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Linking Water Balance to Irrigation Scheduling: a Case Study in the Piedmont of Mount Taihang

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Abstract

Irrigation scheduling could reduce the amount of water used to irrigate crops and help to achieve water balance in the piedmont of Mount Taihang on the North China Plain (NCP), where the two staple crops are winter wheat and summer corn. A study at the Chinese Academy of Sciences Eco-Agro-System Experimental Station in Luancheng on the NCP investigated the effect of different irrigation regimes on grain yield and water use efficiency (WUE) in these crops. Irrigation schedules for maximum yield or WUE were established. Yield and WUE did not appear to be linearly related to total evapotranspiration. Maximum profit from a crop was obtained using less water than was needed for maximum yield. High yield, efficient use of water and a net profit from winter wheat were achieved using one, two and three irrigations (60 mm of water per irrigation) in wet, normal and dry years, respectively. Thus, the general practice of irrigating winter wheat four times during the growth period could be changed to irrigating one to three times a year, depending on the rainfall during the winter growing season, a practice that would greatly reduce supplemental water use.

为了维持山前平原地下水采补平衡，减缓地下水位急剧下降的趋势，在太行山山前平原中部的中国科学院栾城生态农业系统试验站进行了冬小麦和夏玉米优化灌溉制度的试验研究。研究结果表明作物的总耗水量与产量的关系不是直线关系，随着耗水量的增加，产量增加，当总耗水量增加到一定程度，产量反而减少，存在着对于产量或水分利用效率的最优耗水量。根据试验结果，建立了灌溉水的生产函数。目前山前平原最大产量下的灌水量大于最大经济效益下的作物灌水量。根据试验结果，太行山山前平原高产区冬小麦常年灌溉次数在3~4水，如果实施优化灌溉制度，干旱年灌3水、平水年灌2水、湿润年灌1水，灌水定额60毫米，可减少生育期灌水次数1~2次，

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冬小麦产量提高 8%-10%，水分生产效率提高 11%-24%，这对减缓本区地下水位的下降有重要意义。

THE NORTH China Plain (NCP) is one of the most important grain production bases in China, providing more than 15% of China's total annual grain production and over 19% of its total winter wheat production. However, the average water resource per capita and per area is about 14% of the average for China (Shi 1995) and the amount of groundwater available for irrigation is decreasing. The Overview provides background information about the region.

The piedmont (the area lying at the foot of a mountain range) of Mount Taihang is a region of high production on the NCP and covers some 50,000 km^2. The groundwater table in the region is currently declining at the rate of 1–1.5 m per year. If this situation continues, the shallow groundwater will run out within 20–30 years and irrigated agriculture will no longer be possible.

Despite the shortage of water, irrigation water is often wasted. Water use efficiency (WUE) and the profit gained from supplemental irrigation is low, due to poor decisions about *when* to irrigate and *how much* water to apply to a crop (Pereira 1999). Improved irrigation scheduling practices could increase yields and profits for farmers, save significant amounts of water, reduce the environmental impacts of irrigation and improve the sustainability of irrigated agriculture (Smith et al. 1996). Irrigation scheduling requires an understanding of the water requirements of a crop and the effect of water on yield. This study investigated the impact of the frequency and timing of irrigation on the yield and WUE of crops in order to establish appropriate irrigation scheduling and thus reduce water use.

Water Deficit in the Piedmont of Mount Taihang

Rainfall

The piedmont of Mount Taihang is in a monsoon climatic zone. Mean annual rainfall is about 480–500 mm but fluctuates greatly from year to year, with a relative variability of 24.4% (Fig. 1). The distribution within a year is also very uneven (Fig. 2), with about 70% of the total rainfall occurring during July to September, the growing season of summer crops. About 25% of the total rainfall occurs during the growing season for winter wheat (October to June) when supplemental irrigation is needed.

Water requirements of crops

In the piedmont of Mount Taihang, two crops are grown each year: winter wheat and summer corn. Winter wheat is usually sown at the beginning of October and harvested during the first 10 days of June; corn is planted in the wheat fields about 5–7 days before harvesting the wheat. Figure 3 shows the total evapotranspiration due to winter wheat and corn under full irrigation at the Chinese Academy of Sciences Luancheng Eco-Agro-System Experimental Station (hereafter referred to as Luancheng Station), located in the central part of the piedmont of Mount Taihang. Measurements were taken over five seasons (1995–2000), using a large-scale weighing lysimeter.

