	-
	1.5	-	-	75	100	-
	2.0	70	-	70	75	-
Probability 95%	2.5	70	-	70	75	-
	3.0	-	-	70	75	-

The crop coefficients for spring maize have been calculated similarly to those for winter wheat (Table 30).

Table 30. Crop coefficients for different growth stages of spring maize in the Central Experimental Station, North China.

Growing stage	Date (day month)	Duration (days)	K_c	Potential evaporation (mm)	Crop water requirements (mm)
Whole season	1st June~17th Sept.	140		948.9	391.0
Sowing ~ jointing	1st June~20th June	51	0.305	408.9	124.7
Jointing ~ heading	21st June~10th July	20	0.415	150.6	62.5
Heading ~ grain filling	11th July~5th August	26	0.647	173.6	112.3
Grain filling ~ maturity	6th August~17th Sept.	43	0.423	215.9	91.3

A statistical analysis of long term average precipitation for the spring maize growing season is given in Table 31. Precipitation less than 2 mm is considered non-effective and precipitation exceeding the storage capacity at field capacity of the rooting depth (0-80 cm) is considered drainage.

Table 31. Long term average precipitation during the spring maize growing season in the Central Experimental Station, North China (1961-2002).

Precipitation	Probability 25% (mm)	Probability 50% (mm)	Probability 75% (mm)
Total precipitation	474.0	332.0	286.0
Precipitation less than 2 mm	57.0	26.0	44.0
Effective precipitation	417.0	306.0	242.0

Irrigation requirements were calculated in the same way as for winter wheat (Table 32).

Table 32. Average crop water requirements for spring maize under different water table depths in the Central Experimental Station, North China (1992-1996).

Water Table depth (m)	Thickness of soil layer (cm)	Available soil water before sowing (mm)	Tot al capillary rise (mm)	Irrigation demand in different rainfall years		
				25% (mm)	50% (mm)	75% (mm)
0.5	50	42.0	229.6	0	0	0
1.0	80	42.0	80.3	0	0	0
1.5	80	42.0	54.0	0	10	75
2.0	80	42.0	26.1	0	35	100
2.5	80	42.0	3.9	0	60	125
3.0	80	42.0	2.1	0	60	125

Calculated irrigation requirements for different growth stages for spring maize show (Table 33) that when the water table is below 2.0 m, irrigation is needed twice in dry years (75%) and once in other years.

Table 33. Irrigation demands for different growth stages for spring maize under different water table depths in the Central Experimental Station, North China (1992-1996).

Rainfall year	Water table depth (m)	Jointing (mm)	Heading (mm)	Grain filling (mm)
Probability 25%	1.0	0	0	0
	1.5	0	0	0
	2.0	0	0	0
	2.5	0	0	0
	3.0	0	0	0
Probability 50%	1.0	0	0	0
	1.5	0	0	0
	2.0	35	0	0
	2.5	60	0	0
	3.0	60	0	0
Probability 75%	1.0	24	0	0
	1.5	75	0	0
	2.0	50	0	50
	2.5	60	0	60
	3.0	60	0	60

4.6 Influence of sowing date and crop variety on crop growth

4.6.1 Light-temperature characteristics of winter wheat at different sowing dates

Experimental results showed that sowing date has a strong effect on crop phenological development (Table 34). Irrespective whether sowing was in autumn or spring, there was not much difference in phenological development between DZ5 and JD8 during the sowing to re-greening stage. After jointing, the difference in phonological development becomes larger. For the crops sown on September 27, heading was 8 days earlier for DZ5, flowering was 5 days earlier and maturity 4 days earlier. For the crops sown on November 15, heading for DZ5 was 2 days earlier, flowering 3 days earlier and maturity 6 days earlier. In early summer 2001, a drought occurred, so that both varieties suffered heat stress, but DZ5 reached maturity 3 to 4 days earlier than JD8. For the spring sowings, phenological events occurred about 15 days earlier for DZ5. In the absence of vernalization, JD8 remained vegetative, but DZ5 reached the reproductive stage. Hence, DZ5 can be sown both in autumn and in spring.

Table 34. Phenological development of winter wheat under different sowing dates in Beijing, North China (2000-2001).

Sowing (Date)	Variety	Emergence (Date)	Wintering (Date)	Re-greening (Date)	Jointing (Date)	Heading (Date)	Flowering (Date)	Maturity (Date)
27th Sep	DZ5	2nd Oct	24th Dec	26th Feb	4th Apr	27th Apr	4th May	2nd Jun
	JD8	2nd Oct	24th Dec	26th Feb	8th Apr	5th May	9th May	6th Jun
15th Nov	DZ5	2nd Mar	24th Dec	26th Feb	23rd Apr	12th May	15th May	1st Jun
	JD8	3rd Mar	24th Dec	26th Feb	23rd Apr	14th May	18th May	7th Jun
1st Mar	DZ5	18th Mar	-	-	24th Apr	15th May	17th May	12th Jun
	JD8	18th Mar	-	-	5th May	-	-	-
1st Apr	DZ5	1st Apr	-	-	9th May	22nd May	25th May	18th Jun
	JD8	1st Apr	-	-	29th May	-	-	-

Light and temperature conditions during the growing period are given in Table 35. For the autumn sowings, time from sowing till heading was shorter for DZ5 and hence daily average temperature is lower than for JD8. From physiological jointing till heading, average day length for DZ5 is slightly less than for JD8; DZ5 can complete vernalization under shorter day lengths, because it is photo-insensitive. From heading to maturity, average temperature for DZ5 is 1-3 °C higher than for JD8.

Table 35. Phenological development under different sowing dates and its relation to temperature and day length in Beijing, North China (2000-2001).

Sowing time	Variety	Sowing date	Sow. ~ Jointing			Jointing ~ Heading			Heading ~ maturity		
			Duration (d)	$T_{aver.}$ (°C)	Day length (h)	Duration (d)	$T_{aver.}$ (°C)	Day length (h)	Duration (d)	$T_{aver.}$ (°C)	Day length (h)
Autumn	DZ5	27th Sept.	191	3.4	6.4	23	15.0	7.3	36	23.5	8.7
		11th Oct.	182	2.6	6.4	25	16.4	7.3	38	25.2	10.0
	JD8	27th Sept.	195	3.6	6.4	27	16.5	8.0	31	25.5	10.0
		11th Oct.	184	2.7	6.5	27	17.1	8.2	32	26.5	9.7
Spring	DZ5	1st March	54	10.6	8.0	21	19.4	8.9	29	27.2	10.5
		1st April	38	15.9	6.9	13	25.8	9.4	27	27.5	10.4
	JD8	1st March	78	13.6	7.8	–	–	–	–	–	–
		1st April	58	19.4	8.0	–	–	–	–	–	–

Under the standard sowing date, the young ear elongation stage of DZ5 started 2 days earlier than that of JD8, increasing to 8 days at heading (Table 36).

Table 36. Development of young ear differentiation and caulis leave under standard sowing date in Beijing, North China (2000-2001).

Young ear differentiation stage	Date	
	DZ5	JD8
Elongation	10th March	12th March
Single ridge	17th March	19th March
Double ridge	22nd March	26th March
Floret differentiation	5th April	9th April
Stamen and pistil differentiation	8th April	12th April
Anther diaphragm formation	12th April	14th April
Tetrad formation	17th April	23rd April
Heading	27th April	5th May

Leaves are growing faster and young ear differentiation is shortened under higher temperatures. The light-temperature characteristics of wheat crops are an indication for ecological adaptation. The value of the product of sunshine hours and cumulative thermal time can scale development rates of wheat crops (long day crops). Experiment results (Table 37) show that astronomical sunshine hours and efficient thermal time of DZ5 in every young ear development stage were smaller than those for JD8. This is the main reason for the faster development rate of DZ5.

Table 37. Sunshine hours and thermal time during the whole growing season and during young ear differentiation in Beijing, North China (2000-2001).

Development of young ear differentiation	Astronomical sunshine hours (h)		Efficient thermal time (°C d)		Sunshine hours × thermal time (h °C d)	
	DZ5	JD8	DZ5	JD8	JD5	DZ8
Elongation~ single ridge	118.5	119.3	55.8	80.7	6613.6	9625.0
Single ridge~ double ridge	90.6	121.9	66.5	104.9	6024.0	12791.8
Double ridge~ floret differentiation	233.5	236.5	141.9	143.0	33132.4	33823.9
Floret differentiation ~ stamen and pistil differentiation	64.0	64.8	47.1	46.8	3014.2	3034.2
Stamen and pistil differentiation~ anther diaphragm formation	80.9	82.0	62.3	87.7	5040.7	7188.7
Anther diaphragm formation~ tetrad formation	98.5	133.5	108.8	141.2	10719.2	18850.6
Tetrad formation~ heading	185.0	223.6	180.5	221.9	33400.5	49611.0

The effective thermal time during young ear differentiation for DZ5 was obviously less than for JD8, and it was almost the same in the double ridge to floret differentiation stage. In the period from double ridge till stamen and pistil differentiation, the key period for grain formation, astronomical sunshine hours and efficient thermal time of were not much different for DZ5 and LD8, which is an advantage for DZ5 in spikelet and grain formation. Overall, phenological development in DZ5 proceeds faster in the early and late stages of young ear differentiation compared to JD8.

4.6.2 Frost hardiness and crop yield

Winter wheat seedings can stand a certain low temperature. In general, 10% death of seedlings during winter is called initial death, 50% substantial death and 70% fatal death, the corresponding temperature values are called critical temperature values. The temperature of the tillering node is the criterion for chilling injury for wheat, and also the criterion for wheat frost hardiness characteristics. The lower the critical temperature values, the greater frost hardiness. The temperature leading to 50% death of wheat seedlings in the manual freezing method is called limiting temperature (LT50).

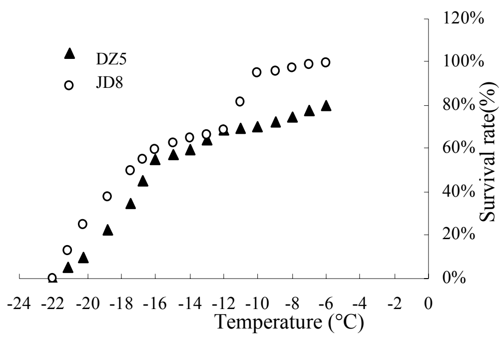


Figure 20. The relation between temperature and survival rate of wheat after re-greening in the laboratory in Beijing, North China (2000-2001).

The relations between temperature and survival rate for the wheat varieties DZ5 and JD8 established in the laboratory for the 'standard' sowing date (27th Sept. 2000) are shown in Figure 20. The limiting temperature (LT50) for DZ5 is -14.9 °C, only 1.83 °C lower than for the winter-hardy variety JD8. According to, DZ5 is a medium frost hardy variety. It is expected that under normal management practices, DZ5 can safely survive winter in Beijing and the south of Northern China.

The relation between survival rate, Y and temperature, T_n, is logistic for both varieties (Table 38), with correlation coefficients exceeding 0.97 (n=20, α=0.001).

Table 38. The relation between temperature and survival rate of wheat after re-greening in the laboratory in Beijing, North China (2000-2001).

Variety	Fitted curve	R	T value	Significance	LT50 (°C)
Dongzao5	Y=0.82/[1+exp(-5.53-0.34 T_n)]	0.98	0.048	***	-14.94
Jingdong8	Y=1.07/[1+exp(-4.23-0.34 T_n)]	0.97	0.090	***	-16.77

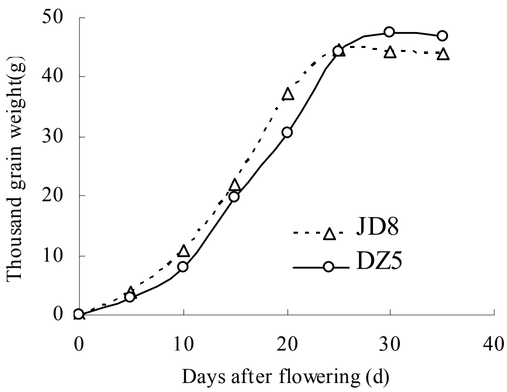


Figure 21. Cumulative grain weight of winter wheat varieties JD8 and DZ5 in Beijing, North China (2000-2001).

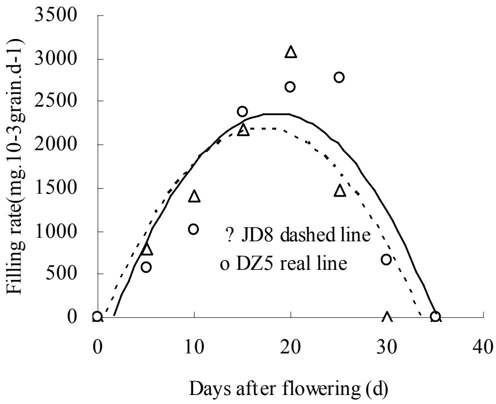


Figure 22. Rate of grain filling winter wheat varieties JD8 and DZ5 in Beijing, North China (2000-2001).

Analysis of the rate of grain filling indicates a logistic growth curve for grain weight associated with a unimodal curve for grain filling rate for both varieties, DZ5 and JD8 (Figures 21 and 22). The rate of grain filling in JD8 increases faster than in DZ5 in the early stages, but also decreases earlier. In the late grain filling stage, DZ5 maintains a higher grain filling rate than JD8. The relation between grain filling rate Y (Y_{dz5} and Y_{jd8} for DZ5 and JD8, respectively and day number after flowering could be expressed by:

Y_{dz5} = -8.4143x^2 + 308.89x – 469.07 R^2 = 0.7962 ** (significance level is 0.025)

Y_{jd8} = -8.1391x^2 + 278.18x – 191.55 R^2 = 0.7709 ** (significance level is 0.025)

Temperatures in early 2001 were above-normal. As young ear differentiation in JD8 started late and drought and high temperatures shortened the floret differentiation stage, grain number per spike and the duration of grain filling were reduced (Table 39). That is the main reason for the difference in harvest index HINDEX between DZ5 and JD8. Pest and disease incidence was high during the seedling and grain filling stages in the 4th Oct. 2000 sowing, hence yield was strongly reduced. Average grain yield for the autumn sowings of DZ5 was 38.5% (total aboveground dry matter 10.6% higher) higher than that of JD8. DZ5 produced 4000 kg ha^{-1} grain yield when sown in spring, when JD8 remained vegetative.

Table 39. Grain yield and yield components of DZ5 and JD8 wheat varieties for different sowing dates (2000~2001).

Variety	Sowing date	Grains/ spike	10^3-Grain weight (g)	Ear density (10^4 ha^{-1})	Harvest index	$Y_{theoritical}$ (kg ha^{-1})	Y_{actual} (kg ha^{-1})
DZ5	20th Sept.	39.7	45.5	444.0	0.49	8020	6817
	27th Sept.	39.9	46.8	469.5	0.46	8767	7452
	4th Oct.	34.9	41.3	513.0	0.49	7394	6285
	11th Oct.	38.3	38.6	477.0	0.41	7051	5994
JD8	20th Sept.	30.3	42.6	415.5	0.38	5363	4559
	27th Sept.	35.0	44.1	396.0	0.38	6112	5195
	4th Oct.	33.8	42.9	334.5	0.38	4850	4123
	11th Oct.	36.7	42.0	444.0	0.38	6844	5817

4.7 Vegetable experiments

Sweet potato experiments, conducted in Yuhe experimental station, show (Table 40) a highest yield of 22 800 kg ha^{-1} at high water input of 421 mm, with net revenue of 7479 Yuan[3] ha^{-1} (sweet potato price was 0.57 Yuan kg^{-1} in 2002). The highest WUE of 59.69 kg ha^{-1} mm^{-1} was observed at a water input of 367 mm. Without irrigation, total economic input exceeded total output, i.e. a net loss of 78 Yuan ha^{-1}. If water saving is the main objective, treatment 2 with a total irrigation of 189 mm is recommended.

Table 40. Sweet potato water use, yield and revenue under different irrigation management regimes in Yuhe, Shanxi Province, North China.

Treatment	Total irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield (fresh) (kg ha^{-1})	Water use efficiency (kgha^{-1} mm^{-1})	Total Input (Yuan ha^{-1})	Total output (Yuan ha^{-1})	Net revenue (Yuan ha^{-1})
1	258	10	154.5	421	22800	54.11	5571	13050	7479
2	189	23	154.5	367	21885	59.69	5388	12485	7097
3	144	58	154.5	356	20775	58.36	5267	11909	6642
4	0	116	154.5	271	9150	33.81	4875	4797	-78

Results of the jequirity experiments, conducted in Xiaohe experimental station, show (Table 41) that without irrigation, total economic input exceeded total output, i.e. a net loss of 93 Yuan ha^{-1} (jequirity price 2 Yuan kg^{-1} in 2002). For further analysis more irrigation treatments were recommended.

[3] 1 U$ = 8.25 Yuan

Table 41. Jequirity water use, yield and revenue under different irrigation management regimes in Xiaohe, Shanxi Province, North China.

Treatment	Total irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield (fresh) ($kg \cdot ha^{-1}$)	Water use efficiency ($kg\ ha^{-1}\ mm^{-1}$)	Total input ($Yuan\ ha^{-1}$)	Total output ($Yuan\ ha^{-1}$)	Net revenue ($Yuan\ ha^{-1}$)
1	150	-46	339	443	2601	5.88	3942	5202	1260
2	0	25	339	364	1722	4.73	3537	3444	-93

Sesame is very sensitive to soil water conditions. Under excessive water supply before flowering, the flower buds are shed, leading to substantial yield loss. Experiments were conducted in CES to support this statement (Table 42). The highest yield of 1182 kg ha^{-1} is observed at a water input of 349 mm with a highest WUE and net revenue of 3.38 kg ha^{-1} mm^{-1} and 1933 Yuan ha^{-1} (sesame price was 2.49 Yuan kg^{-1} in 2002), respectively. Both higher and lower irrigation doses lead to lower WUE and net revenue. For higher crop yields, irrigation in small doses is recommended.

