5.5 Improving Water Use Efficiency of Irrigated Crops in the North China Plain – Measurements and Modelling

H.X. Wang, L. Zhang, W.R. Dawes, C.M. Liu

Abstract

High crop productivity in the North China Plain relies on irrigation. However, as a result of rapid regional development in the last two decades, the competition for water has become very high. This presents a serious problem for sustaining agriculture in the region. This work examines relationships between irrigation, evapotranspiration, crop growth, and water use efficiency of a corn–wheat rotation common in the region. During the period of 1984 to 1996, field experiments were conducted at Luancheng Agricultural Ecosystem Station in the North China Plain to measure water and energy balance components and crop growth of corn and wheat. A process-based model (WAVES) was used to analyse the measurements and to simulate the effect of irrigation management on crop growth. The summer dominant rainfall of the region means that irrigation is required during the winter wheat growing season, when the difference between rainfall and evapotranspiration is large. While corn grows during summer, some irrigation is still required. Soil evaporation (E_s) is a significant proportion of total evapotranspiration (E_t) especially when leaf area index (L) is low, and on average E_s under a wheat canopy accounted for 30 % of E_t. Mulching reduced soil evaporation by up to 50% and saved 80 mm of water during a wheat growing season. Current irrigation schemes in the area can be improved by reducing irrigation frequency and amount.

5.5.1 Introduction

The North China Plain (NCP) is a major agricultural area in China. The region covers an area of 3 × 10^5 km^2, supports a population of over 300 million people, and produces 19% of the nation's food and 42% of the cotton (Huang, 1989). Traditional agriculture is well developed in the area. However, due to limited summer dominant precipitation and annual variability, agricultural productivity is low without irrigation. As a result of rapid regional development in the last two decades, the competition for water has become very high. There are no reliable surface water resources for irrigation, so groundwater has been used causing the regional groundwater table to drop significantly (Zhang and You 1996). On the other hand, the demand for high crop yield has led to irrigation water for winter wheat to increase from 100 mm/ha in the 50s to 300mm/ha in the 1980s (Zhang and You, 1996). This presents a serious problem for sustainable agricultural development in the region.

It is known that shortage of water restricts crop productivity and the purpose of irrigation is to minimise crop water stress and to achieve maximum yield. However, maximising yield should not be the sole objective and other constraints (e.g. water availability, irrigation cost, etc.) should be considered, especially in the arid regions. The response of crop yield to irrigation has been studied extensively (Skogerboe *et al.* 1979). Through proper irrigation management, it should be possible to provide only the water that matches the crop evapotranspiration. An important issue in sustainable agriculture is to optimise productivity with respect to resource inputs such as water.

It is believed that substantial improvement can be made to the current agricultural and irrigation practices in the North China Plain. A key area under investigation is the development of strategies for water-saving agriculture and to identify water management problems. In order to study this area, it is essential to understand the exchange processes between soil–plant–atmosphere in terms of water and carbon, dry matter accumulation and yield, and to improve partitioning of total evapotranspiration into soil evaporation and plant transpiration. This will provide considerable insight into efficient water use and better management.

In the last decade, a number of process-based models have been developed to simulate crop growth and water balance (Ritchie and Otter-Nacke 1985, Zhang *et al.* 1996). It is believed that these models can help us to better understand the processes and feedbacks in these systems and to identify key factors controlling plant growth and water use. During the period of 1984 to 1996, several field experiments were carried out at Luancheng Agricultural Ecosystem Station in the North China Plain to measure water balance components, crop yield, and physiological parameters. The purpose of this report is to investigate relationships between soil evaporation, transpiration, crop growth, and irrigation for corn and winter wheat in the North China Plain. This report also examines the effects of mulching on soil evaporation to reduce unnecessary loss of water.

The WAVES model (Zhang *et al.,* 1996, Dawes *et al.,* 1997) is used to assist in analysing the field data and to simulate the effects of irrigation scheduling on crop growth. This work is part of a larger study on water-saving agriculture in the North China Plain.