During the five seasons of the study, climate conditions were normal and rainfall was variable. Under full irrigation, the crops encountered no water deficit, so total evapotranspiration represents local evapotranspiration of these crops in normal years without water deficit. Average total transpiration was about 453 mm for winter wheat

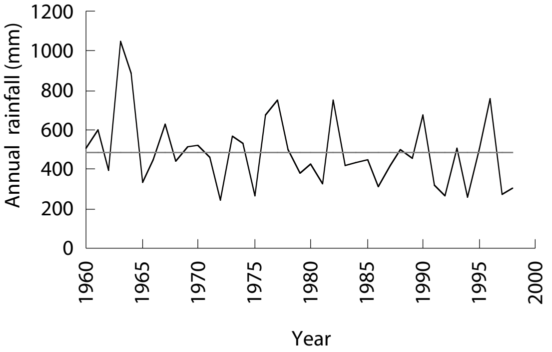

Figure 1. Fluctuation of annual rainfall in the piedmont of Mount Taihang (data averaged from several sites).

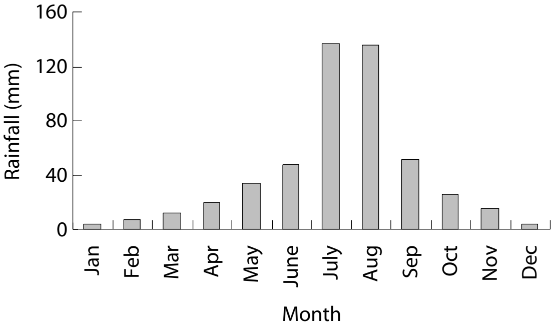

Figure 2. Average monthly rainfall in the piedmont of Mount Taihang (data averaged from several sites from 1961 to 1998).

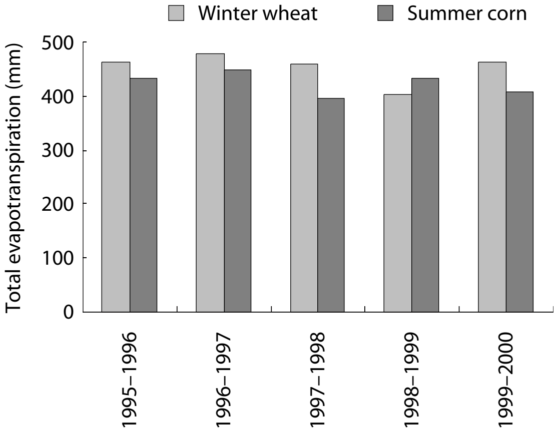

Figure 3. The total evapotranspiration (mm) of winter wheat and summer corn measured by a large-scale weighing lysimeter from 1995 to 2000 at Luancheng Station. The large-scale weighing lysimeter is designed to contain the original (undisturbed) soil, which weighs 15 tonnes and is 3 m^2 in area and 2.5 m deep. Its metrical precision can reach 0.02 mm.

and about 423.5 mm for corn. The annual water requirements of the two crops in the region ranged from 830 mm (1998–99 season) to 927 mm (1996–97 season), with an average of 876 mm. Average seasonal rainfall is about 126 mm for winter wheat and 362 mm for summer corn. The average difference between water requirements and rainfall is 327 mm for winter wheat and 61 mm for summer corn. The average annual supplemental water required by the two crops can be as high as 388 mm. Irrigation is particularly necessary for winter wheat, because seasonal rainfall may provide less than one-third of the crop's water requirement.

Overdraft of groundwater

Groundwater is the source of most supplemental irrigation. In the piedmont of Mount Taihang, farmers generally irrigate winter wheat four or five times, and summer corn two or three times. As explained above, about 400 mm of supplemental irrigation is needed to ensure that crops in the region encounter no water deficit during the growing period. The quantity of groundwater recharged each year is about 200–250 mm (You 1998), giving a shortfall of 100–150 mm per year. Thus, current irrigation practices are rapidly depleting groundwater resources (Fig. 4). At present, WUE is 1.2–1.5 kg/m^3, well below the level of 2.0 kg/m^3 found in the developed world. It is vital to optimise irrigation scheduling in order to reduce irrigation water use and achieve water balance so that agriculture will be sustainable.

Effective Irrigation Scheduling

The relationship between crop yield and water use is complex. Both the timing of irrigation and the amount of water used can affect yield. The efficient use of irrigation water requires information on the optimum time to apply limited amounts of water to crops to obtain maximum yield and high quality (Al-Kaisi et al. 1997). Crops show different sensitivities to moisture stress at different stages of development (Doorenboss and Kanssan 1979; English and Nakamura 1989; Ghahraman and

Sepaskhah 1997). At some stages, moderate water deficit may not affect crops. Irrigation can be scheduled to take account of the responses of crops to water at different stages of development.