Table 42. Sesame water use, yield and revenue under different irrigation management regimes in CES, Shanxi Province, North China.

Treatment	Total irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield ($kg\ ha^{-1}$)	Water use efficiency ($kg\ ha^{-1}\ mm^{-1}$)	Total Input ($Yuan\ ha^{-1}$)	Total output ($Yuan\ ha^{-1}$)	Net income ($Yuan\ ha^{-1}$)
1	216	-112.9	226.2	329.3	848	2.57	1311	2119	808
2	126	38.5	226.2	390.7	821	2.10	1071	2052	981
3	76	63.1	226.2	349.3	1182	3.38	1022	2955	1933
4	62	47.1	226.2	321.3	864	2.69	1008	2160	1152
5	0	39.1	226.2	265.3	801	3.02	795	2003	1208

Yields and water use of intercropped water melon and black bean are given in Table 43. Total water consumption of both species combined varied between 305 mm and 630 mm. The highest yields for water melon and black bean were observed under a total irrigation supply of 188 mm. Highest WUE was observed in the non-irrigated treatment. Under high irrigation supply, seedlings died and yield was reduced.

Table 43. Intercropped water melon and black bean water use, yield and revenue under different irrigation management regimes in Zhangziliang, Shanxi Province, North China.

Treatment	Total Irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Water melon		Black bean	
					Yield (fresh) (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Yield (fresh) (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
1	390	73.3	170.6	633.9	68393	107.90	2505	3.95
2	300	115.7	170.6	586.3	74205	126.57	2918	4.98
3	210	130.9	170.6	511.5	95498	186.71	3098	6.06
4	120	136.9	170.6	427.5	81458	190.56	2258	5.28
5	0	134.7	170.6	305.3	70607	231.24	1958	6.41

Economic analysis for water melon and black bean shows a high net income (Table 44). The highest net revenue of 27 578 Yuan ha^{-1} (water melon price was 0.17 Yuan kg^{-1} and black bean price 2.80 Yuan kg^{-1} in 2002) was calculated for a total irrigation application of 210 mm.

Table 44. Total income and costs of intercropped water melon and black bean.

	Total irrigation	Input (Yuan ha^{-1})	Output		Net income (Yuan ha^{-1})
			Water melon (Yuan ha^{-1})	Black bean (Yuan ha^{-1})	
	390	5100	17010	7014	18924
	300	4920	18510	8169	21759
watermelon/black bean	210	4740	23645	8673	27578
	120	4560	20091	6321	21852
	0	4320	17483	5481	18644

Results of musk melon experiments, conducted in Shenxi experimental station show (Table 45) a highest yield of 24 750 kg ha^{-1} at an irrigation application of 68 mm, with the highest WUE of 90.59 kg ha^{-1} mm^{-1} and the highest net income of 12782 Yuan ha^{-1} (muskmelon price was 0.69 Yuan kg^{-1} in 2002). The highest irrigation supply (120 mm) resulted in low yields and waste of water, compared to the treatment with 68 mm.

Table 45. Musk melon water use, yield and revenue under different irrigation management regimes in Shenxi, Shanxi Province, North China.

Treatment	Total Irrigation (mm)	Change in soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield (fresh) (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Total Input (Yuan ha^{-1})	Total output (Yuan ha^{-1})	Net income (Yuan ha^{-1})
1	120	83	142	345	24600	71.40	5046	16974	11928
2	68	63	142	273	24750	90.59	4926	17708	12782
3	0	74	142	216	15750	72.78	4620	10868	6248

Experimental results for turnip, collected in Shenxi experimental station, showed (Table 46) a highest yield of 105 000 kg ha^{-1} under a total irrigation supply of 319 mm, associated with the highest net income of 14 970 Yuan ha^{-1} (turnip price was 0.21 Yuan kg^{-1} in 2002), but the highest WUE 235.65 kg ha^{-1} mm^{-1} was observed at a total irrigation input of 135 mm. Without irrigation, turnip yield was very low.

Table 46. Turnip water use, yield and revenue under different irrigation management regimes in Shenxi, Shanxi Province, North China.

Test	Total Irrigation (mm)	Change In soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield (fresh) (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Total Input (Yuan ha^{-1})	Total output (Yuan ha^{-1})	Revenue (Yuan ha^{-1})
1	319	-61	219.5	478	105000	219.79	7080	22050	14970
3	219	-26	219.5	413	90000	218.02	6945	18900	11955
5	152	-28	219.5	344	81000	235.65	6810	17010	10200
6	0	29	219.5	248	48000	193.24	6510	10080	3570

Experimental results indicate that irrigation strongly influences chilli pepper yields (Table 47). Highest yield, coinciding with highest WUE and highest net income, is observed at the lowest irrigation supply. As effective precipitation was 281 mm, rain was enough to almost completely satisfy total water requirements; high irrigation supply leads to high soil moisture and reduced aeration of the soil, finally leading to yield reductions. It is recommended to irrigate in small doses in rainy years.

Table 47. Chilli pepper water use, yield and revenue under different irrigation management regimes in Zhangbei, Shanxi Province, North China.

Test	Total irrigation (mm)	Change In soil moisture (mm)	Effective precipitation (mm)	Water consumption (mm)	Yield fresh (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Total Input (Yuan ha^{-1})	Total output (Yuan ha^{-1})	Revenue (Yuan ha^{-1})
1	212	-34.2	281	459	15000	32.69	4475	9000	4526
2	180	-65.5	281	395	13130	33.19	4425	7875	3450
3	125	-37.7	281	368	27600	74.95	4343	16560	12218
4	90	-28.9	281	342	28500	83.30	4290	17100	12810
5	0	-7.7	281	273	21300	77.93	4155	12780	8625

5. WOFOST crop model

5.1 WOFOST crop model description

The WOFOST model, applied in this study, as tool for quantitative analysis of the growth and production of annual field crops (Boogaard *et al.*, 1998), originates from the Center for World Food Studies (CWFS). It is a member of the family of crop growth models developed in Wageningen in the footsteps of C.T. de Wit (Bouman *et al.*, 1996). Related models are SUCROS (Simple and Universal CROp Simulator) (Spitters *et al.*, 1989), Arid Crop (van Keulen *et al.*, 1981; van Keulen, 1975), spring wheat (van Keulen & Seligman, 1987), MACROS (Penning de Vries *et al.*, 1989) and ORYZA1 (Kropff *et al.*, 1993). All these models follow the hierarchical pattern of potential and resource-limited production and share similar crop growth sub-models, with light interception and CO_2 assimilation as growth-driving processes and crop phenological development as growth-controlling process. However, the sub-models for soil water balance and soil and crop nutrient (nitrogen) balance may vary appreciably in approach and level of detail. WOFOST simulates crop dry matter accumulation and yield formation from emergence till maturity, as a function of radiation, temperature and crop genetic properties in time intervals of one day. Meteorological input consists of maximum temperature (°C), minimum temperature (°C), radiation (kJ m^{-2} d^{-1}), wind speed at 2 m height (m s^{-1}), early morning vapor pressure (kPa), and precipitation (mm d^{-1}); both daily and long-term monthly data can be used in crop simulation.

WOFOST simulates phenological development of the crop, which is characterized by the rate and order of appearance of the various organs, i.e. roots, leaves, stems and storage organs. The most important phenological transition is that from growth of the vegetative organs to growth of the reproductive organs. For example, in grain crops, practically all assimilates produced after anthesis are used for filling of the grains. Phenological development stage is expressed in a dimensionless variable, having the value 0 at seedling emergence, 1 at anthesis and 2 at maturity, which is obtained through integration of the development rate defined as a function of temperature. Development rate is higher at higher temperatures, and growth duration is shorter (Van Keulen and Wolf, 1986).

The basis for calculating dry matter production is gross canopy CO_2 assimilation rate, calculated as a function of incoming radiation and crop leaf area. Gross assimilation rate per unit leaf area is calculated from absorbed radiation and the photosynthetic characteristics of single leaves. Part of the carbohydrates (CH_2O) produced is used to provide energy for maintenance of existing live biomass (maintenance respiration). The remainder is converted into structural plant dry matter that is partitioned among roots, leaves, stems and storage organs, using partitioning factors that depend on the phenological development stage of the crop (Spitters *et al.*, 1989). These growth rates are integrated over time to yield dry weights of plant organs. The fraction partitioned to the leaves determines leaf area development and hence the dynamics of light interception.

WOFOST keeps track of the soil moisture content to determine when and to what degree the crop is exposed to water stress. A water balance is included, which compares incoming water in the rooted zone, treated in the model as a single ‘container’, with outgoing water and quantifies the difference between the two as the change in total soil moisture content (SM). This soil moisture content influences the rate of both soil evaporation and plant transpiration. When SM in the root zone decreases below the critical soil moisture content, crop transpiration rate is reduced and so is its gross assimilation rate. When SM decreases further and drops below wilting point, transpiration of the crop and hence crop growth completely stops.

The effects of nutrient availability (nitrogen, phosphorus and potassium) on yield are calculated following the dynamic calculations of potential and water-limited production, according to the procedure developed by Janssen *et al.* (1990). This procedure consists of four steps. First, the potential soil supplies of nitrogen, phosphorus and potassium are calculated from soil chemical characteristics, or they may be entered by the user. In the second step, the actual uptake of each nutrient is calculated as a function of the potential supply of that nutrient, taking into account the potential supply of the other two nutrients. Subsequently, three yield ranges are established in dependence of the actual uptake of nitrogen, phosphorus and potassium, respectively. In step four these yield ranges are combined to obtain a mean yield estimate. In WOFOST, potential soil supplies of nutrients are entered by the user, based on expertise and available experimental evidence. For potential and water-limited production WOFOST also calculates fertilizer nutrient requirements based on potential soil supplies and apparent recovery fractions of applied nutrients.

Table 48. Sensitivity analysis of WOFOST crop parameters (see Appendix I for explanation of acronyms).

Parameter	Increased Value	MaxTWLV	MaxTWST	LAIM	MWLV	MTWST	MTWSO	MTAGP	MLAI
TDWI	21	0.482	0.078	3.719	1.261	1.634	0.235	1.491	0.990
RGRLAI	0.000817	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SLATB1(0.0)	0.000212	7.450	3.656	9.091	3.151	3.658	0.899	3.297	2.970
SLATB2(0.5)	0.000212	5.083	4.145	13.636	4.517	4.150	3.489	4.126	13.366
SLATB3(2.0)	0.000212	0.044	0.117	0.620	0.105	0.104	0.257	0.149	1.485
SPAN	3.13	0.000	0.000	0.000	51.050	0.000	1.348	0.522	50.990
KDIFTB1(0.0)	0.006	0.56968	-0.9384	0.41322	-1.2605	-0.9339	-1.0702	-0.7125	-1.4851
KDIFTB2(2.0)	0.006	-0.131	-0.899	-0.207	-0.735	-0.908	-2.354	-1.317	-0.990
EFFTB1(0.0)	0.045	5.083	4.340	4.959	4.412	4.332	2.954	3.935	4.455
EFFTB2(40.0)	0.045	3.944	4.184	3.926	4.307	4.176	4.666	4.316	4.455
AMAXTB1(0.0)	3.583	6.091	3.421	5.992	3.571	3.424	0.342	2.726	3.465
AMAXTB2(1.0)	3.583	4.032	4.497	3.926	4.517	4.488	1.434	3.223	4.455
AMAXTB3(1.3)	3.583	0.000	0.000	0.000	0.000	0.000	4.880	1.881	0.000
AMAXTB4(2.0)	0.448	0.000	0.000	0.000	0.000	0.000	0.385	0.149	0.000
TMNFTB1(3.0)	0.1	18.361	16.540	18.388	16.702	16.524	14.255	16.280	16.337
CVL	0.0685	6.748	3.910	6.612	4.307	3.917	0.385	3.074	4.455
CVS	0.0662	6.705	8.074	6.612	8.193	8.067	-0.428	4.524	7.921
CVO	0.0709	0.000	0.000	0.000	0.000	0.104	8.733	3.422	0.000
CVR	0.0694	3.506	1.896	3.512	1.891	1.894	0.300	1.574	1.980
RML	0.003	-0.964	-1.114	-1.033	-1.050	-1.115	-1.948	-1.417	-0.990
RMO	0.001	0.000	0.000	0.000	0.000	0.000	-0.985	-0.381	0.000
RMR	0.0015	-0.351	-0.293	-0.413	-0.210	-0.311	-0.449	-0.373	-0.495
RMS	0.0015	-0.351	-0.684	-0.413	-0.525	-0.700	-2.247	-1.243	-0.495
RDRRTB3	0.002	0.000	0.000	0.000	0.000	0.000	0.021	0.008	0.000
RDRSTB3	0.002	0.000	0.000	0.000	0.000	-1.349	0.064	0.025	0.000

SLATB1~SLATB3 refer to values for different growing seasons or as function of independent variable.

5.2 Procedure for model calibration for local conditions

Calibration in relation to crop modeling can be defined as 'adjustment for a particular function' (Merriam-Webster, 1998). For model applications in specific situations, model calibration is required, because models generally do not perform well outside the domain for which they have been developed ((Sinclair and Seligman, 2000; Jamieson *et al.*, 1998; Kabat *et al.*, 1995). Hence, model parameters have to be adapted to the specific combination of environmental conditions and crop variety. Proper calibration requires site-specific information on crop phenology, crop growth dynamics and yield.

Model calibration is performed first for the potential production situation, in which crop growth is not limited by excess or shortage of water or by nutrient deficiency, and yield losses due to weed competition, pest and disease infestation or other factors are negligible. This requires optimum crop management with respect to nutrient supply, irrigation and drainage and crop protection. Subsequently, calibration is performed for the water-limited production situation, in which crop growth is limited by excess or shortage of water as a result of sub-optimal irrigation and/or drainage.

Calibration is performed in the following order: 1) growth duration and phenological development; 2) light interception and potential biomass production; 3) assimilate distribution among crop organs; and for water-limited production 4) water availability; 5) evapotranspiration.

5.2.1 Calibration of crop parameters for the potential production situation

In the potential production situation, water supply, nutrient supply and crop protection and management are all optimal. In this case, soil information is not used. For the purpose of identifying the main crop parameters to which the model results are sensitive, it is necessary to perform a sensitivity analysis on all parameters. In this paper we define the sensitivity as the percentage change in model output (MaxTWLV, MaxTWST, LAIM; TWLV, TWSO, TAGP and MLAI) as the value of the test parameter is increased by 10% (while the other parameters retain their default values).

The results (Table 48) show that biological production (leaves, stems, storage organs and total production) was sensitive to specific leaf area (SLAT), extinction coefficient for diffuse visible light (KDIF), light use efficiency (EFF), light-saturated assimilation rate of single leaves (AMAX), conversion efficiencies of photosynthate in dry matter and respiration rate. Maximum LAI (LAIM) was very sensitive (13%) to the initial specific leaf area (SLATB). LAI at maturity (MLAI) and TWLV at maturity (MWLV) were very sensitive (up to 50%) to life span of leaves.

The final results of the calibration of crop parameters for FID are given in Table 49.

Table 49. Calibrated values for main crop parameters for the Fenhe Irrigation Station, North China (see Appendix I for explanation of acronyms).

Parameters	Source	Calibrated value			Remarks
		Wheat	Maize	Sunflower	
TSUMEM	Experiment	110	150	130	
TSUM1	Experiment	945	920	950	
TSUM2	Experiment	695	800	900	
TDWI	Experiment	298.6	50.0	120	
RGRLAI	WOFOST	0.00817	0.0294	0.0187	
SLATB1(0.0)	Calibrated	0.00171	0.0021	0.0045	
SLATB2 (0.5)	Calibrated	0.00280	0.0019	0.0035	For sunflower SLATB2 (1.0)
SLATB3 (2.0)	Calibrated	0.0009	0.0008	0.0025	
SPAN	Calibrated	31.3	31.0	30.0	
KDIFTB1 (0.0)	WOFOST	0.6	0.6	0.9	
KDIFTB2 (2.0)	WOFOST	0.6	0.6	0.9	
EFFTB1 (0.0)	Calibrated	0.49	0.49	0.49	
EFFTB2 (40.0)	Calibrated	0.45	0.48	0.46	
AMAXTB1(0.0)	Calibrated	35.83	70.0	40	
AMAXTB2(1.0)	Calibrated	40.83	70.0	40	For sunflower AMAXTB2 (1.22)
AMAXTB3(1.3)	Calibrated	40.83	70.0	-	
AMAXTB4(2.0)	Calibrated	40.83	70.0	35	
CVL	Calibrated	0.74	0.613	0.75	
CVS	Calibrated	0.80	0.8571	0.69	
CVO	Calibrated	0.69	0.7090	0.55	
CVR	Calibrated	0.74	0.7658	0.72	
RML	WOFOST	0.030	0.020	0.03	
RMO	WOFOST	0.010	0.010	0.012	
RMR	WOFOST	0.015	0.015	0.010	
RMS	WOFOST	0.015	0.010	0.015	

5.2.2 Calibration of soil and crop parameters for the water-limited production situation

In the water-limited production situation, soil properties and the soil water balance are taken into account. Water availability is determined first by the soil physical characteristics and second, the water balance. The water balance in the rooted zone during the growth period is equal to the difference between water supply from precipitation and irrigation and water losses by crop transpiration, soil evaporation and percolation to deeper soil layers. The soil physical characteristics determine the amount of water that can be stored at maximum in the soil and that can be supplied to the crop.