5.5.2 *Field measurements*

Experimental site

The experiments were conducted at Luancheng Agricultural Ecosystem Station in the North China Plain (37°53′N, 114°41′E) with an elevation of 50 m above the sea level (Fig. 5.34). The annual precipitation is about 480 mm, concentrated in the period of July to September. The dominant soil type is loam with average bulk density of 1.53 g/cm^3. Cropping practice in the region is corn followed by winter wheat and Table 5.11 shows growth stages for the two crops. The groundwater table is about 28 m below the ground surface with mineral content less than 0.5 g/ℓ.

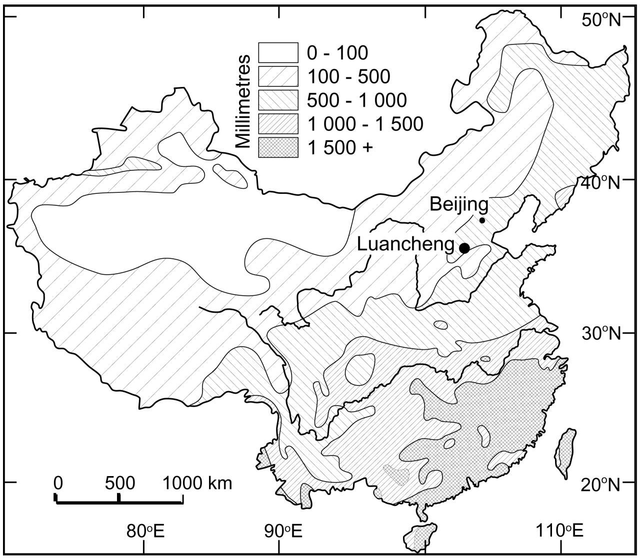


Fig.5.34. Location of study site in the North China Plain

Evapotranspiration and soil evaporation measurement

One large weighing lysimeter was installed at the station in 1985. It has a surface area of 3 m^2, and is 2.5 m deep, containing approximately 11.5 tonnes of soil. A mechanical scale allowed readings to 0.02 mm of water. A data-logger recorded changes in weight every 5 minutes and these were aggregated to daily total evapotranspiration. Inside the lysimeter, neutron access tubes were installed to monitor soil water content. Evapotranspiration was also measured using the Bowen Ratio method in an adjacent field.

Soil evaporation under the crop canopy was measured directly using micro-lysimetry. The micro-lysimeters were made of 12 cm I.D. PVC tubing 20cm long. The micro-lysimeters were weighed once per day at 8:00 am and daily soil evaporation could be inferred. For this size of lysimeter, 1 g weight change in the soil core equals 0.09 mm of water evaporated. The soil core within the lysimeter was changed every two or three days to keep the same water status as the surrounding fields.

Table 5.11. Cropping practice and date of growth stage of corn and winter wheat in the North China Plain

Growth stage	Sowing	emergence	over-wintering	turn-green	jointing	heading	flowering	grain filling	grain harvest
wheat	1 Oct	7 Oct	15 Nov	1 Mar	10 Apr	1 May	5 May	20 May	20 Aug
corn	12 Jun	15 Jun			18 Jul		10 Aug	10 Jun	29 Sep

Soil water content measurement

Soil water content was measured using neutron probes at 20 cm intervals down to 200 cm. The measurements were taken once a week or according to the crop growth stage. The soil water content of the surface 0–20 cm interval was measured gravimetrically because neutron probes could not get an accurate readings near the surface.

Leaf area index measurement

At each crop growth stage, samples of thirty plants were randomly harvested and the length and width of each leaf was measured manually. The leaf areas of the samples were averaged to give a single value for each plot.

Meteorological data

Meteorological data were recorded hourly at the experimental site. Wet and dry bulb temperatures were measured using temperature sensors with a standard muslin wick. A tipping bucket rain gauge recorded rainfall amount and intensity. Sunshine hours and wind speed were also measured. Any missing meteorological data were filled in from neighbouring weather stations.