How evapotranspiration relates to grain yield and water use efficiency

In field experiments at Luancheng Station, the most frequent irrigation did not result in maximum yield or WUE. Figures 5 and 6 show how total water consumption for winter wheat and summer corn related to yield and WUE. The relationship was not as linear as reported by Turner (1990). Initially, increasing total water consumption led to an increase in yield and WUE. However, once yield and WUE peaked, any further increase in evapotranspiration led to a decrease in yield and WUE. The amount of water needed for maximum yield is greater than the amount needed for maximum WUE.

Sensitivity of crops to water stress at different stages of development

Crop sensitivity to water stress can be expressed as a mathematical relationship between relative yield and the relative amount of applied water (Jensen 1968):

$$\frac{Y}{Y_m} = \prod_{i=1}^{n}\left(\frac{ET_i}{ET_{i\,\max}}\right)^{\lambda_i} \qquad (1)$$

In Equation 1, Y is the actual yield under partial irrigation, Y_m is the yield under nonlimiting water use from full irrigation, n is the number of growth stages, ET_i is the actual amount of water used by the crop, ET_{imax} is the nonlimiting crop water use or potential water requirement and λ_i (sensitivity index) is the relative sensitivity of the crop to water stress during the ith stage of growth. The value of λ_i for a given crop is different at the various stages of growth: a more sensitive growth stage has a higher sensitivity index.

Figure 7 shows the effects of water stress on the yield of winter wheat at different growth stages. The highest reduction in yield occurred with water stress at jointing to booting, followed by stress at booting to heading. Water deficit when the crop was turning green or maturing did not affect yield. Equation 1

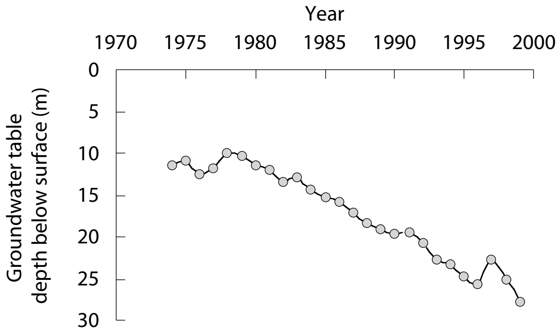

Figure 4. The rapid decline in the groundwater table at Luancheng Station.

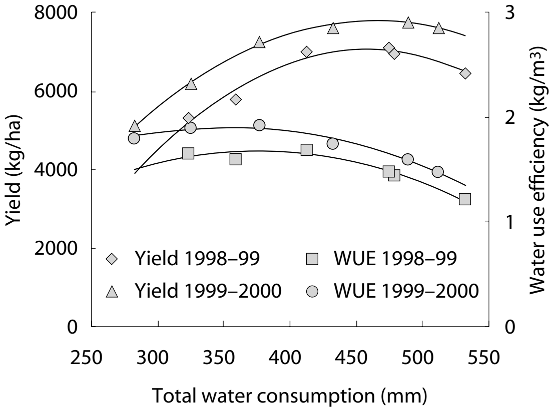

Figure 5. The relation of total water consumption, grain yield and water use efficiency of winter wheat from 1998 to 2000 at Luancheng Station.

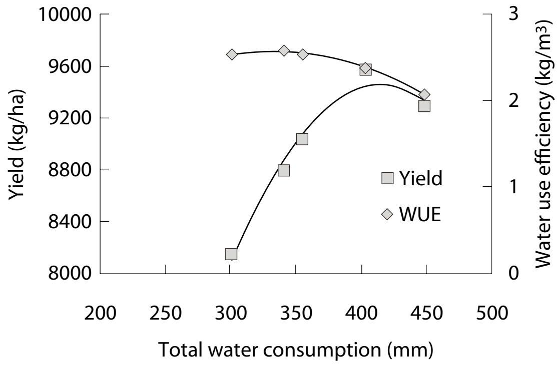

Figure 6. The relation of total water consumption, grain yield and water use efficiency of summer corn in the 1999 season at Luancheng Station.

was used to determine the sensitivity index of winter wheat and summer corn at various growing stages (Table 1). The highest index was at the jointing stage for winter wheat and at the heading to milky filling stage for corn. The negative sensitivity index for winter wheat when recovering (turning green) and maturing may indicate that at these stages moderate water stress is beneficial. The sensitivity index provides a means to determine the optimum time to apply limited amounts of water to obtain maximum yield.

Table 1. The sensitivity index (λ_i) of winter wheat and summer corn to water stress at various growth stages. Results are averaged from data accumulated over several years at Luancheng Station.