WOFOST simulates soil moisture content of the actual rooting depth and takes the whole soil layer as one 'container'. Therefore, soil physical characteristics have been calibrated for a homogeneous soil profile. Calibrated results for CES soil (bulk density 1.36 g cm^{-3}) are given in Table 50. Soil moisture content at wilting point (SMW) is 0.226 $cm^3\,cm^{-3}$; soil moisture content at field capacity (SMFCF) is 0.360 $cm^3\,cm^{-3}$; soil moisture content at saturation (SMO) is 0.435 $cm^3\,cm^{-3}$; critical soil air content for aeration CRAIRC is 0.090 $cm^3\,cm^{-3}$; hydraulic conductivity of saturated soil (K0) is 18.50 cm d^{-1}; maximum percolation rate root zone (SOPE) is 12.47 cm d^{-1}; maximum percolation rate subsoil (KSUB) is 24.03 cm d^{-1}.

Table 50. Calibrated values for soil physical properties for the Central Experimental Station, North China.

pF [log (cm)]	SMTAB cm^3 cm^{-3}	CONTAB [log (cm d^{-1})]
-1.000	0.487	1.079
1.000	0.435	0.971
1.300	0.420	0.864
1.491	0.390	0.746
2.000	0.360	0.002
2.400	0.310	-1.626
2.700	0.270	-2.357
3.400	0.255	-3.337
4.204	0.226	-4.457
6.000	0.160	-

The initial rooting depth, RDI was set to 20 cm (observed value on 1 January) and 10 cm (observed value at emergence) for winter wheat and spring maize, respectively; maximum rooting depth RDMCR was set to 140 cm and 100 cm for winter wheat and spring maize, respectively.

5.3 Validation of model results

5.3.1 Crop phenology and grain yield

WOFOST was calibrated for winter wheat and spring maize to examine model performance for different phenological phases and climate conditions; model results have been compared with results from field experiments in CES in 1992~1996, 2001 and 2002.

Comparison of simulated and observed flowering and maturity dates (Figure 23 left) and grain yield (Figure 23 right) shows satisfactory agreement for both winter wheat and spring maize. For winter wheat, simulated grain yields are linearly correlated to observed values with a slope of 1.2936 and an intercept of -1.0178. For spring maize, simulated grain yields are linearly correlated to observed values with a slope of 0.7571 and an intercept of 2.0701.

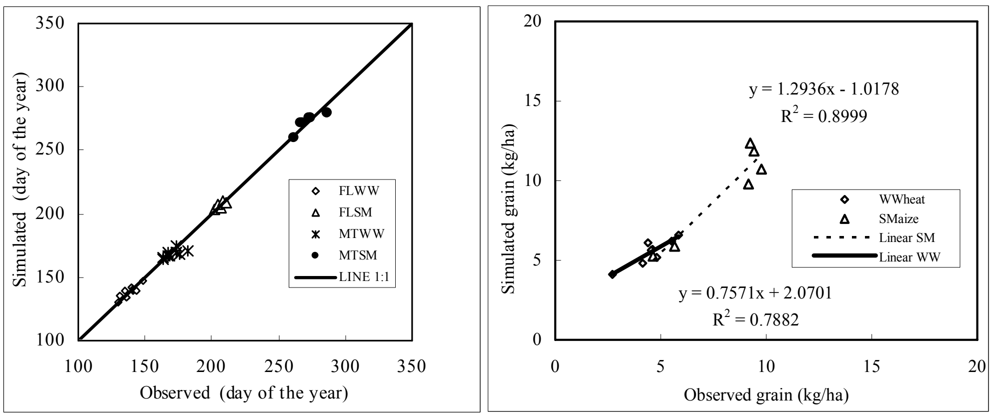


Figure 2. Simulated and observed winter wheat flowering (FLWW) and maturity dates (MTWW) in 1992-1996 and 2001-2002, and spring maize flowering (FLSM) and maturity dates (MTSM) in 1992, 1994, 2001 and 2002 (left) and simulated and observed grain yield for winter wheat (WWheat) in 1992-1995 and 2001-2002 and spring maize (SMaize) in 1992-1995 and 2001-2002, Central Experimental Station, Shanxi Province, North China.

5.3.2 Soil moisture content and water balance

Simulated soil moisture contents (actual rooting depth) have been tested for experiments carried out in CES in 2002. Initial available water in the potential root zone (WAV, moisture content above wilting point) was set to 2.0 cm and Initial moisture content in the initial rooting depth, SMLIM, to 0.263 $cm^3 cm^{-3}$. Results showed that simulated and measured soil moisture content were in satisfactory agreement during the winter wheat growing season for the irrigation treatments 100 mm (Figure 24, left) and 140 mm in two doses in 2002 (Figure 24, right), with correlation coefficients of 0.88 (R value).

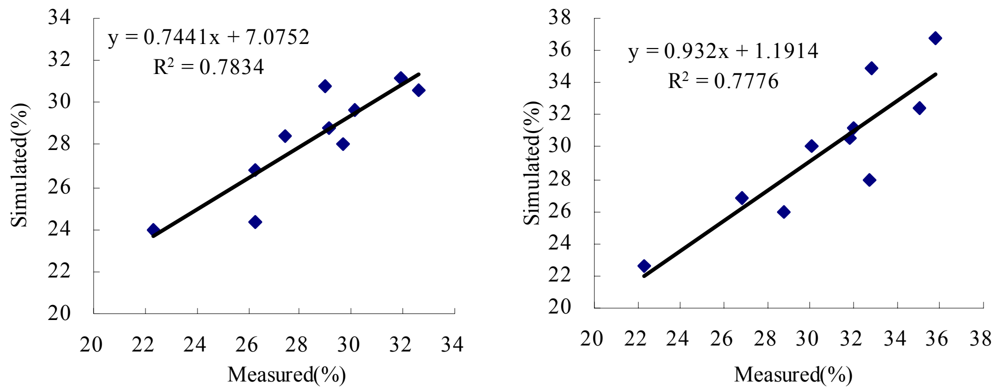


Figure 24. Measured and simulated soil moisture content (actual rooting depth) for winter wheat in 2002 irrigated with 100 mm (left) and 140 mm (right) in two doses in the Central Experimental Station, Shanxi Province, North China.

Measured soil moisture content under winter wheat (actual rooting zone) in CES in 1992 (Figure 25a) and 1994 (Figure 25e) clearly illustrate the effects of irrigation and precipitation (Figures 25b, c, e and f). Simulated soil moisture was in close agreement with the observed data.

Comparison of simulated and observed soil moisture content (actual rooting depth) of winter wheat (1992, 1994, 2001, 2002) and spring maize (2001, 2002) during the whole growing season (Figure 26) shows satisfactory agreement for both crops. For winter wheat, simulated values are linearly correlated to observed values with a slope of 0.8991 and an intercept of 0.0274. For spring maize, simulated values are linearly correlated to observed values with a slope of 0.8673 and an intercept of 0.0324. Correlation coefficients for the relation between measured and simulated total rooting depth soil moisture contents are above 0.9 for both, winter wheat and spring maize.

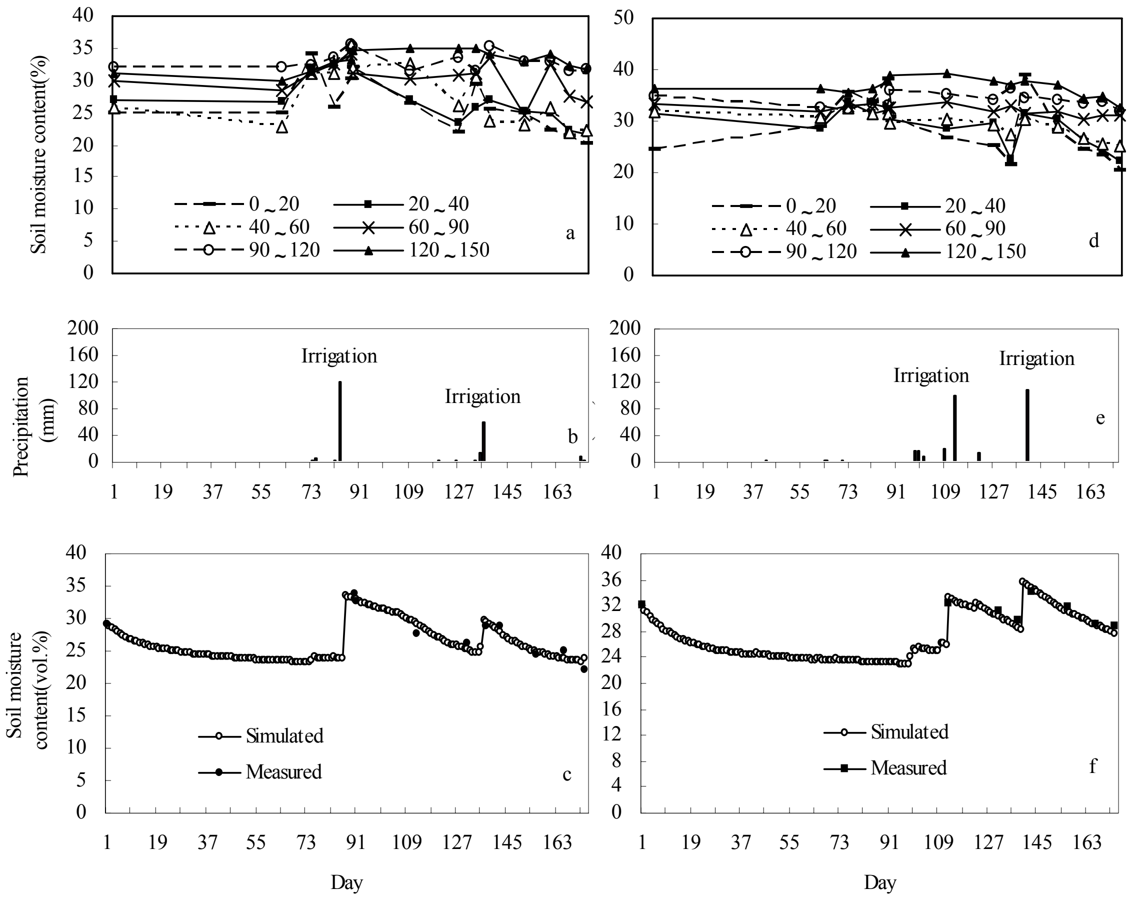


Figure 25. *Measured and WOFOST simulated soil moisture content (actual rooting zone) for winter wheat in 1992 (a, b and c) and 1994 (e, f and g) in Central Experimental Station, Shanxi Province, North China.*

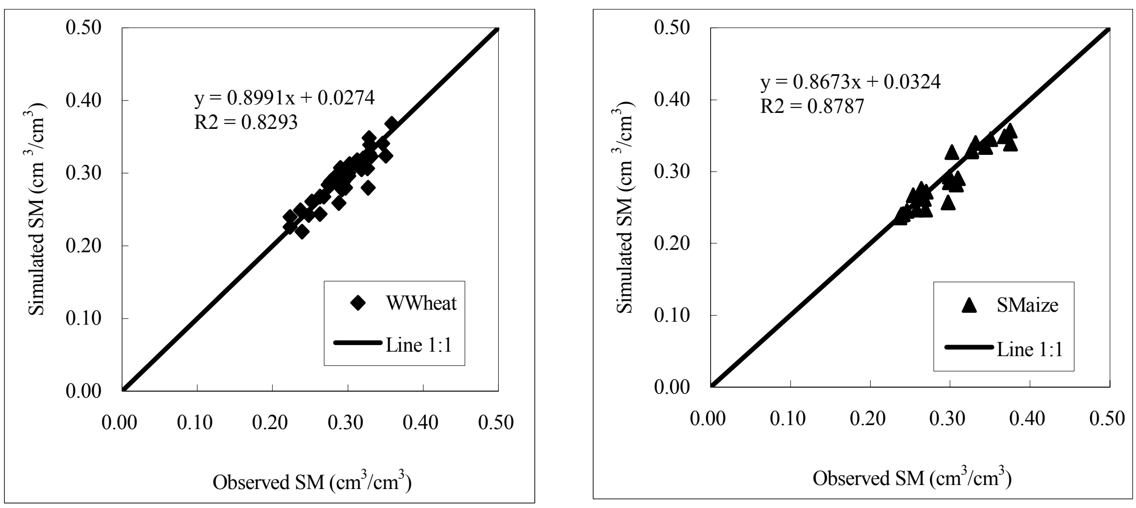


Figure 26. *Measured and WOFOST-simulated soil moisture content (potential rooting zone) for winter wheat (1992, 1994, 2001, 2002) (left), and spring maize (2001, 2002) (right) in Central Experimental Station, Shanxi province, North China.*

6. Potential crop production

6.1 Potential total aboveground production

6.1.1 Winter wheat

The variation in simulated total aboveground dry matter production (18 000~23 000 kg ha^{-1}, with an average of 20.500 kg ha^{-1}; Figure 27, left) for Taiyuan and Jiexiu for the 42 years is very similar. The maximum value of 24 133 kg ha^{-1} was simulated for 1997. In 1962, production in Jiexiu is much lower than in Taiyuan, due to lower production of leaves (maximum LAI was 4.22, the lowest value for the 42 years) and stems.

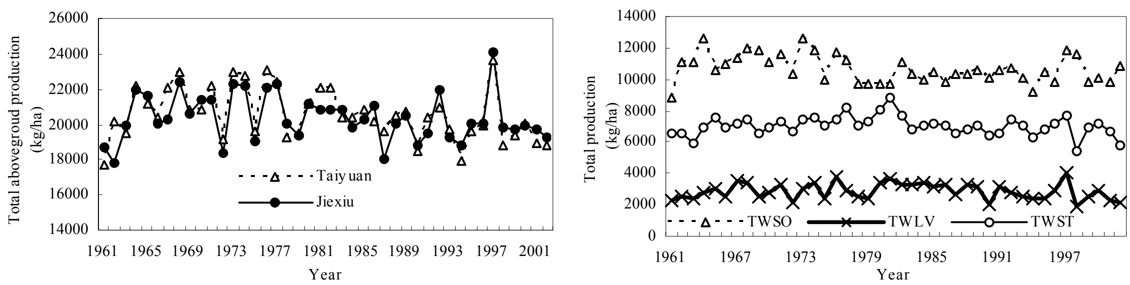


Figure 27. Simulated potential total aboveground dry matter production (TAGP; left) and (right) potential dry weights of leaves (TWLV), stems (TWST) and grain (TWSO) for the period 1961 to 2002 for winter wheat in Taiyuan and Jiexiu, Shanxi Province, North China.

Simulated potential grain yields (TWSO in kg dry matter kg ha^{-1}; Figure 27 right) range between 9 000 and 12 000, with an average of about 10 500 for the 42 years. In years with favorable weather conditions (e. g. 1964, 1973, 1997, 1998) the potential exceeds 12 000 (equivalent to 13 950 at 14% moisture content, i.e. air-dry) kg ha^{-1}, in years with unfavorable weather conditions (e. g. 1961, 1972, 1980, 1994) potential yields are below 9 500 kg ha^{-1}. The variation in simulated total dry weight of leaves (TWLV) and stems (TWST) over the 42 years in relative terms is similar to that in TWSO. For the 42 years, average values for TWLV and TWST are around 2 850 and 7 050 kg ha^{-1}, respectively. The correlation between TWLV and TWST appears much higher than between TWLV/TWST on one hand and TWSO on the other. This is because TWSO is mostly determined by the weather conditions (radiation and temperature) during the post-flowering phase (Nix, 1976; Fischer and Maurer, 1976) and TWLV and TWST by the conditions pre-flowering. In addition, if weather conditions are favorable for vegetative growth, the crop produces relatively large quantities of leaves and stems. During the post-flowering phase, this large vegetative biomass requires high maintenance respiration, restricting assimilate availability for grain growth.

6.1.2 Spring maize

The variation in simulated total aboveground dry matter production (23 500-31 500 kg ha^{-1}; average about 27 110; Figure 28) for Taiyuan and Jiexiu is very similar. The maximum value of 31 694 kg ha^{-1} is simulated for 1965. For almost all years, the production in Jiexiu is somewhat lower (on average 3.5% for the 42 years) than in Taiyuan, due to lower production of leaves (maximum LAI was on average 0.1 lower for the 42 years).

Simulated potential grain yields (TWSO in kg dry matter kg ha^{-1}; Figure 28, right) range between 11 500 and 17 000, with an average of about 14 100 (equivalent to 16 395 at 14% moisture content, i.e. air-dry) kg ha^{-1} for the

42 years. In years with favorable weather conditions (e. g. 1965, 1969, 1980, 1986, 1987, 1993), potential yield exceeds 16 000 kg ha^{-1}, in years with unfavorable weather conditions (e. g. 1967 and 1996) potential yields are below 12 000 kg ha^{-1}.

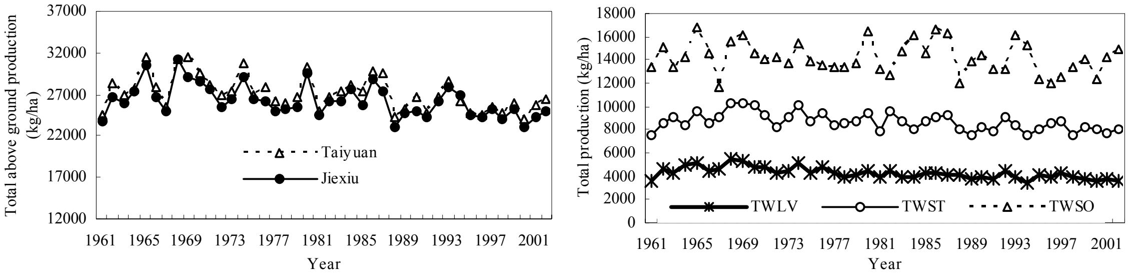


Figure 28. Simulated potential total aboveground dry matter production (TAGP, left) and dry weights of leaves (TWLV), stems (TWST) and grain (TWSO) (right) for the period 1961 to 2002 for spring maize in Taiyuan and Jiexiu, Shanxi Province, China.