5.5.3 Calibration

WAVES was run from January 1984 to June 1996 using daily values of maximum and minimum air temperatures, precipitation, vapour pressure deficit, and solar radiation. The initial vegetation parameters for corn and wheat were set from previous studies (Hodges 1992; Hatton and Dawes 1993; Dawes *et al.* 1997; Zhang *et al.* 1999*a,b*). The length of growing season, and bulk respiration coefficient were fitted to match leaf area development over the first three years; previous studies have been mainly concerned with C3 plants in the southern hemisphere.

The soil profile was based on soil texture profile data. The BW parameters were estimated from measured soil moisture, and soil texture (Table 5.12). Short *et al.* (1995) have shown the large dimensionless region where Richards' equation is guaranteed to work with the BW soil parameters, and the soil parameters were kept within their ranges.

Table 5.12. List of Broadbridge–White soil parameters and soil layer depths at Luancheng Station used in the study

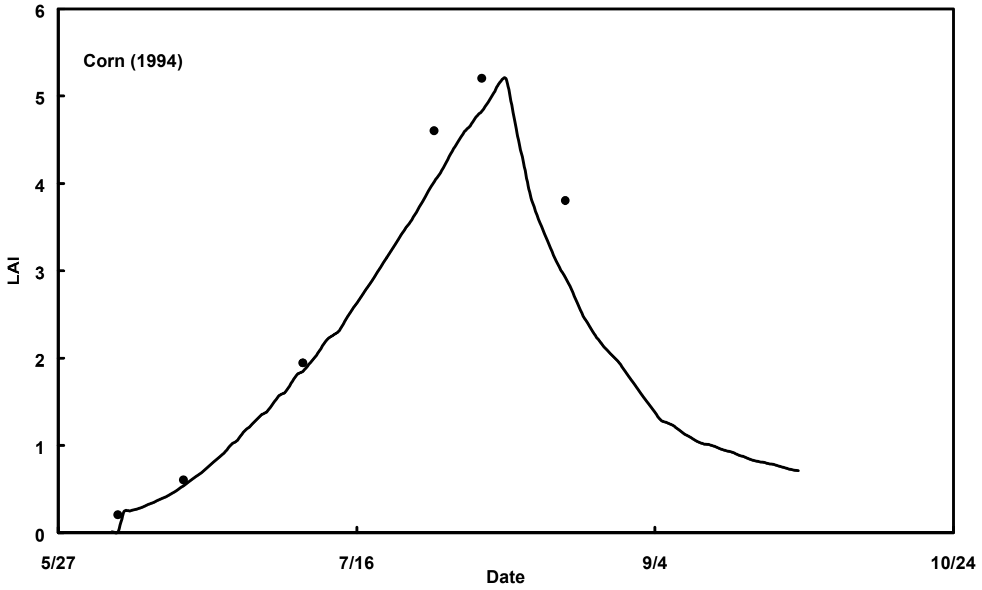
Layer	Texture	Depth (cm)	K_s (m/d)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	λ_c (m)	C
1	sandy-loam	0–35	1.0	0.40	0.05	0.05	1.02
2	loam	35–90	0.1	0.40	0.10	0.10	1.50
3	clay-loam	90–200	0.001	0.45	0.10	0.50	1.50

5.5.4 Results and discussion

Simulated crop growth and evapotranspiration

Fig. 5.35 shows a comparison of simulated and measured leaf area index for corn and winter wheat. The simulated leaf area index followed the measurements very well and the model captured the peak leaf area index in terms of timing and magnitude. Winter wheat in the North China Plain has a much longer growing season than to corn. During the winter period, wheat is usually covered by snow and its leaf area index stays constant, then starts to grow in spring; the model was able to simulate these changes. For the period 1984 to 1996, simulated peak leaf area index varied from 4.5 to 6.1 for winter wheat and 5.0 to 6.3 for corn (not shown in Fig. 5.35).