The variation in simulated total dry weight of leaves (TWLV) and stems (TWST) over the 42 years in relative terms is similar to that in TWSO. For the 42 years, average values for TWLV and TWST are around 4 264 and 8 681 kg ha^{-1}, respectively. The correlation between TWLV and TWST is much higher than that between TWLV/TWST on the one hand and TWSO on the other. This is because TWSO is mostly determined by the weather conditions (radiation and temperature) during the post-flowering phase and TWLV and TWST by the conditions pre-flowering.

6.1.3 Sunflower

The variation in simulated total aboveground production (10 000~13 300 kg ha^{-1}; average about 11 500; Figure 29, left) for Taiyuan and Jiexiu for the 42 years is very similar. The maximum value of 13 302 kg ha^{-1} is simulated for Taiyuan in 1980. Potential production on average was lower in Jiexiu than in Taiyuan, due to lower production of leaves and stems.

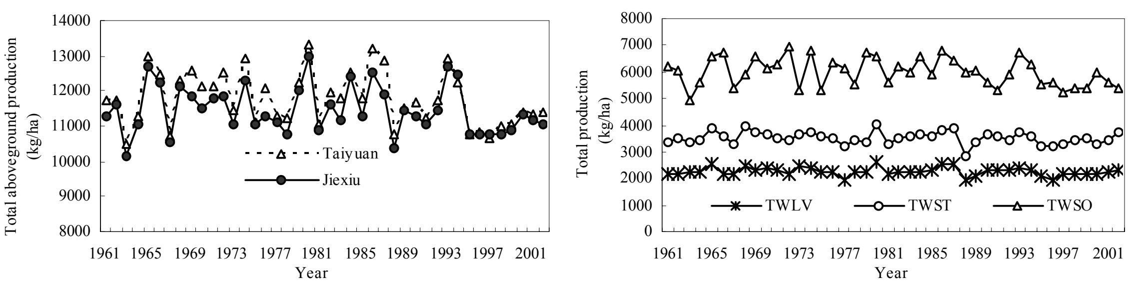


Figure 29. Simulated potential total aboveground production (TAGP, left) and dry weights of leaves (TWLV), stems (TWST) and grain (TWSO) (right) for the period 1961 to 2002 for sunflower in Taiyuan and Jiexiu, Shanxi Province, China.

Simulated potential grain yields (TWSO in kg dry matter kg ha^{-1}; Figure 30, right) range between 5 000 and 6 750, with an average of about 5 990 (equivalent to 6 965 at 14% moisture content, i.e. air-dry) kg·ha^{-1} for the 42 years. In years with favorable weather conditions (e. g. 1965, 1966, 1969, 1972, 1974, 1979, 1980, 1984, 1986, 1993) potential yield exceeds 6 500 kg ha^{-1}, in years with unfavorable weather conditions (e. g. 1963, 1967, 1973, 1975, 1991, 1997) it is below 5 400 kg ha^{-1}.

The variation in simulated total dry weight of leaves (TWLV) and stems (TWST) over the 42 years in relative terms is similar to that in TWSO. For the 42 years, average values for TWLV and TWST are around 2 300 and 3 500 kg ha^{-1}, respectively. The correlation between TWLV and TWST is much higher than between TWLV/TWST on the one hand and TWSO on the other. This is because TWSO is mostly determined by the weather conditions (radiation and temperature) during the post-flowering phase and TWLV and TWST by the conditions pre-flowering.

6.2 Maximum leaf area and harvest index

6.2.1 Winter wheat

Maximum values of simulated leaf area index (LAIM) for Taiyuan and Jiexiu are very similar (Figure 30, left), ranging between 4 and 8, with an average for the 42 years of about 6.5. The highest LAIM-values, slightly above 8, are simulated in 1976 and 1997, with favorable weather conditions before anthesis, associated with simulated values of TWLV of about 4 000 kg ha^{-1}. Such high values are unlikely to be encountered in the field and point to inadequacies in model description. In reality, when LAI reaches high values (exceeding about 6), incident light intensity at the lower leaves is so low that their assimilate balance (gross photosynthesis minus respiration) becomes negative, and the leaves die. This effect is not included in the WOFOST model description, contrary to the spring wheat model of van Keulen and Seligman (1987). This deviation from reality has only limited consequences for the calculated net assimilation rates (and thus dry matter production) in the model, as only small negative values for the lower leaves are calculated. High values for LAIM are also calculated for 1967, 1968, 1980 and 1984.

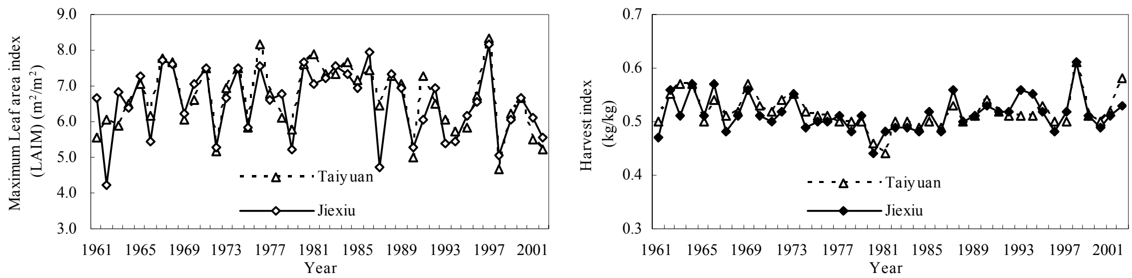


Figure 30. Simulated maximum leaf area index (left) and harvest index (right) for potential growth conditions for the period 1961 to 2002 for winter wheat in Taiyuan and Jiexiu, Shanxi Province, China.

Simulated harvest index (HINDEX), the ratio of grain yield to total aboveground dry matter production, varies between 0.44 and 0.61, with an average for the 42 years of 0.51 (Figure 30, right). Such values of HI are common for modern so-called high-yielding wheat varieties (Austin, 1994). The highest value (0.61) is calculated for 1998, a year with relatively unfavorable conditions before anthesis (LAIM 4.69) and favorable conditions during grain-filling. Similar conditions prevailed in 1963, 1964 and 1969.

6.2.2 Spring maize

Maximum values of simulated leaf area index (LAIM) for Taiyuan and Jiexiu are very similar (Figure 31, left), ranging between 6 and 8, with an average for the 42 years of about 6.8. The highest LAIM-values, slightly above 8, are simulated in 1968, with favorable weather conditions before anthesis, associated with simulated values of TWLV of about 5 508 kg ha^{-1}.

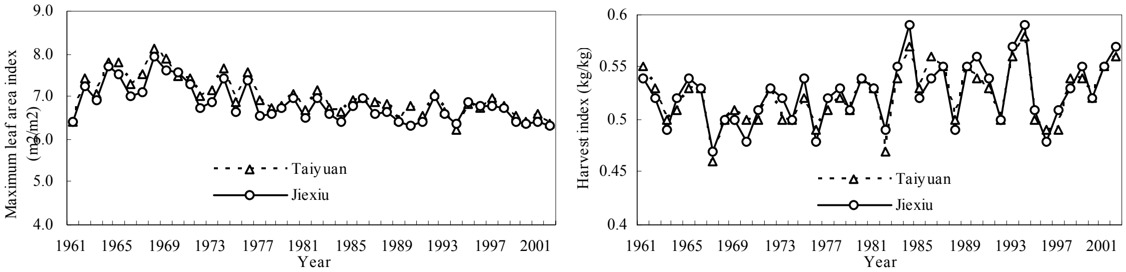


Figure 31. Simulated maximum leaf area index (LAIM, left) and harvest index (right) for the period 1961 to 2002 for spring maize in Taiyuan and Jiexiu, Shanxi Province, China.

Such high values are unlikely to be encountered in the field and point to inadequacies in model description. In reality, when LAI reaches high values (exceeding about 6), incident light intensity at the lower leaves is so low that their assimilate balance (gross photosynthesis minus respiration) becomes negative, and the leaves die. This deviation from reality has only limited consequences for the calculated net assimilation rates (and thus dry matter production) in the model, as only small negative values for the lower leaves are calculated. High values for LAIM were also calculated for 1964, 1965, 1969 and 1974.

Simulated harvest index (Figure 32, right), the ratio of grain yield to total aboveground dry matter production, varies between 0.48 and 0.59, with an average for the 42 years of 0.52 (Figure 32). The highest value (0.59) is calculated for 1994.

6.2.3 Sunflower

Maximum values of simulated leaf area index (LAIM) for sunflower for Taiyuan and Jiexiu are very similar (Figure 32, left), ranging between 5.9 and 7.4, with an average for the 42 years of about 6.5. The highest LAIM-values, slightly above 7.2, were simulated in 1980, with favorable weather conditions before anthesis, associated with simulated values of TWLV of about 2 645 kg ha^{-1}. Such high values are unlikely to be encountered in the field and point to inadequacies in model description. High values for LAIM are also calculated for 1965, 1973 and 1986.

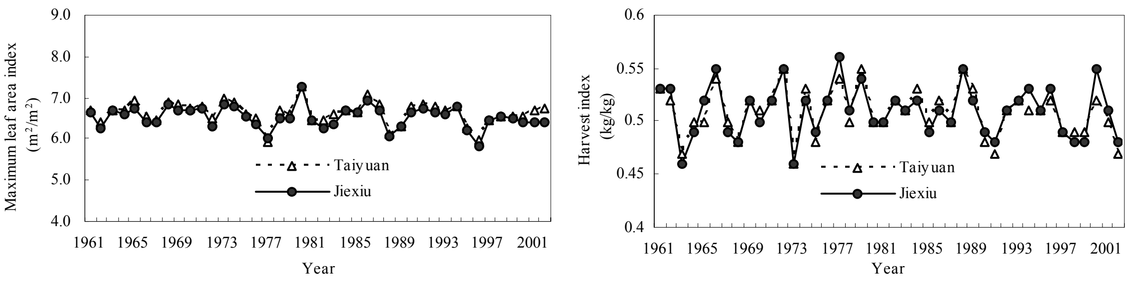


Figure 32. Simulated maximum leaf area index (left) and harvest index (right) for the period 1961 to 2002 for sunflower in Taiyuan and Jiexiu, Shanxi Province, China.

Simulated harvest index (HINDEX, Figure 32, right), the ratio of grain yield to total aboveground dry matter production, varies between 0.46 and 0.55, with an average for the 42 years of 0.51. The highest values (0.55) are calculated for 1972, 1979 and 1982.

7. Water-limited crop production

7.1 Crop production under rainfed conditions

7.1.1 Winter wheat

Precipitation varied between 50-250 mm during the winter wheat growing season for the period 1961 to 2002 in FID. Hence, to create optimum growth conditions for the crop, supplementary irrigation is required in all years. Simulated winter wheat yields are very low without irrigation. The lowest grain yield is about 1 000 kg ha^{-1}. For 1991, with 245 mm precipitation, simulated grain yield is 6484 kg ha^{-1} for Taiyuan, and for 1964 with 191 mm, 2226 kg ha^{-1}. For 1990, also with 191 mm precipitation simulated grain yield is 1478 kg·ha^{-1}, indicating that in addition to total rainfall, the distribution is of importance (van Keulen and Seligman, 1987).

7.1.2 Spring maize

Precipitation varied between 90~610 mm (325 mm on average) during the spring maize growing season for the period 1961 to 2002 in FID. Hence, to create optimum growth conditions for the crop, supplementary irrigation is required in dry years. Simulated results show (Figure 33) that spring maize yield is low under rainfed conditions. In some years (e. g. 1966 and 1969) total precipitation exceeded 550 mm, but crop yield is still very low, due to unfavorable rainfall distribution (during a rainstorm precipitation was 180 mm in one day in 1969). Conditions were similar for 1973 and 1977. Spring maize grain yield exceeded 11 000 kg ha^{-1} in 1964, 1988 and 1996 because of favorable rainfall conditions during the growing season

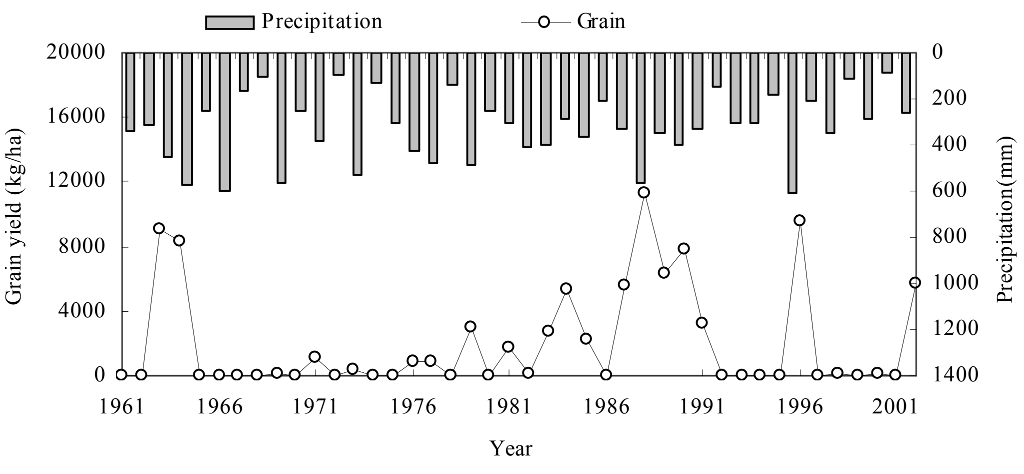


Figure 33. Growing season precipitation and smulated spring maize grain yield under rainfed conditions for the period 1961-2002 in Taiyuan, Shanxi Province, North China.

7.1.3 Sunflower

Precipitation varied between 120-702 mm (398 mm on average) during the sunflower growing season for the period 1961 to 2002 in FID. Simulated results show (Figure 34) that sunflower grain yield (dry weight) is correlated to precipitation, and can be expressed by a logarithmic curve, with a correlation coefficient of 0.75 and a slope of

4465.8 and an intercept of -23 388. Average grain dry weight for the simulated period under rainfed conditions is 3 074 kg ha^{-1}.

In some years (e. g. 1992 and 1999) precipitation exceeded 300 mm, but simulated crop yields are still very low (Figure 35), due to unfavorable distribution of rainfall. Sunflower grain yield exceeds 6 300 kg ha^{-1} in 1976 and 1982 thanks to favorable rainfall distribution during the growing season.

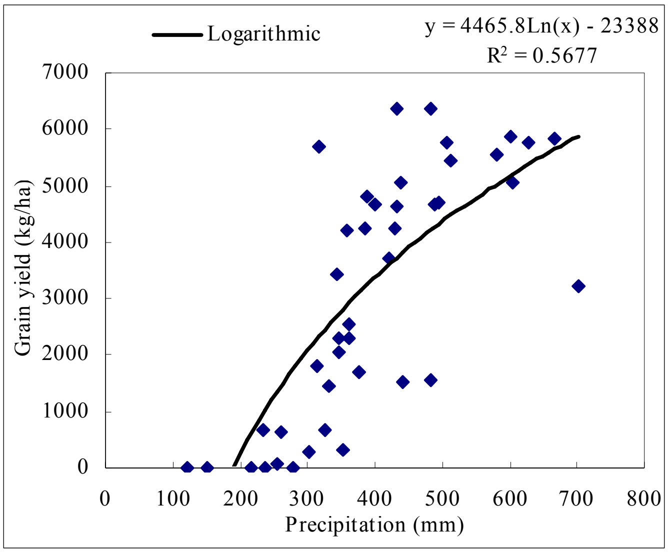


Figure34. The relation between simulated sunflower grain yield and precipitation under rainfed conditions (1961-2002) in Taiyuan, Shanxi Province, North China.

Hence, to create optimum growth conditions for the crop, supplementary irrigation is required in dry years, especially in years with precipitation below 400 mm during the growing season.

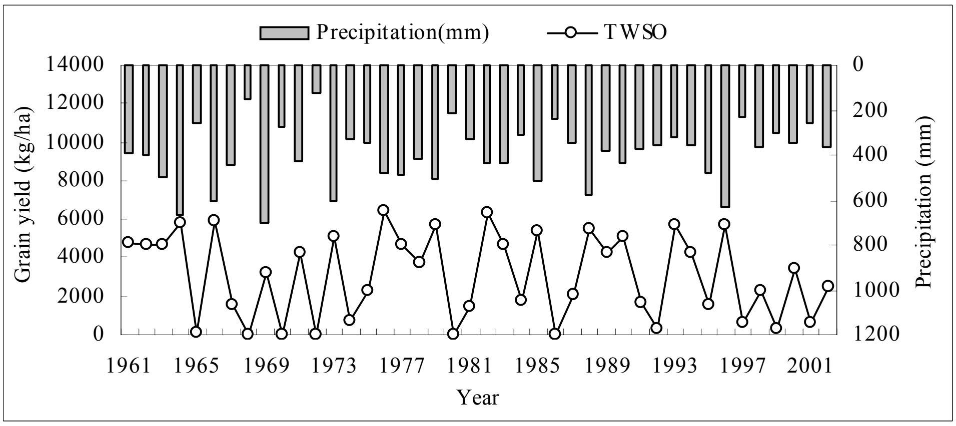


Figure 35 Growing season precipitation and simulated sunflower grain yields under rainfed conditions for the period 1961-2002 in Taiyuan, Shanxi Province, North China.

7.2 Crop production under irrigated conditions

7.2.1 Winter wheat

Under the prevailing irrigation scheduling for winter wheat in FID, the crop is irrigated twice (100 mm per application) after the winter period: once before jointing (end of March) and once before grain filling (end of April). Simulated grain yields (TWSO in kg dry matter per ha; Figure 36) for the period 1961 to 2002 for winter wheat under this irrigation regime vary between 100 and 10 000 kg ha^{-1} with an average of 5 205 (equivalent to 6 052 at 14% moisture content, i.e. air-dry) kg ha^{-1}.

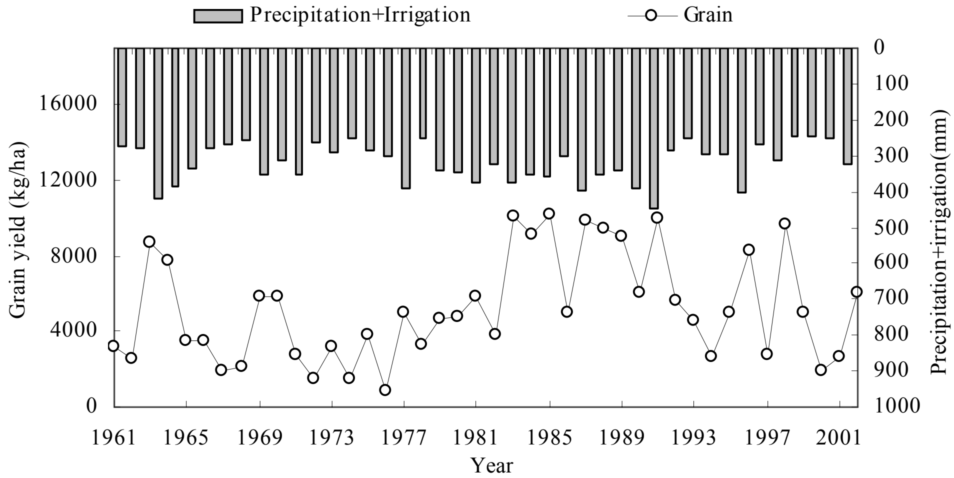


Figure 36. Simulated grain yield for the period 1961 to 2002 for winter wheat under irrigated conditions (100 mm twice after the winter period) in Taiyuan, Shanxi Province, North China.

Statistical analysis shows that simulated winter wheat grain yield is correlated to precipitation+irrigation during the simulated growing season, and can be described by a logarithmic curve (Figure 37), with correlation coefficient of 0.73, a slope of 12 376 and an intercept of -66 015.

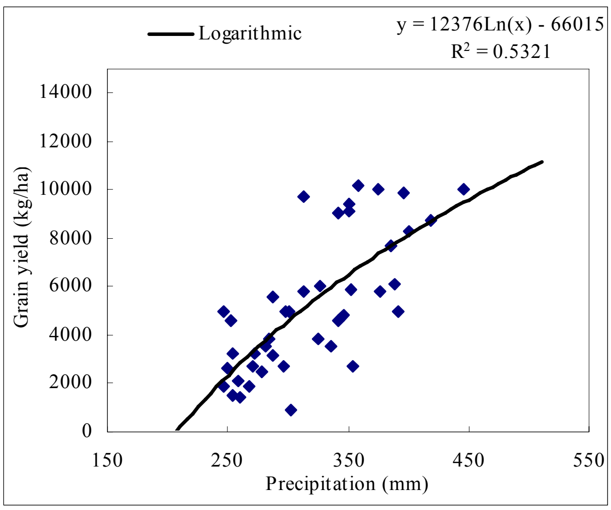


Figure 37. The relation between simulated winter wheat grain yield and precipitation+irrigation for the period 1961-2002 in Taiyuan, Shanxi Province, North China.

7.2.2 Spring maize

Under the prevailing irrigation scheduling for spring maize in FID, the crop is irrigated once (90 mm) after jointing. Simulated results show (Figure 38) that spring maize grain yield is correlated to precipitation+irrigation, and can be described by a logarithmic curve, with correlation coefficient of 0.76, a slope of 9781 and an intercept of -51 575.

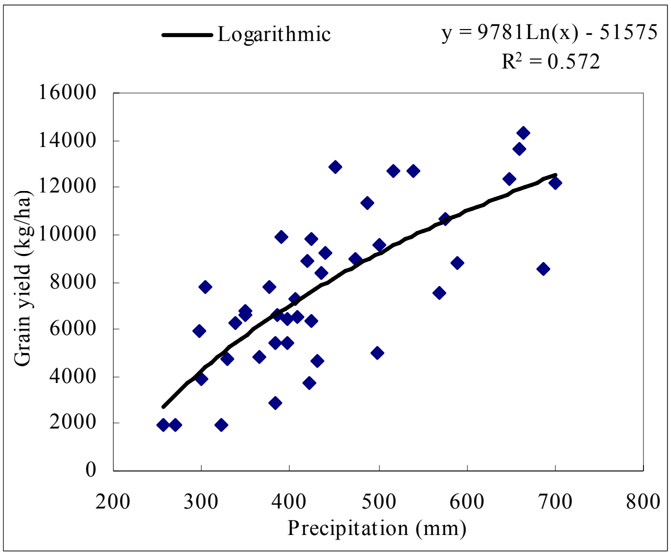


Figure 38. The relation between simulated spring maize grain yield and precipitation+irrigation for the period 1961-2002 in Taiyuan, Shanxi Province, North China.

Simulated grain yield (TWSO in kg dry matter per ha; Figure 39) for the simulated period (1961~2002) under irrigated condition varies between 1900 and 14 380 kg ha^{-1} with an average of 7 689 (equivalent to 8 940 at 14% moisture content, i.e. air-dry) kg ha^{-1}.

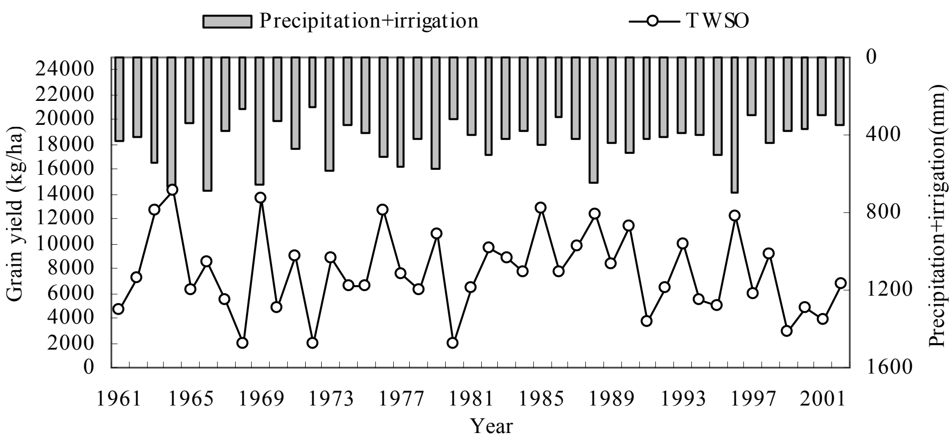


Figure 39. Growing season precipitation + irrigation and simulated grain yield (TWSO) for the period 1961 to 2002 for spring maize under irrigated conditions (single application of 90 mm after jointing) in Taiyuan, Shanxi Province, North China.

7.2.3 Sunflower

Under the prevailing irrigation scheduling for sunflower in FID, the crop is irrigated once (60 mm) before head appearance. Simulated results show (Figure 40) that sunflower grain yield is correlated to precipitation+irrigation, and can be described by a logarithmic curve, with a correlation coefficient of 0.71, a slope of 5912.7 and an intercept of -32 286. Simulated grain yield (TWSO in kg dry matter per ha; Figure 41) for the simulated period (1961~2002) under irrigated conditions varies between 36 and 6 469 kg ha^{-1} with an average of 3 805 (equivalent to 4 424 at 14% moisture content, i.e. air-dry) kg ha^{-1}, an increase of 731 kg ha^{-1} compared to rainfed conditions.

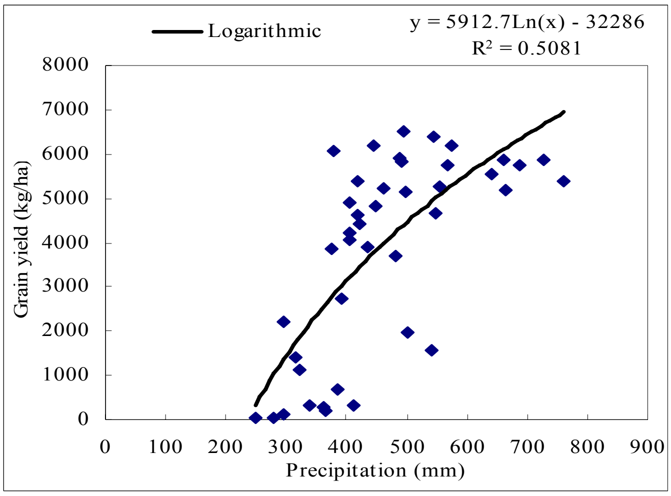


Figure 40. Growing season (precipitation + irrigation) and simulated grain yield (TWSO) for the period 1961 to 2002 for spring maize under irrigated conditions (single application of 90 mm after jointing) in Taiyuan, Shanxi Province, North China.

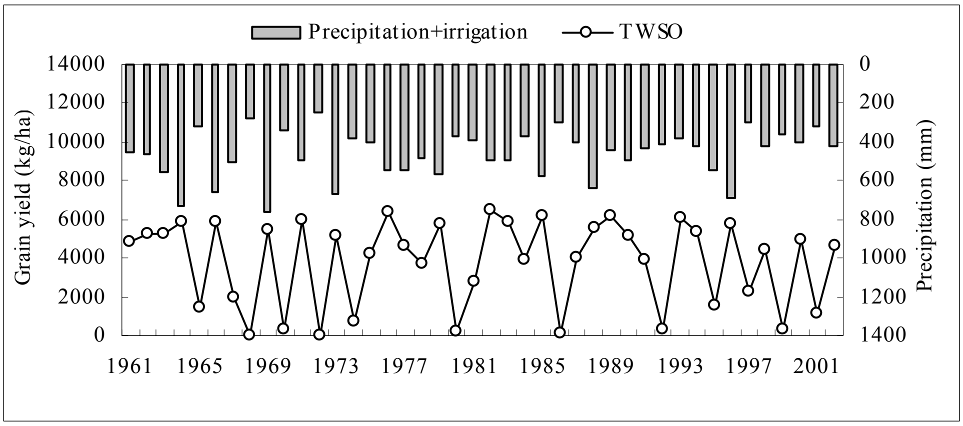


Figure 41. Growing season (precipitation + irrigation) and simulated grain yield (TWSO) for the period 1961 to 2002 for spring maize under irrigated conditions (single application of 90 mm after jointing) in Taiyuan, Shanxi Province, North China.

7.3 Yield gap analysis

The average yield gap (1992-1996 and 2001-2002) between simulated water-limited yield and actual yield is 0.7 and 1.0 Mg kg·ha^{-1} for spring maize and winter wheat, respectively (Figure 42). Simulated results overestimate grain yield for spring maize by 8.75% and for winter wheat by 22.3%. The difference could be due to effects of diseases and pests that are not taken into account in the model. Simulated water-limited grain yield for spring maize is 0.8 Mg ha^{-1} higher than simulated potential yield in 1995, because of irrigation and more favorable weather conditions after anthesis, that lead to a higher harvest index (Boogaard *et al.*, 1998).

In FID, average winter wheat yield under irrigation is 4 500 kg ha^{-1}. Experimental results have shown that winter wheat yield can reach 7 710 kg ha^{-1} under best water management and nutrient supply (Wang and Cun, 2003). The highest yield that has been reported for winter wheat was 11 180 kg ha^{-1} (equivalent to 13 000 kg ha^{-1} at 14% moisture content, i.e. air-dry) in 1998. In this report, the simulated potential yield is 12 137 kg ha^{-1} for 1998, just 8.6% higher than that reported. Hence, the yield gap between calculated potential yield and actual yield for this specific site is very small. But the yield gap between the average yield of 4 500 kg·ha^{-1} and the 'attainable' yield of 11 180 kg·ha^{-1} is still very large. This indicates the need for fine-tuning of water- and nutrient management and improved and integrated pest and disease management.

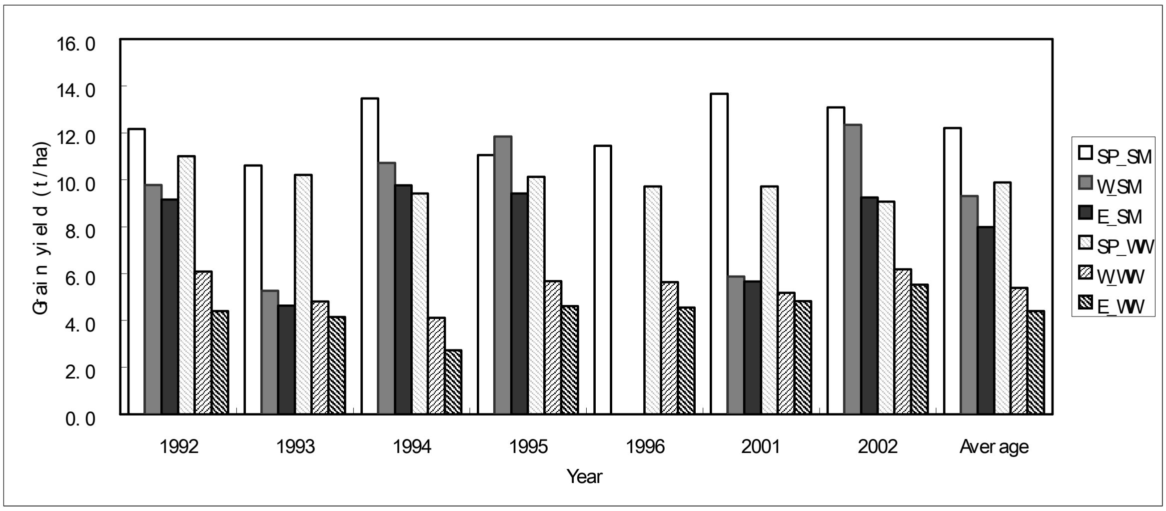


Figure 42. *Simulated potential grain yield, water-limited grain yield and experimental data for spring maize (SP_SM, W_SM and E_SM)and winter wheat (SP_WW, W_WW and E_WW) for the period 1992 -1996 and 2001-2002 in the Central Experimental Station, Shanxi Province, North China.*

8. Nutrient-limited crop production

Soil nutrient availability, fertilizer application, nutrient uptake by crop roots and distribution of nutrients in crop organs should be taken into account under nutrient-limited crop production. Nutrient applications were calculated based on fertilizer application in 2003 and 2004 (Table 4) for winter wheat. Three fertilization levels, i.e. high, medium and low for N, P and K were applied (Table 51).

Table 51. Winter wheat fertilizer application (kg ha^{-1}) in the Central Experimental Station in Shanxi province, North China (2003 and 2004).

	2003			2004		
Supply	N	P	K	N	P	K
High	232.5	45.8	41.1	232.5	90.0	37.5
Medium	155.0	30.5	27.4	168.8	60.0	25.0
Low	77.5	15.3	13.7	105.1	30.0	12.5

Indigenous soil nutrient contents were measured before sowing and after harvest for 2004 (Table 52). Soil nutrient content before sowing plus fertilizer applied minus soil nutrient content after harvest is considered crop uptake plus leaching.

Table 52. Fertilizer application for winter wheat and the change in soil nutrient content in the 0-50 cm soil layer under sufficient irrigation in the Central Experimental Station in Shanxi province, North China (2004)

Elements	Fertilization level	Fertilizer	Soil nutrient content		Uptake by crop and leaching
		(kg ha^{-1})	Before sowing l(kg ha^{-1})	After harvest (kg ha^{-1})	(kg ha^{-1})
	High	232.5	160.8	231.4	161.9
N	Medium	168.8	134.4	193	110.2
	Low	105.1	93.6	166.1	32.6
	High	90	64.6	109.5	45.1
P	Medium	60	76.9	93.1	43.8
	Low	30	78	82.9	25.1
	High	37.5	295.4	242.8	90.1
K	Medium	25	280.6	244.5	61.1
	Low	12.5	258	250	20.5

WOFOST estimates nutrient requirements, following the dynamic calculations of potential and water-limited production, following the QUEFTS-method of Janssen *et al.* (1990). This method takes into account indigenous soil nutrient supply that can be either calculated from soil chemical characteristics or can exogenously be supplied by the user, if nutrient uptake in the non-fertilized situation is known. Total crop nutrient requirements are calculated from dry matter production and crop-specific characteristic nutrient concentrations. To calculate fertilizer requirements, the user has to supply an estimated recovery fraction of applied fertilizers, i.e. the fraction of the fertilizer nutrient that is actually taken up by the vegetation. As in the experiments no data on nutrient uptake were determined, nor the soil chemical characteristics necessary for calculation of indigenous soil nutrient supply, as this stage, we have not further analyzed nutrient requirements.

Detailed nutrient data for spring maize and sunflower are presented in Tables 53 and 54.

Table 53. Fertilizer application for spring maize and the change in soil nutrient content in the 0-50 cm soil layer under sufficient irrigation in the Central Experimental Station in Shanxi province, North China (2004).