Estimates of evapotranspiration from WAVES are plotted against the lysimeter measurements in Fig. 5.36. The best fit slope through the origin is 0.98, with a correlation coefficient of 0.94. During the period of the measurements, leaf area index changed from less than 1 to above 5 and evapotranspiration rates varied between 0.5 to 7.0 mm per day. The model was able to reproduce this range and variation in evapotranspiration.



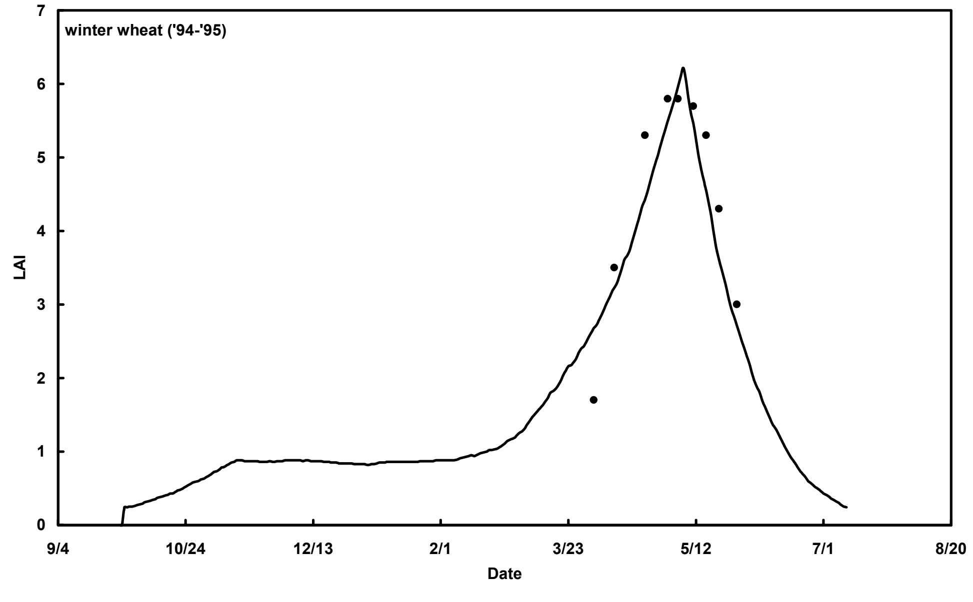


Fig.5.35. Comparison between modelled and measured leaf area index (LAI) for (a) corn and (b) winter wheat.

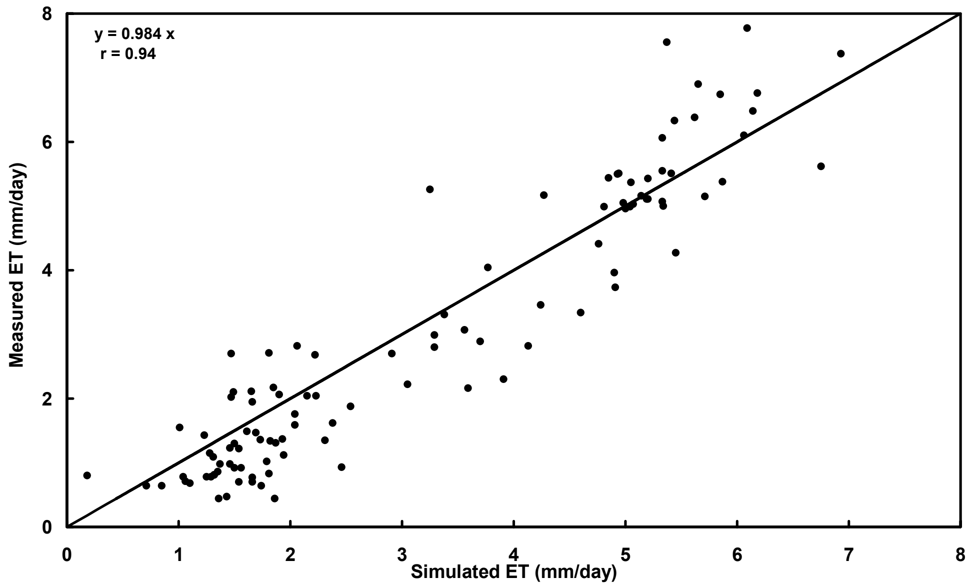


Fig.5.36. Comparison between evapotranspiration modelled by WAVES and evapotranspiration measured by lysimeter.