Elements	Fertilizer		Soil nutrient content		Uptake by crop and leaching
	level	Rate (kg ha^{-1})	Before sowing (kg ha^{-1})	After harvest (kg ha^{-1})	(kg ha^{-1})
N	High	276.0	1111.2	333.6	1053.6
	Medium	172.5	1188.0	537.6	822.9
	Low	103.5	993.6	458.4	638.7
P	High	126	47.8	108.9	64.9
	Medium	84	50.1	84.1	50
	Low	42	65.9	87.8	20.1
K	High	0	231.5	183.9	47.6
	Medium	0	217.0	208.0	9
	Low	0	220.3	203.8	16.5

Table 54. Fertilizer application for sunflower and the change in soil nutrient content in 0-50 cm soil layer under sufficient irrigation in the Central Experimental Station in Shanxi province, North China (2004).

Elements	Fertilizer		Soil nutrient content		Uptake by crop and leaching
	level	Rate (kg ha^{-1})	Before sowing (kg ha^{-1})	After harvest (kg ha^{-1})	(kg ha^{-1})
N	High	393.0	2078.4	3984.0	-1512.6
	Medium	270.0	1965.6	3403.2	-1167.6
	Low	147.0	1629.6	3792.0	-2015.4
P	High	144.0	131.8	198.8	77.0
	Medium	108.0	159.8	244.6	23.2
	Low	72.0	141.9	243.3	-29.4
K	High	60.0	244.1	211.6	92.5
	Medium	45.0	230.9	220.3	55.6
	Low	30.0	232.6	221.9	40.7

9. Conclusions

In Fenhe Irrigation District (FID), farmers can irrigate crops only once in conventional irrigation systems in dry years. To supplement water supply from the irrigation system, water is pumped on an individual farm basis from the groundwater. For the purpose of increasing revenue, farmers increasingly grow vegetables that need more irrigation water. However, the lack of water increasingly constrains increases in agricultural production. Moreover, the unreliability of water supply makes fertilizer management difficult. Therefore, improvements in water and nutrient management practices in crop production systems are urgently required in FID.

In this study, experiments from 1992 to 2004 were analyzed. Soil water dynamics, soil surface evaporation under shallow water table were discussed and simulated. Irrigation management under different hydrological conditions and water table management (depths: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 m) were discussed. Light-temperature characteristics of a new early maturing wheat variety were tested and possibilities for introducing this variety in study area were discussed. Vegetable experiments on irrigation management were introduced and effects of irrigation management and its economic benefits were analyzed. In addition, WOFOST crop growth simulation model were used to estimate potential and water-limited crop production in FID as a study case. To examine the variability in crop production for Fenhe Irrigation District, weather data (1961-2002) for Taiyuan (north Fenhe), Jiexiu (south Fenhe) and the central meteorological stations were used to simulate potential and water-limited winter wheat, spring maize and sunflower yields with the WOFOST simulation model. Main conclusions from the study are:

1. The results show maximum grain yields of 5842, 9769 and 2231 kg$\cdot$ha^{-1}, under adequate nutrient supply for winter wheat, spring maize and sunflower, respectively. Highest observed water use efficiencies (WUE) under these conditions, based on grain yield and total water input (rainfall + irrigation) were 17.8, 25.2 and 8.8 kg ha^{-1} mm^{-1} for winter wheat, spring maize and sunflower, respectively. The relation between water consumption and grain yield under different fertilizer inputs could be expressed by a logarithmic curve; the relation between water consumption and WUE for winter wheat could be expressed by a negative logarithmic curve. As spring maize and sunflower are growing in the rainy season, the relations between water consumption and water use efficiency are hardly significant, but for sunflower, crop yield and water use efficiency starts to decrease at water consumption values exceeding 310 mm, hence supplementary irrigation is not needed in high rainfall years.
2. Root zone (0-100 cm) soil water dynamics are influenced by capillary rise under shallow water table depths, for both winter wheat and spring maize. Soil water content varies more strongly under shallower water table depths, which leads to more uptake from the groundwater and higher water use. Percolation after irrigation or rainfall started later under deeper water tables. The relation between rate of soil surface evaporation and water table depth can be expressed by an exponential curve, while the relation between cumulative soil surface evaporation over the crop growing season and water table depth for winter wheat and spring maize could also be expressed by an exponential curve. The effects of shallow water table depths on crop growth and yield were mainly mediated through more profuse tillering and higher spike densities, but not through individual grain weight. Crop yields and WUE were highest for water table depths of 1.0 and 1.5 m for spring maize and winter wheat, respectively. WUE for winter wheat attained the highest values at water table depths of 1.0 m and was lower at both shallower and greater depths. Crop water requirements, calculated by the FAO method, were 405 and 391 mm for winter wheat and spring maize, respectively. On this basis, irrigation requirements for winter wheat and spring maize, aimed at realizing high crop yields, were calculated for shallow water table depths under varying rainfall regimes.
3. The new photo-insensitive and early-maturing wheat variety, Dongzao 5 (DZ5), matured 4-5 days earlier and showed a 20% higher yield than Jingdong 8 (JD8). Moreover, DZ5 uses less thermal time for ear differentiation and does not need vernalization and can thus be sown either before or after winter. The temperature limit for 50% seedling mortality was -14.9 °C, 1.8 °C higher than that for JD8. It is expected to over-winter safely in Beijing and the southern part of North China.
4. Results of the vegetable experiments show that efficient water use and economic benefits are best combined by applying small irrigation doses, e.g. 20~40 mm per application (except for water melon). Recommended doses are: sweet potato: 200 mm irrigation (total water consumption 400 mm), jequirity: 100 mm (total water

consumption 440 mm), sesame: 68 mm (total water consumption 350 mm), water melon/black bean: 188 mm (total water consumption 510 mm), muskmelon: 84 mm (total water consumption 270 mm), turnip: 250 mm (total water consumption 470 mm), sharo pepper: 110 mm (total water consumption 370 mm).

5. The WOFOST simulation model yielded an average total aboveground dry matter production under optimal conditions of 20 500 kg·ha^{-1} (10 500 kg·ha^{-1} in grain) for winter wheat, 27 110 kg·ha^{-1} (14 500 kg·ha^{-1} in grain) for spring maize and 11 650 kg·ha^{-1} (5 900 kg·ha^{-1} in grain) for sunflower. Potential production in Taiyuan was somewhat higher (winter wheat grain yield 1.6% higher, spring maize 3.4% higher, sunflower 2.3% higher) than in Jiexiu.
   Simulated grain yield under irrigated conditions was overestimated by 8.75% and 22.3% for spring maize and winter wheat, respectively, compared to measured yield. Simulated maximum leaf area indices and harvest indices were somewhat higher than observed value. Simulated grain yield and precipitation plus irrigation can be correlated by logarithmic curves for all three crops (correlation coefficients higher than 0.7).
   Crop production under water-limited (rainfed) conditions was low for all three crops, albeit acceptable for spring maize and sunflower, growing in the rainy season. For sunflower, simulated water-limited grain yields are logarithmically correlated to precipitation.
6. Anticipated developments in the agricultural sector will lead to a shift from cultivation of bulk products such as rice, wheat and maize, in view of the shift in consumer preferences and the continuing economic growth, to more remunerative high-value commodities, such as vegetables and fruits, and animal products, i.e. milk, meat, eggs, etc. As shown in the experiments reported in this report, vegetables (and the same holds for fruits), are high-intensity crops that require higher inputs, both in terms of water and in terms of nutrient elements.
7. The shift away from bulk products brings to the fore, the conflict between the dual objectives of the Chinese government of maintaining self-sufficiency in basic foodstuffs and reducing the income gap between the rural and the urban population. As China is now a full member of WTO, scope for policy measures is limited; it is doubtful therefore whether both objectives can be realized in the long run. In terms of water management this might mean that a choice will have to be made between the different water users in the Yellow river basin, i.e. agriculture, industrial and domestic. When industrial and domestic users will continue to receive priority, total agricultural production in Fenhe Irrigation District will decline.
8. As water availability from Fenhe reservoir is limited, farmer will increasingly resort to the use of groundwater for irrigation of the high-value commodities. Already there is a serious drop in groundwater table depths, and this will aggravate under the anticipated changes in structure of the agricultural sector. Whether this increased groundwater use can be restricted through economic measures such as water pricing is doubtful. The price of water required for full-cost recovery would be such that it would seriously affect the profitability of farm enterprises.
9. Expansion of the animal production sector which also will lead to high-intensity production activities involving import in the region of concentrate feed, to supplement the roughage that could be grown as an alternative to the current bulk food crops of low profitability, will lead to a surplus of nutrients, especially nitrogen and phosphorus. An active land use policy is then required to balance the intensity of the animal production systems and the associated manure production and the land area on which the manure can be applied as a fertilizer. Rules and regulations that would condition required licenses-to-produce for animals are the required.
10. In this report attention has focused on water use for agriculture. Increasingly, the requirements of water for ecosystem functions are stressed. In the Yellow river basin, including Fenhe River, these functions have largely been ignored in the past. More emphasis on this use is another serious threat to the agricultural sector, as it will reduce the availability of water for agricultural purposes.
11. There is therefore in Fenhe Irrigation District a need for formulation of water use paln, including the necessary enabling policy measures. This water use paln should not only take into account the bio-physical possibilities and constraints, but should also llook at the (socio-)economic consequences. When agricultural water availability is seriously declining, the livelihoods of (many of) the small farmers now dependent on Fenhe reservoir will be under pressure. It will then be absolutely necessary to take measures creating alternative employment in the region.

10. References

Adhikari, C., K.F. Bronson, G.M. Panuallah, A.P. Regmi, P.K. Saha, A. Dobermann, D.C. Olk, P.R. Hobbs & E. Pasuquin, 1999.
On-farm soil N supply and N nutrition in the rice-wheat system of Nepal and Bangladesh. Field Crops Res. 64, 273-286.

Aggarwal, P.K. & N. Kalra, 1994.
Analyzing the limitations set by climatic factors, genotype, and water and nitrogen availability on productivity of wheat II. Climatically potential yields and management strategies. Field Crops Res. 38, 93–103.

Allen, R.G., L.S. Pereira, D. Raes & M. Smith, 1998.
Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy.

Alocilja, E.C. & J.T. Richie, 1988.
Upland rice simulation and its use in multicriteria optimization. University of Hawaii and Michigan State University, IBSNAT. 95 pp.

Austin, R.B., 1994.
Plant breeding opportunities. In: Boote, K.J., Bennett, J.M., Sinclair, T.R. and Paulsen, G.M. (Eds.), Physiology and determination of crop yield. ASA, CSSA and SSSA, Madison, Wi, USA. pp. 567-586.

Babijiang, B., D.W. Zheng, Y.M. Jia, Ch.B. Wu & G. Ren, 2004a.
Influence of water table on winter wheat soil water and crop yield. J. Water Saving Irr. 5, 5-9. (Chinese with English abstract)

Babijiang, B., D.W. Zheng, H. Kerime, Ch. Meng, Zh.Sh. Wang & J.Q. Qiu, 2004b.
Influence of water table on spring maize soil water and crop yield. J. Soil and Water Cons. 18, 57-69. (Chinese with English abstract)

Becker, M., D.E. Johnson, M.C.S. Wopereis & A.Sow, 2003.
Rice yield gaps in irrigated systems along an agro-ecological gradient in West Africa. J. Plant Nutr. Soil Sci. 166, 61-67.

Boogaard, H.L., C.A. van Diepen, R.P. Roetter, J.M.C.A. Cabrera & H.H. van Laar, 1998.
WOFOST 7.1 User's guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center 1.5, Alterra, Wageningen. 143 pp.

Bouman, B.A.M., H. van Keulen, H.H. van Laar & R. Rabbinge, 1996.
The 'School of de Wit' crop growth simulation models: A pedigree and historical overview. Agric. Syst. 52, 171-198.

Bouman, B.A.M., M.J. Kropff, T.P. Tuong, M.C.S. Wopereis, H.F.M. ten Berge & H.H. van Laar, 2001.
ORYZA2000: modelling lowland rice. International Rice Research Institute, Los Baños. 235 pp.

Drenth, H., H.F.M. ten Berge & J.J.M. Riethoven, 1994.
ORYZA simulation modules for potential and nitrogen limited rice production. SARP Research Proceedings, IRRI/AB-DLO, Wageningen. 223 pp.

Fischer, R.A. & R. Maurer, 1976.
Crop temperature modification and yield potential in a dwarf spring wheat. Crop Sci. 16, 855-859.

Foltescu, V.L., 2000.
Prediction of crop yield in Sweden based on mesoscale meteorological analysis. Meteorol. Appl. 7, 313-321.

Goudriaan, J., H. van Keulen & van H.H. Laar, 1997.
SUCROS1: Crop growth model for potential production. In: Goudriaan, J., van Keulen, H. and van Laar, H.H. (Eds.) SUCROS97: Simulation of crop growth for potential and water-limited production situations as applied to spring wheat. Quantitative Approaches in Systems Analysis No. 14. DLO-Research Institute for Agrobiology and Soil Fertility and C.T. de Wit Graduate School for Production Ecology, Wageningen, The Netherlands. 52 pp. + Ann.

Jame, Y.W. & H.W. Cutforth, 1996.
Crop growth models for decision support systems. Can. J. Plant Sci. 76, 9–19.

Jamieson, P.D., J.R. Porter, J. Goudriaan, J.T. Ritchie, H. van Keulen & W. Stol, 1998.
A comparison of the models AFRCWHEAT 2, CERES-Wheat, Sirius, SUCROS 2 and SWHEAT with measurements from wheat grown under drought. Field Crops Res. 55, 23-44.

Janssen, B.H, F.C.T. Guilking, D. van der Eijk, E.M.A. Smaling, J. Wolf & H.van Reuler, 1990.
A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, 299-318.

Jones, C.A. & J.R. Kiniry, 1986.
CERES-Maize. A Simulation Model of Maize Growth and Development, Texas A&M University Press, College Station, Temple. 194 pp.

Jones, C.A., J.T. Ritchie, J.R. Kiniry, D.C. Godwin & S.I. Otter, 1984.
The CERES wheat and maize models. In: (ICRISAT) Proceedings International Symposium on Minimum Data Sets for Agrotechnology Transfer. ICRISAT, Patancheru, India. pp. 95-100.

Kabat, P., B. Marshall & B.J. Van den Broek, 1995.
Comparison of simulation results and evaluation of parameterization schemes. In: P. Kabath, B. Marshall, B.J. van den Broek, J. Vos & H. van Keulen, (Eds), Modelling and parameterization of the soil-plant-atmosphere system – a comparison of potato growth models. Wageningen Press, Wageningen, The Netherlands. pp. 439-499.

Karthikeyan, R., G. Hoogenboom & R.W. McClendon, 1996.
Regional yield forecasting using crop models and GIS: A conceptual framework. An ASAE meeting presentation, Phoenix, Arizona, Paper No. 96-5010

Kropff, M.J., H.H. van Laar & H.F.M. ten Berge, (Eds.), 1993.
ORYZA1 A basic model for irrigated lowland rice production. IRRI, Los Baños, The Philippines.

Mastrorilli, M., N.Keterji & B. Ben Nouma, 2003.
Using the CERES-Maize model in a semi-arid Mediterranean environment. Validation of three revised versions. Eur. J. Agron. 19, 125-134.

Matthews, R.B., 2003.
Crop management. In: Matthews, R. and Stephens, W. (Eds.). Crop-Soil Simulation Models. Applications in Developing Countries, CABI Publishing, New York, USA. pp. 29-54.

Merriam-Webster, 1998.
Merriam-Webster's Collegiate Dictionary. 10th Edition. Merriam-Webster, Springfield, MA.

Monteith, J.L., 1996.
The quest for balance in crop modeling. Agron. J. 88, 695–697.

Nix, H.A., 1976.
Climate and crop production in Australia. In: Yoshida, S. (Ed.), Climate and rice. IRRI, Los Baños, Philippines. pp. 495-507.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema, 1989.
Simulation of ecophysiological processes of growth in several annual crops. Simulation Monographs, Pudoc, Wageningen. 271 pp.

Pinnschmidt, H. O., V. Chamarerk, N. Cabulisan, F. Dela Pena, N. D. Long, S. Savary, H.W. Klein-Gebbinck & P.S., Teng, 1997.
Yield gap analysis of rainfed lowland systems to guide rice crop and pest management. In: Kropff, M. J., Teng, P. S., Aggarwal, P. K., Bouma, J., Bouman, B. A. M., Jones, J. W. and van Laar, H. H. (Eds.) Application of systems approaches at the field level. Systems Approaches for Sustainable Agricultural Development, Vol. 2, Kluwer Acad. Publ., Dordrecht, the Netherlands. pp. 321-338.

Ritchie, J.T. & S. Otter, 1985.
Description and performance of CERES-Wheat: A user-oriented wheat yield model. ARS-38, USDA-ARS. Temple. pp. 159-175.

Roetter, R., P.K. Aggarwal, P.S. Tan, C.T. Hoanh, J.M.C.A. Cabrera & B. Nunez, 1998.
Use of crop simulation models and alternative yield estimation techniques for optimizing agricultural land use and resource management. In: Roetter R., Hoanh, C. T., Luat, N. V., Van Ittersum, M. K. and Van Laar, H. H. (Eds.) SysNet Research Paper Series No. 1, IRRI, Los Baños, Philippines. pp. 15-29.

Rijsberman, F.R., 2004.
Water scarcity: fact or fiction? In: Fischer, T., Turner, N., Angus, J., McIntyre, L., Robertson, M., Borrell, M. and Lloyd, D. (Eds.), New directions for a diverse planet: Proceedings for the 4th International Crop Science Congress, Brisbane, Australia, 26 September – 1 October 2004. The proceedings are available online at: www.cropscience.org.au.