Soil evaporation and leaf area index

The partitioning of the total evapotranspiration (E_t) into plant transpiration (E_v) and soil evaporation (E_s) was evaluated using WAVES. Denmead (1973) proposed that the ratio E_s/E_t should decrease monotonically as leaf area index increases. Villalobos and Fereres (1990) and Wallace *et al.* (1991) confirmed the relationship by measuring E_s under corn, sunflower, and sugar cane canopies. The results from WAVES showed a similar relationship between E_s/E_t and leaf area index (L) (Fig. 5.37). The best-fit exponential relationship to the data is $E_s/E_t = exp(-0.61L)$. This conformed to the relationship obtained by Denmead *et al.* (1997).

This relationship resembles Beer's law for radiation partitioning. It can be argued that this relationship is valid for relatively wet soil where available energy is the controlling factor and this suggests that available energy at the ground surface is a good indicator of stage one soil evaporation (Villalobos and Fereres, 1990).

As shown in Fig. 5.37, calculated soil evaporation was lower than the values obtained from the theoretical curve for low leaf area index. This can be attributed to the fact that the soil moisture content of the top 10 cm of soil was only 10%. As a result, soil evaporation was limited by the available water, or stage two evaporation. A relevant issue in irrigated agriculture is the relative importance of soil evaporation and transpiration. Fig. 5.37 suggests that before canopy closure (LAI < 1) soil evaporation accounted for 50% to 90% of the total evapotranspiration. There appears to be scope to improve irrigation efficiency by altering the balance between these two fluxes. One strategy is to reduce soil evaporation by mulching. Covering the surface with plant residues can reduce radiation and wind at the surface and hence reduce evaporation. Reduction of soil evaporation during the first stage can provide the crops with a greater opportunity to use the moisture of the top soil layers. During the second stage of drying, the rate of evaporation is usually much lower than during the first stage and the effect of mulching is likely to be small. Measured values from this study showed that mulching reduced soil evaporation by 50% under winter wheat (Fig. 5.38) and this is equivalent to 80 mm of water. In terms of irrigation efficiency, it means that we can reduce irrigation water by 25%.