RWCMWR (Department of Rural Area, Ministry of Water Resources P. R. China), 1994.
Irrigation management enchiridion. Water Conservancy and Electric Power Press, Beijing, China.

SBSP (Statistical Bureau of Shanxi Province), 2002.
Shanxi Statistical Yearbook-2002: Agricultural economics sector. China Statistical Press, Beijing, China.

Sinclair, T.R. & N. G. Seligman, 2000.
Criteria for publishing papers on crop modeling. Field Crops Res. 68, 165-172.

Spitters, C.J.T., H. van Keulen & D.W.G. van van Kraalingen, 1989.
A simple and universal crop growth simulator: SUCROS87. In: Rabbinge, R., Ward, S.A. and van Laar, H.H. (Eds.) Simulation and systems management in crop protection. Simulation Monographs, Pudoc, Wageningen, The Netherlands. pp 147–181.

Van Keulen, H., 1975.
Simulation of water use and herbage growth in arid regions. Simulation Monographs, Pudoc, Wageningen. 175 pp.

Van Keulen, H. & N.G. Seligman, 1987.
Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen, The Netherlands. 310 pp.

Van Keulen, H. & J. Wolf, (Eds.), 1986.
Modelling of agricultural production: weather, soils and crops, Simulation Monographs, Pudoc, Wageningen. 479 pp.

Van Keulen, H., N.G. Seligman & R.W. Benjamin, 1981.
Simulation of water use and herbage growth in arid regions - A re-evaluation and further development of the model 'Arid Crop'. Agric. Syst. 6, 159-193.

Wang, Y.R. & X.P. Cun 2003.
Agricultural water-saving theories and high efficient water use methods of Shanxi Province. China Science and Technology Press, Beijing. pp. 25-30.

Witt, C., A. Dobermann, S. Abdulrachman, H.C. Gines, Wang Guanghuo, R. Nagarajan, S. Satawatananont, Tran Thuc Son, Pham Sy Tan, Le Van Tiem, G.C. Simbahan & D.C. Olk, 1999.
Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63, 113-138.

Wolf, J., 1993.
Effects of climate change on wheat production potential in the European Community, Eur. J. Agron. 2, 281-292.

Wolf, J. & C.A. van Diepen, 1995.
Effect of climate change on grain maize yield potential in the European Community. Climate Change 29, 299-331.

Wopereis, M.C.S., B.A.M. Bouman, T.P. Tuong, H.F.M. ten Berge & M.J. Kropff, 1996.
ORYZA_W: Rice growth model for irrigated and rainfed environments. SARP Research Proceedings. IRRI/AB-DLO, Wageningen. 159 pp.

Yun, J.I., 2003.
Predicting regional rice production in South Korea using spatial data and crop-growth modelling. Agric. Syst. 77, 23-28.

Appendix I.
List of abbreviations

AMAXTB	Maximum leaf CO_2 assimilation rate as a function of development stage of the crop (kg/ha/h)
CES	Central Experimental Station
CONTAB	10-log hydraulic conductivity as function of pF [log (cm); log (cm/d)]
CRAIRC	Critical soil air content for aeration (cm^3/cm^3)
CVL	Conversion efficiency of assimilates into leaf tissue (kg/kg)
CVO	Conversion efficiency of assimilates into storage organs (kg/kg)
CVR	Conversion efficiency of assimilates into root tissue (kg/kg)
CVS	Conversion efficiency of assimilates into stem tissue (kg/kg)
DUR	Duration of simulation period (d)
EFFTB	Initial light-use efficiency of CO_2-assimilation rate of single leaves as function of daily temperature [(kg/ha/h) per $J/m^2/s$)]
EVSOL	Evaporation rate from soil or from water stored on soil surface (mm/d)
FID	Fenhe Irrigation District
GASST	Gross assimilation rate (kg (CO_2)/ha/d)
HALT	Day number at harvest (Julian calendar day)
HINDEX	Harvest index: weight of storage organs/weight of total aboveground material (kg/kg)
K0	Saturated soil hydraulic conductivity (cm/day)
KDIFTB	Extinction coefficient for diffuse visible light as function of development stage
KSUB	Maximum percolation rate subsoil (cm/d)
LAIM	Maximum leaf area index (ha/ha)
MaxTWLV	Maximum TWLV (kg/ha)
MaxTWST	Maximum TWST (kg/ha)
MLAI	LAI-value at maturity
MREST	Maintenance respiration rate (kg (CO_2)/ha/d)
MTAGP	TAGP at maturity (kg/ha)
MWSO	TWSO at maturity (kg/ha)
MWST	TWST at maturity (kg/ha)
RDI	Initial rooting depth (cm)
RDRRTB	Relative death rate of roots as a function of development stage (kg/kg/d)
RDRSTB3	Relative death rate of stems as a function of development stage (kg/kg/d)
RDMCR	Maximum rooting depth (cm)
RDMSOL	Maximum rooting depth as dictated by soil characteristics (cm)
RGRLAI	Maximum relative increase in LAI (ha/ha/d)
RML	Relative maintenance respiration rate leaves [kg (CH_2O)/kg/d]
RMO	Relative maintenance respiration rate storage organs [kg (CH_2O)/kg/d]
RMR	Relative maintenance respiration rate roots [kg (CH_2O)/kg/d]
RMS	Relative maintenance respiration rate stems [kg (CH_2O)/kg/d]
SLATB	Specific leaf area as a function of development stage (ha/kg)
SMFCF	Soil moisture content at field capacity (cm^3/cm^3)
SMLIM	Initial maximum moisture content in initial rooting depth (cm^3/cm^3)
SMO	Soil moisture content at saturation (cm^3/cm^3)
SMTAB	Volumetric soil moisture content as function of pF [log (cm); (cm^3/cm^3)]
SMW	Soil moisture content at wilting point (cm^3/cm^3)
SOPE	Maximum percolation rate root zone (cm/d)
SPAN	Life span of leaves growing at 35°C (d)
TAGP	Total aboveground production (dead and living plant organs) (kg/ha)
TDWI	Initial total crop dry weight (kg/ha)

TMNFTB	Reduction factor of gross assimilation rate as function of average temperature
TRANSP	Transpiration rate (mm/d)
TRC	Transpiration coefficient (kg (H_2O)/kg dry matter)
TSUM1	Thermal time from emergence to anthesis (°C d)
TSUM2	Thermal time from anthesis to maturity (°C d)
TSUMEM	Thermal time from sowing to emergence (°C d)
TWLV	Total dry weight of leaves (dead and living) (kg/ha)
TWRT	Total dry weight of roots (dead and living) (kg/ha)
TWSO	Total dry weight of storage organs (dead and living) (kg/ha)
TWST	Total dry weight of stems (dead and living) (kg/ha)
WAV	Initial available water in total potential root zone (mm, moisture content above wilting point)

Appendix II.
WOFOST Model Simulation Results

Potential winter wheat production for (the northern part, Taiyuan, of) Fenhe Irrigation District (1961-2002)

YEAR	DUR* /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	173	1018	2308	6570	8813	17691	5.58	0.5	205	31899	7835	36.3	19.7
1962	181	1029	2508	6581	11082	20171	6.03	0.55	179	35491	8290	36	23.2
1963	180	1031	2430	5922	11100	19451	5.87	0.57	149	33829	7601	29.1	19.1
1964	180	1208	2745	6908	12565	22218	6.49	0.57	154	38860	8785	34.3	15.9
1965	181	1299	3045	7568	10597	21209	7.05	0.5	188	38392	9350	39.8	20.8
1966	175	1116	2568	6877	10996	20440	6.17	0.54	192	36207	8508	39.2	20.4
1967	177	1538	3536	7193	11316	22044	7.78	0.51	176	40214	9772	38.8	17.7
1968	179	1485	3458	7504	11994	22956	7.66	0.52	171	41367	9839	39.3	18.9
1969	179	1104	2504	6520	11857	20881	6.07	0.57	176	36624	8434	36.7	20.3
1970	185	1230	2815	6965	11062	20842	6.63	0.53	171	36993	8595	35.6	22.2
1971	179	1436	3314	7266	11562	22141	7.5	0.52	195	40066	9664	43.2	20.4
1972	178	942	2126	6724	10316	19167	5.17	0.54	197	33544	7748	37.8	22.5
1973	172	1300	2991	7403	12562	22957	6.93	0.55	180	40498	9291	41.4	18.3
1974	177	1379	3347	7540	11880	22766	7.52	0.52	191	41041	9910	43.4	20.8
1975	179	1060	2424	7106	10022	19553	5.84	0.51	180	34916	8399	35.2	21.6
1976	185	1573	3806	7482	11760	23048	8.17	0.51	178	41867	10064	40.9	17.7
1977	176	1251	2936	8218	11251	22406	6.8	0.5	167	39832	9309	37.4	19.8
1978	174	1077	2550	7050	9687	19287	6.11	0.5	175	34348	8131	33.7	20.7
1979	180	1033	2405	7358	9750	19513	5.79	0.5	163	34547	8095	31.8	19.1
1980	180	1409	3462	8061	9693	21217	7.62	0.46	178	39157	9855	37.8	18.2
1981	176	1528	3607	8816	9691	22114	7.9	0.44	163	40732	10046	36	16.5
1982	173	1380	3247	7709	11095	22051	7.36	0.5	167	39810	9564	36.8	15.4
1983	180	1438	3285	6836	10314	20434	7.36	0.5	156	37495	9271	31.8	16.1
1984	183	1508	3432	7022	9991	20445	7.64	0.49	141	37299	8927	28.8	15.8
1985	178	1438	3171	7228	10446	20845	7.18	0.5	151	37924	9160	31.5	15.9
1986	177	1390	3280	7042	9877	20199	7.46	0.49	153	36622	8741	30.9	15.9
1987	177	1144	2707	6604	10315	19626	6.44	0.53	151	34785	8077	29.6	16.3
1988	181	1535	3301	6860	10299	20460	7.29	0.5	159	37800	9401	32.5	16.7
1989	178	1362	3097	7040	10545	20682	7.03	0.51	139	37203	8776	28.7	13
1990	180	912	2059	6444	10039	18541	5.02	0.54	147	32316	7381	27.2	15.1
1991	182	1268	3172	6606	10611	20389	7.3	0.52	151	36559	8671	30.8	15.3
1992	177	1252	2783	7424	10712	20918	6.51	0.51	158	37417	8849	33.1	15.9
1993	176	1161	2543	7107	10110	19761	6.04	0.51	158	35768	8834	31.3	14.5
1994	175	1072	2359	6369	9211	17939	5.73	0.51	193	32536	8101	34.6	22.3
1995	178	1014	2367	6800	10443	19611	5.83	0.53	178	34891	8359	34.8	22.2
1996	182	1235	2889	7199	9900	19989	6.75	0.5	168	36130	8758	33.5	20
1997	171	1788	4037	7756	11877	23670	8.32	0.5	174	43668	10726	41.3	13.1
1998	168	872	1918	5371	11574	18863	4.69	0.61	146	32006	6850	27.5	15.8
1999	167	1111	2584	6952	9827	19362	6.2	0.51	170	34975	8622	32.9	17.4
2000	171	1220	2841	7147	10033	20021	6.67	0.5	174	36341	8961	34.9	16.6
2001	169	991	2265	6734	9883	18881	5.49	0.52	182	33610	8086	34.4	17.5
2002	166	1019	2146	5779	10868	18792	5.2	0.58	133	32859	7515	25.0	13.8
Average	177	1242	2866	7040	10655	20561	6.6	0.52	169	36868	8789	34.7	18.1

Potential winter wheat production for (the southern part, Jiexiu, of) Fenhe Irrigation District (1961-2002)

YEAR	DUR /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	170	1256	2851	7093	8722	18666	6.68	0.47	189	34389	8656	35.2	15.9
1962	176	801	1785	6045	9933	17762	4.22	0.56	175	30634	6901	31	24.4
1963	178	1234	2936	6862	10179	19978	6.82	0.51	141	35890	8564	28.2	16.7
1964	178	1225	2698	6834	12396	21929	6.37	0.57	135	38421	8696	29.7	12.5
1965	177	1371	3206	7352	11065	21623	7.28	0.51	170	39089	9432	36.7	16.5
1966	171	974	2252	6404	11385	20041	5.47	0.57	169	34817	7901	34	19
1967	175	1546	3524	6979	9774	20278	7.74	0.48	178	37905	9683	36	15.2
1968	177	1436	3428	7537	11417	22381	7.61	0.51	168	40482	9742	37.5	18.7
1969	175	1144	2583	6461	11593	20637	6.22	0.56	166	36356	8411	34.2	17.2
1970	181	1381	3087	7363	10980	21430	7.06	0.51	161	38446	9026	34.6	19.8
1971	174	1477	3345	7280	10823	21448	7.48	0.5	198	39216	9619	42.4	17.7
1972	176	977	2163	6733	9494	18389	5.26	0.52	190	32903	8024	34.9	19.4
1973	169	1226	2824	7218	12294	22337	6.68	0.55	172	39359	9071	38.5	17.3
1974	173	1432	3363	8013	10828	22204	7.5	0.49	191	40514	9959	42.4	18
1975	175	1057	2415	7079	9516	19010	5.83	0.5	162	34190	8359	30.8	19.5
1976	182	1384	3396	7599	11081	22077	7.58	0.5	161	40082	9794	35.5	16.6
1977	170	1244	2849	8005	11407	22261	6.63	0.51	143	39469	9167	31.9	16.6
1978	171	1240	2896	7514	9633	20043	6.76	0.48	164	36256	8778	32.9	18.2
1979	177	973	2179	7244	9939	19362	5.24	0.51	147	33948	7805	28.4	19.4
1980	176	1419	3485	8407	9341	21233	7.68	0.44	162	39016	9642	34.3	15.5
1981	171	1281	3033	7682	10088	20803	7.08	0.48	165	37603	9083	34.3	15.9
1982	170	1324	3143	7393	10282	20819	7.21	0.49	166	37916	9333	34.5	14.2
1983	178	1539	3439	7280	10168	20888	7.54	0.49	147	38731	9733	30.8	14.6
1984	179	1436	3242	7005	9622	19869	7.33	0.48	136	36262	8734	26.9	14.4
1985	175	1276	2948	6752	10547	20247	6.93	0.52	154	36448	8733	31.3	15.6
1986	175	1575	3683	7300	10119	21103	7.94	0.48	150	38671	9326	31.6	16.1
1987	171	864	1967	6041	10037	18044	4.72	0.56	145	30930	6735	26.2	19.2
1988	178	1523	3371	6673	10060	20104	7.34	0.5	162	37352	9427	32.5	17.2
1989	176	1312	3036	6936	10502	20474	6.93	0.51	156	36542	8464	31.9	14.2
1990	180	955	2151	6709	9966	18826	5.26	0.53	172	33295	7905	32.5	16.6
1991	179	1033	2522	6844	10082	19448	6.06	0.52	150	34336	8005	29.2	16.6
1992	177	1323	3001	7538	11458	21997	6.92	0.52	151	39420	9366	33.3	15.9
1993	172	1042	2237	6300	10723	19260	5.4	0.56	175	34094	8069	33.8	17.5
1994	174	1013	2242	6333	10297	18873	5.47	0.55	183	33360	7857	34.5	23.7
1995	176	1073	2565	7132	10371	20068	6.17	0.52	188	35841	8644	37.8	22.8
1996	182	1193	2802	7547	9658	20007	6.56	0.48	180	36142	8782	36	21.7
1997	171	1710	3916	7780	12438	24133	8.18	0.52	185	43963	10563	44.5	14.6
1998	170	929	2054	5662	12137	19853	5.04	0.61	162	33887	7367	32.2	18.9
1999	167	1076	2523	7180	9970	19673	6.08	0.51	175	35283	8576	34.3	18.8
2000	170	1183	2817	7263	9869	19949	6.65	0.49	188	36118	8873	37.5	16.9
2001	167	1114	2546	7215	9998	19759	6.1	0.51	175	35552	8677	34.5	17.7
2002	166	1006	2293	6725	10251	19270	5.55	0.53	150	33981	7946	28.8	15.4
Average	174	1228	2828	7079	10487	20394	6.54	0.51	166	36598	8748	33.8	17.4

Potential spring maize production for (the northern part, Taiyuan, of) Fenhe Irrigation District (1961-2002)