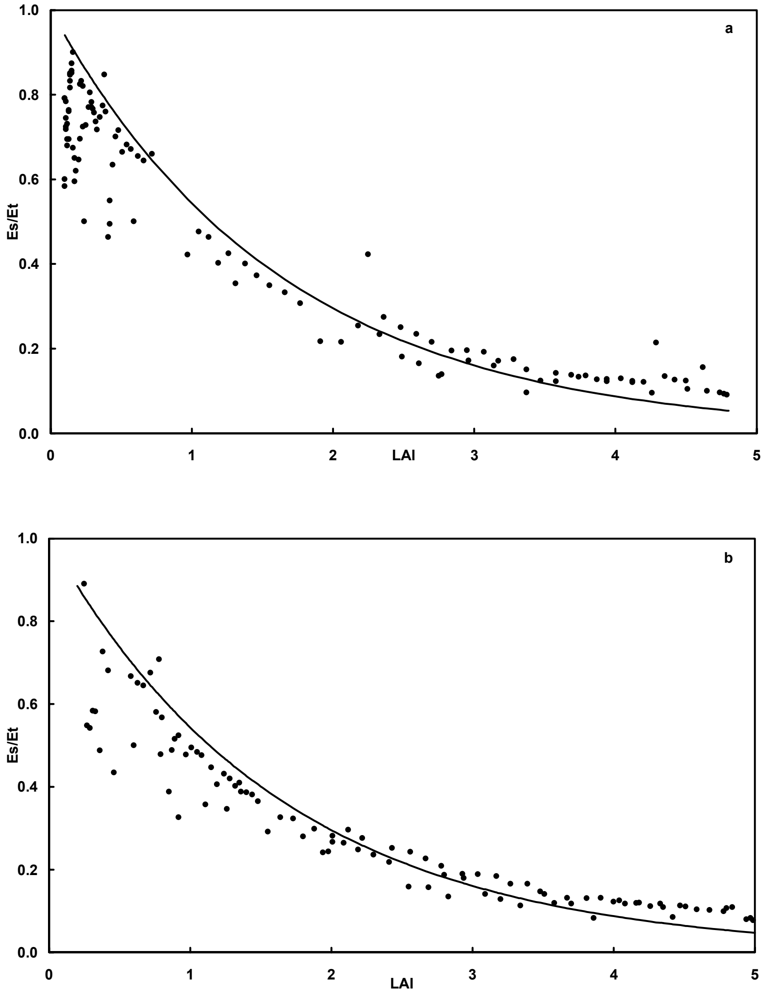


Fig.5.37. Variation of E_s/E_t with LAI for (a) corn and (b) winter wheat as simulated by WAVES. Fitted curve is for $E_s/E_t = \exp(-0.61\mathrm{LAI})$. E_s is soil evaporation and E_t is evapotranspiration.

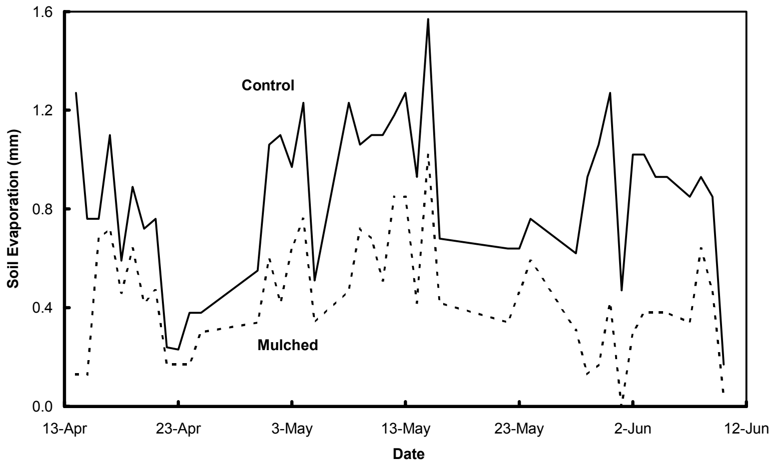
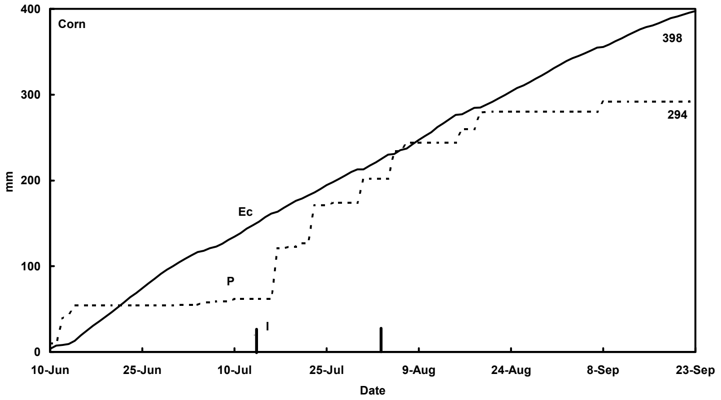


Fig.5.38. Effect of mulching on soil evaporation under winter wheat.