YEAR	DUR /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	100	2056	3564	7501	13391	24456	6.42	0.55	129	43883	9824	31.5	14.2
1962	106	2723	4658	8608	15039	28305	7.43	0.53	127	51588	11435	36	12.9
1963	106	2525	4349	9097	13374	26820	7.05	0.5	126	49252	11186	33.9	11.8
1964	112	3063	5014	8446	14173	27634	7.79	0.51	131	52136	12144	36.1	12.1
1965	107	3035	5100	9570	16821	31491	7.78	0.53	136	57438	12790	42.7	13.8
1966	109	2658	4508	8639	14633	27780	7.29	0.53	130	50761	11378	36	13.6
1967	103	2863	4677	9121	11702	25499	7.52	0.46	140	49185	11746	35.6	13.2
1968	108	3298	5508	10228	15556	31291	8.14	0.5	130	58549	13481	40.8	12.8
1969	110	3236	5251	10257	16053	31561	7.91	0.51	122	58407	13127	38.5	13.1
1970	110	2751	4770	10127	14608	29504	7.46	0.5	130	53919	12064	38.3	13.8
1971	106	2837	4755	9296	14009	28060	7.44	0.5	130	52248	12079	36.4	14.6
1972	106	2529	4318	8275	14230	26823	7	0.53	144	49157	11212	38.8	14.9
1973	109	2605	4536	9153	13763	27452	7.13	0.5	128	50576	11565	35	13.3
1974	106	3011	5139	10111	15445	30696	7.68	0.5	130	56572	12791	39.8	13.4
1975	104	2524	4252	8710	13831	26793	6.87	0.52	137	49378	11445	36.8	14.6
1976	113	2854	4882	9400	13529	27811	7.55	0.49	127	51491	11516	35.4	13
1977	110	2504	4229	8483	13449	26160	6.9	0.51	121	47951	10827	31.7	13
1978	105	2216	3966	8573	13317	25857	6.75	0.52	124	46653	10398	32.1	13
1979	109	2305	4085	8825	13651	26561	6.79	0.51	122	47879	10587	32.4	13.2
1980	106	2527	4460	9390	16505	30355	7.07	0.54	142	53848	11563	43.1	13.5
1981	105	2214	3888	7845	13167	24901	6.69	0.53	123	45113	10113	30.6	12.3
1982	109	2573	4478	9629	12646	26753	7.15	0.47	121	49329	11141	32.3	11.1
1983	110	2255	3958	8668	14769	27395	6.71	0.54	114	48664	10550	31.2	11.8
1984	112	2168	3866	8108	16094	28068	6.62	0.57	112	48834	10177	31.5	11.3
1985	107	2467	4247	8721	14511	27480	6.92	0.53	112	49734	11079	30.7	11.4
1986	109	2368	4233	9025	16611	29869	6.97	0.56	112	52342	11004	33.4	11.2
1987	110	2243	4092	9242	16261	29596	6.87	0.55	112	51736	10929	33.1	12
1988	110	2370	4109	8101	12050	24260	6.82	0.5	115	44675	10064	27.8	11.2
1989	111	2223	3750	7616	13966	25333	6.46	0.55	113	45420	10000	28.6	11.4
1990	108	2347	4011	8148	14483	26642	6.77	0.54	120	48082	10764	32	12.4
1991	105	2131	3750	7903	13177	24831	6.55	0.53	129	44944	10199	31.9	12
1992	107	2513	4373	9012	13169	26553	7.06	0.5	129	49093	11357	34.2	12.3
1993	114	2208	3954	8441	16075	28469	6.65	0.56	108	49709	10441	30.7	11.7
1994	100	1822	3388	7473	15287	26147	6.22	0.58	120	45180	9564	31.4	14.8
1995	106	2403	4158	8087	12424	24670	6.84	0.5	135	45805	10650	33.3	12.9
1996	109	2296	4009	8578	11950	24537	6.72	0.49	123	45277	10428	30.2	12.5
1997	99	2529	4253	8679	12472	25404	6.94	0.49	148	47859	11543	37.7	14.6
1998	102	2277	3956	7477	13403	24836	6.76	0.54	130	45421	10428	32.4	12.8
1999	99	2076	3741	8167	13991	25900	6.55	0.54	123	46363	10416	31.8	13.2
2000	101	2016	3575	8045	12380	24000	6.4	0.52	123	43442	9891	29.4	12.9
2001	99	2084	3717	7775	14294	25785	6.58	0.55	147	45950	10191	37.8	13.8
2002	103	1953	3550	8045	14844	26438	6.38	0.56	103	46385	10090	27.2	11.8
Average	107	2468	4264	8681	14169	27114	6.99	0.52	126	49291	11052	34.1	12.8

Potential spring maize production for (the southern part, Jiexiu, of) Fenhe Irrigation District(1961-2002)

YEAR	DUR /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	98	1971	3386	7586	12635	23607	6.15	0.54	117	42424	9678	27.6	12.9
1962	104	2571	4391	8054	14737	27182	7.14	0.54	117	49267	11010	31.9	12.5
1963	103	2444	4187	8891	12827	25905	6.92	0.5	119	47533	10916	30.8	10.9
1964	110	2934	4867	8128	14133	27128	7.6	0.52	115	50740	11821	31.2	11
1965	103	2732	4643	9000	16506	30149	7.31	0.55	118	54091	11907	35.7	12.6
1966	105	2418	4144	8121	14449	26715	6.93	0.54	118	48023	10623	31.4	12.4
1967	99	2543	4403	8863	11571	24836	7.06	0.47	129	46670	11072	32	13.6
1968	106	3093	5203	9870	15676	30749	7.94	0.51	118	56718	12964	36.4	11.9
1969	103	2933	4843	9359	14844	29045	7.57	0.51	123	53467	12153	35.8	13.2
1970	108	2749	4747	9939	13647	28332	7.44	0.48	126	52313	12050	35.8	12.5
1971	105	2650	4395	9015	13785	27195	7.17	0.51	121	50300	11781	32.9	13.5
1972	101	2231	3866	7806	13757	25429	6.63	0.54	134	45815	10340	34.2	14
1973	104	2275	4035	8566	13598	26199	6.82	0.52	125	47355	10742	32.7	13
1974	102	2855	4891	9624	14882	29397	7.49	0.51	128	54013	12340	37.6	13.8
1975	101	2206	3819	8226	13936	25981	6.61	0.54	120	46758	10636	31.1	13.2
1976	108	2697	4626	8812	12501	25939	7.33	0.48	123	48356	11167	31.8	11.7
1977	106	2212	3773	8028	13247	25048	6.56	0.53	109	44957	9963	27.3	12
1978	101	2011	3644	7757	13260	24661	6.48	0.54	117	43781	9615	28.9	12
1979	108	2202	3886	8473	13649	26007	6.68	0.52	113	46435	10226	29.5	11.5
1980	105	2377	4229	9218	16297	29744	6.93	0.55	132	52360	11294	39.3	12.4
1981	103	1953	3536	7741	12852	24129	6.38	0.53	116	42983	9568	27.9	12.6
1982	105	2343	4105	8888	12454	25447	6.81	0.49	118	46306	10402	30.1	11.1
1983	106	2137	3747	8122	14299	26168	6.57	0.55	112	46285	10088	29.3	11.3
1984	111	2022	3653	7933	16136	27722	6.46	0.58	100	47635	9854	27.6	11
1985	103	2245	3905	8249	13920	26075	6.67	0.53	117	46818	10493	30.4	11.9
1986	107	2231	4009	8735	16012	28756	6.78	0.56	111	50206	10660	31.9	11
1987	104	2079	3762	8536	14745	27044	6.6	0.55	113	47454	10254	30.6	11.3
1988	107	2308	4013	7968	11554	23535	6.78	0.49	113	43329	9872	26.6	11
1989	111	2119	3737	7320	14340	25396	6.52	0.56	120	44954	9799	30.5	12.3
1990	104	2134	3686	7500	14178	25364	6.52	0.56	128	45228	10086	32.4	14.3
1991	103	2034	3567	7472	13246	24286	6.37	0.55	132	43435	9746	32.1	11.9
1992	106	2452	4213	8726	13000	25940	6.9	0.5	132	47847	11189	34.2	12.3
1993	112	2100	3790	8128	15880	27799	6.55	0.57	115	48163	10097	32	13.2
1994	102	1784	3268	7576	15618	26463	6.09	0.59	121	45205	9442	32.1	15.2
1995	104	2333	4007	7515	12363	23885	6.74	0.52	147	44000	10164	35	13.4
1996	109	2303	3878	8246	11876	24001	6.6	0.49	135	44161	10186	32.4	13.2
1997	98	2491	4194	8451	12856	25502	6.91	0.5	163	47400	11245	41.5	15.7
1998	100	2194	3802	7357	12823	23982	6.62	0.53	145	43796	10153	34.7	14.3
1999	98	1967	3574	8077	13599	25251	6.41	0.54	139	44974	10167	35	15.5
2000	100	1935	3398	7673	12006	23077	6.24	0.52	133	41672	9577	30.7	14.3
2001	96	1949	3448	7208	13691	24347	6.32	0.56	133	43257	9704	32.5	14.1
2002	100	1923	3473	7602	14247	25321	6.29	0.56	117	44642	9924	29.6	13.1
Average	104	2313	4018	8294	13848	26160	6.8	0.53	123	47170	10594	32.2	12.7

Potential sunflower production for (the northern part, Taiyuan, of) Fenhe Irrigation District (1961-2002)

YEAR	DUR /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	94	3278	2203	3335	6185	11723	6.69	0.53	264	30468	7066	31	5.8
1962	99	3236	2153	3510	6077	11740	6.38	0.52	245	30257	6923	28.8	5.8
1963	95	3501	2216	3338	4943	10497	6.69	0.47	272	28419	6944	28.6	6.1
1964	100	3336	2255	3434	5595	11285	6.69	0.5	248	29351	6726	28	5.8
1965	97	3830	2512	3922	6554	12988	6.95	0.5	286	33956	7852	37.2	7.1
1966	99	3219	2167	3562	6727	12456	6.54	0.54	250	31647	7060	31.2	6.5
1967	100	3331	2144	3255	5346	10744	6.44	0.5	261	28367	6613	28	6.2
1968	98	3779	2446	3974	5893	12313	6.9	0.48	270	32593	7776	33.3	6.7
1969	102	3571	2342	3710	6544	12596	6.83	0.52	248	32721	7530	31.2	5.9
1970	101	3846	2370	3627	6133	12130	6.73	0.51	291	32387	7645	35.3	6.7
1971	98	3460	2334	3498	6305	12137	6.81	0.52	261	31513	7230	31.6	5.6
1972	100	3281	2170	3430	6921	12521	6.48	0.55	292	31974	7137	36.6	7.1
1973	100	3881	2489	3653	5305	11447	6.98	0.46	264	30731	7248	30.2	5.4
1974	101	3743	2386	3718	6811	12915	6.87	0.53	257	33810	7825	33.2	5.9
1975	93	3413	2262	3558	5301	11121	6.62	0.48	275	29751	7366	30.6	6.2
1976	106	3540	2275	3483	6327	12084	6.52	0.52	235	31384	7051	28.4	6.1
1977	97	3040	1916	3228	6140	11284	5.91	0.54	247	29070	6618	27.9	6
1978	97	3438	2248	3407	5567	11222	6.69	0.5	248	29436	6772	27.9	5.9
1979	104	3421	2225	3344	6701	12270	6.6	0.55	243	31613	7032	29.8	5.2
1980	101	3940	2645	4069	6588	13302	7.29	0.5	304	34524	7817	40.4	5.9
1981	95	3393	2170	3324	5578	11071	6.45	0.5	258	29298	6901	28.5	5.5
1982	104	3581	2260	3492	6220	11972	6.45	0.52	235	31135	6945	28.1	5.6
1983	98	3455	2259	3555	5952	11765	6.59	0.51	235	30755	7138	27.6	5.7
1984	103	3444	2269	3676	6583	12528	6.69	0.53	242	32281	7342	30.3	5.2
1985	102	3520	2317	3583	5888	11789	6.66	0.5	224	30703	6992	26.4	5.2
1986	101	3893	2532	3850	6821	13203	7.06	0.52	241	34569	7944	31.8	5.7
1987	98	3970	2516	3889	6466	12871	6.86	0.5	252	34118	8024	32.5	5.4
1988	99	3103	1970	2854	5965	10789	6.13	0.55	221	28163	6411	23.9	5.4
1989	99	3231	2118	3351	6047	11516	6.33	0.53	223	29841	6844	25.7	5.5
1990	95	3486	2313	3696	5642	11652	6.78	0.48	254	30791	7417	29.6	5.4
1991	91	3460	2339	3552	5325	11215	6.85	0.47	274	29982	7396	30.7	6
1992	100	3573	2314	3469	5930	11712	6.77	0.51	249	30994	7304	29.1	6.1
1993	107	3755	2403	3774	6750	12927	6.7	0.52	220	33671	7676	28.5	5
1994	93	3487	2314	3626	6285	12225	6.77	0.51	257	32057	7613	31.4	5.8
1995	97	3286	2081	3198	5516	10795	6.25	0.51	261	28550	6716	28.2	6.8
1996	97	3187	1971	3233	5624	10827	5.95	0.52	240	28683	6885	26	6.2
1997	87	3305	2145	3303	5222	10671	6.43	0.49	317	29000	7434	33.8	6.6
1998	87	3287	2198	3410	5391	10999	6.57	0.49	274	29254	7181	30.1	6
1999	88	3321	2178	3493	5391	11062	6.55	0.49	262	29746	7533	29	5.7
2000	93	3284	2152	3267	5967	11386	6.55	0.52	249	30096	7248	28.4	5.4
2001	91	3272	2238	3471	5605	11314	6.7	0.5	298	29699	7116	33.8	7.4
2002	93	3599	2336	3709	5372	11418	6.72	0.47	223	30611	7521	25.4	5.1
Average	98	3476	2266	3520	5988	11773	6.63	0.51	256	30904	7234	30.2	5.9

Potential sunflower production for (the southern part, Jiexiu, of) Fenhe Irrigation District (1961-2002)

YEAR	DUR /d	TWRT /kg/ha	TWLV /kg/ha	TWST /kg/ha	TWSO /kg/ha	TAGP /kg/ha	LAIM m^2/m^2	HINDEX /kg/kg	TRC /kg(H_2O)/kg	GASST /kg(CO_2)/ha	MREST /kg(CO_2)/ha	TRANSP /cm	EVSOL /cm
1961	90	3205	2150	3159	5994	11302	6.64	0.53	243	29579	6952	27.5	5.4
1962	96	3080	2069	3412	6139	11620	6.24	0.53	235	29759	6783	27.3	5.7
1963	93	3474	2201	3273	4652	10126	6.69	0.46	258	27764	6969	26.1	5.9
1964	98	3284	2227	3450	5373	11050	6.62	0.49	223	28857	6724	24.7	5.4
1965	94	3589	2373	3703	6600	12675	6.75	0.52	259	32898	7550	32.9	6.4
1966	97	3124	2096	3434	6696	12227	6.41	0.55	228	31043	6924	27.9	6.1
1967	99	3286	2118	3242	5192	10552	6.38	0.49	242	27967	6608	25.6	6.1
1968	96	3677	2387	3874	5848	12108	6.84	0.48	247	32021	7651	29.9	6.4
1969	93	3364	2215	3449	6167	11831	6.67	0.52	253	31011	7340	29.9	6.1
1970	95	3727	2293	3442	5788	11523	6.69	0.5	275	31055	7476	31.7	6.1
1971	95	3310	2254	3463	6076	11794	6.73	0.52	246	30701	7197	29	5.7
1972	95	3194	2090	3246	6490	11826	6.32	0.55	277	30508	6948	32.8	6.6
1973	94	3676	2377	3576	5115	11068	6.85	0.46	268	29691	7101	29.7	5.4
1974	96	3608	2315	3560	6431	12306	6.77	0.52	259	32393	7610	31.9	5.8
1975	92	3302	2210	3447	5377	11033	6.57	0.49	246	29352	7215	27.1	5.8
1976	98	3311	2110	3263	5935	11308	6.34	0.52	225	29469	6703	25.4	6.1
1977	96	2987	1887	3035	6170	11092	6.04	0.56	225	28704	6590	25	5.7
1978	94	3197	2109	3189	5499	10797	6.52	0.51	238	28164	6459	25.7	6.1
1979	102	3343	2172	3384	6468	12024	6.48	0.54	222	31065	7030	26.7	5.3
1980	98	3834	2605	3938	6458	13001	7.27	0.5	287	33796	7716	37.3	5.6
1981	93	3363	2144	3317	5444	10905	6.43	0.5	237	28969	6902	25.9	5.4
1982	102	3426	2153	3432	6057	11642	6.26	0.52	226	30305	6856	26.3	6
1983	93	3253	2131	3394	5644	11169	6.36	0.51	236	29166	6793	26.3	5.8
1984	102	3411	2261	3687	6494	12442	6.67	0.52	214	32033	7297	26.7	5
1985	98	3294	2193	3505	5564	11262	6.63	0.49	228	29357	6828	25.6	6
1986	96	3747	2470	3716	6326	12512	6.95	0.51	248	32945	7727	31	5.8
1987	92	3676	2308	3657	5938	11902	6.67	0.5	252	31777	7666	30	6.1
1988	95	3034	1921	2709	5741	10371	6.05	0.55	224	27189	6216	23.3	5.3
1989	98	3179	2109	3388	5931	11428	6.29	0.52	245	29545	6790	28	5.8
1990	91	3278	2215	3527	5562	11303	6.65	0.49	264	29713	7151	29.9	6
1991	89	3304	2260	3510	5302	11072	6.73	0.48	276	29342	7179	30.5	6.9
1992	97	3402	2225	3376	5877	11478	6.63	0.51	261	30261	7157	30	6.4
1993	104	3631	2334	3689	6651	12674	6.58	0.52	228	32898	7472	28.8	5.8
1994	93	3403	2290	3591	6607	12488	6.78	0.53	268	32262	7433	33.5	6.3
1995	97	3162	2026	3250	5507	10782	6.2	0.51	278	28348	6700	30	7.6
1996	96	3064	1908	3165	5676	10748	5.83	0.53	272	28277	6739	29.3	7
1997	87	3283	2142	3307	5301	10750	6.43	0.49	354	29032	7352	38.1	7.4
1998	85	3202	2157	3390	5214	10761	6.53	0.48	299	28742	7192	32.2	6.6
1999	87	3279	2150	3481	5236	10867	6.49	0.48	302	29335	7516	32.8	6.5
2000	91	3061	2044	3093	6175	11312	6.42	0.55	267	29468	6947	30.2	6
2001	90	2971	2086	3377	5698	11161	6.42	0.51	247	28830	6835	27.6	7.7
2002	91	3299	2161	3636	5286	11082	6.4	0.48	255	29477	7301	28.3	5.9
Average	95	3340	2189	3422	5850	11461	6.53	0.51	253	30073	7086	29.0	6.1