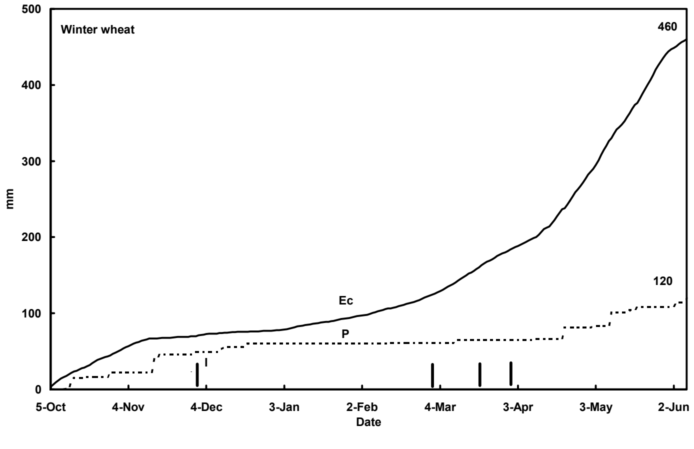


Fig.5.39. Cumulative rainfall and evapotranspiration for (a) corn and (b) winter wheat.

Effects of irrigation on crop growth

Annual precipitation in the North China Plain is extremely variable ranging from 300 to 1000 mm, with an average of 480 mm (Zhang and You, 1996). During the corn growing season (June to September), average rainfall is 350 mm (73% of annual precipitation), while for the winter wheat growing season, average precipitation is only 130 mm (27% of annual precipitation). As shown in Fig. 5.39 for 1989, total evapotranspiration during the corn growing season was 398 mm and rainfall was 294 mm. The difference was supplemented by 160 mm of irrigation water. For winter wheat, the difference between precipitation and evapotranspiration was 320 mm. These results suggest that during the corn growing season rainfall is nearly enough for evapotranspiration and irrigation can be kept to a minimum. For winter wheat however, a significant amount of water has to be supplied by irrigation to maintain high yield.

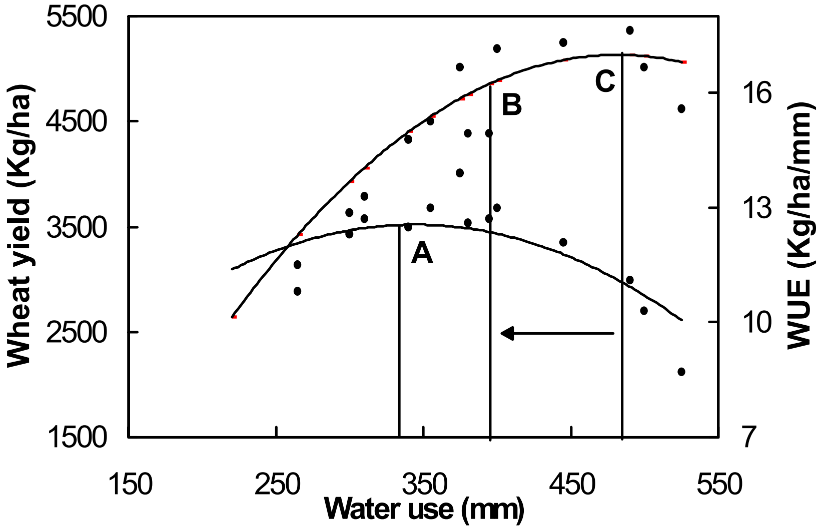


Fig.5.40. Relationship between yield, water use efficiency (WUE), and water use for winter wheat.

Water balance estimates in Fig. 5.39 show that precipitation in the North China Plain can not meet evapotranspiration demands. However, the relationship between crop yield and water use is non-linear (Fig. 5.40). Successive applications of irrigation water increase the yield until there is sufficient water in the soil for crop to meet evapotranspiration demands. It is interesting to note that the rate of increase in crop yield decreases as water use increases. In economic terms, yield response to applied irrigation is a diminishing-return function. The point marked ‘A’ represents maximum water-use efficiency with 200 mm of irrigation water added and a yield of 4.3 t/ha. The point marked ‘C’ represents maximum yield of 5.2 t/ha but this requires 350 mm of irrigation water. The point marked ‘B’ represents the maximum value of the ‘sum’ of the two curves. This point has a yield only 7% less than ‘C’ but uses 21% less irrigation water.

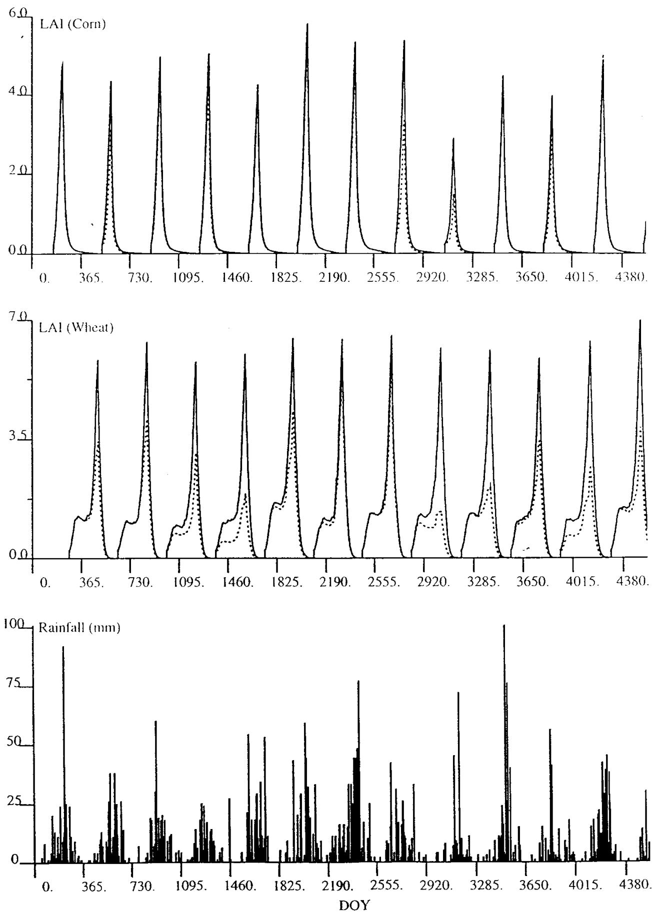


Fig.5.41. Leaf area development under different irrigation regimes. Solid line represents 80 mm of irrigation

To further investigate the effect of irrigation on crop yield (growth), several scenario simulations were conducted using WAVES. The amount of water applied in each irrigation varied from 0 mm to 80 mm and the resulting leaf areas developed are shown in Fig. 5.41. It should be noted that irrigation had no impact on crop growth in wet years, while in dry years it enhanced crop growth significantly. However, the benefit became less obvious as irrigation water supply increased. The results suggest that current irrigation practices in the area tend to over-irrigate crops. Given the water available for irrigation in the region is limited, it is not sustainable to maintain irrigation at current levels.

5.5.5 Conclusions

Precipitation in the North China Plain showed significant temporal variation. The difference between precipitation and evapotranspiration during the corn growing season is much smaller than during the winter wheat growing season. As a result, different irrigation schemes should be applied. Water balance estimates indicate that soil evaporation on average is about 30% of total evapotranspiration and the ratio is significant higher before crop canopy closure. There appears to be scope to improve water use efficiency by altering the water balance and one strategy is to reduce soil evaporation by mulching. The effect of mulching is larger during the first stage of drying than the second stage. Results from this study showed that mulching can reduce soil evaporation by 50%, which is equivalent of 80 mm of water for winter wheat growing season. An irrigation scheme having high irrigation frequency can cause the first stage soil evaporation to persist much longer and result in more water loss than ones with low irrigation frequency. Current irrigation schemes in the North China Plain can be improved by reducing both irrigation frequency and amount, especially during corn growing season.