(a) Winter wheat

Growth stage	λ_i
Before over-wintering	0.0781
Recovering	–0.1098
Jointing	0.2984
Booting	0.2366
Heading to milky filling	0.1102
Maturing	–0.0541

(b) Summer corn

Growth stage	λ_i
Sowing to jointing	0.1496
Jointing to heading	0.2061
Heading to milky filling	0.3645
Milky filling to maturing	0.1116

Irrigation water efficiency

The irrigation production function describes the relationship between irrigation and crop yield. Researchers such as Zhang et al. (1993) have described this function with the following quadratic relationship:

$$Y = b_0 + b_1 W + b_2 W^2 \qquad (2)$$

In Equation 2, Y is the crop yield, W is the total irrigation during the whole growth period of the crop, and b_0, b_1 and b_2 are coefficients.

The yield increase due to irrigation can be divided into three phases. In the first phase, marginal output value is greater than marginal cost; in the second, marginal output value is equal to marginal cost; in the third, marginal output value is lower than marginal cost. The following equations can express the situations:

$$\text{Phase one: } \Delta Y \times Py > \Delta W \times Pw \qquad (3)$$
$$\text{Phase two: } \Delta Y \times Py = \Delta W \times Pw \qquad (4)$$
$$\text{Phase three: } \Delta Y \times Py < \Delta W \times Pw \qquad (5)$$

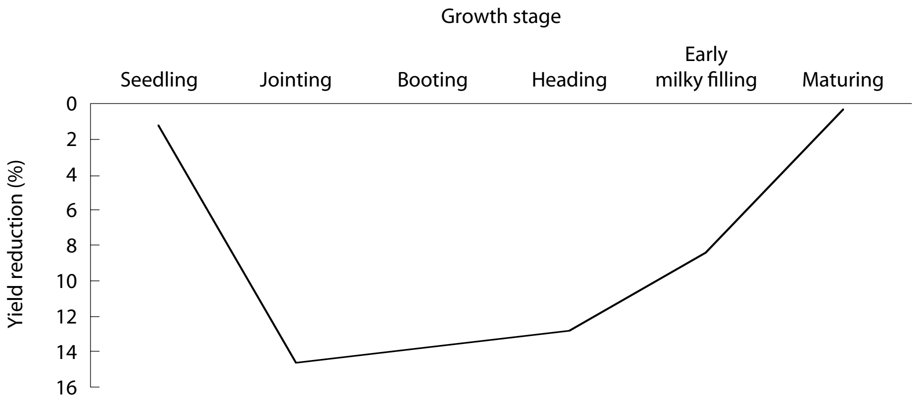

Figure 7. The yield reduction of winter wheat at different growth stages by water deficit in the 1996–97 season at Luancheng Station.

In Equations 3–5, ΔY is the yield increase by irrigation, Py and Pw are the respective unit prices of crop and water, and ΔW is the increase in amount of water used for irrigation.

In phase one, net output value will increase with irrigation; in phase two, net profit from irrigation is at a maximum; and in phase three, net profit from irrigation decreases. The amount of irrigation needed to obtain maximum profit can be calculated from the equation:

$$W = (Pw/Py - b_1)/2b_2 \tag{6}$$

Table 2 shows the relationship between yield and irrigation at Luancheng Station. As maximum profit is obtained using less water than is needed for maximum yield, the general practice of irrigating for maximum yield in this region could be replaced by irrigation for maximum profit. If water prices increase in future, total irrigation quantity will need to be further reduced to obtain maximum profit.

Indicators for water stress

Irrigation scheduling should be based on soil water and plant water status (Stricevic and Caki 1997).

Soil water

There are many methods and measures to determine soil water status, which can act as an indicator for optimal irrigation scheduling. Significant crop stress occurs below a threshold value of soil water depletion. The threshold value varies with growth stage, due to variation in sensitivity to moisture stress. Thus, in winter wheat at jointing stage (the most sensitive stage to water stress), delaying irrigation for seven days caused a reduction in soil moisture content for the top 50 cm of soil from 22.5% to 17.4% by volume; yield was reduced by about 11%. In contrast, a decrease in soil moisture content to 16.5% by volume at maturing had no effect on yield in the 1996–97 season. Table 3 gives the critical soil moisture level (threshold) for various stages of winter wheat obtained from field experiments at Luancheng Station over several years.

Table 2. Relationship between yield and irrigation at Luancheng Station for winter wheat (1997–2000) and for summer corn (1999 season).

Crop	Season	Irrigation production function[a]	Irrigation at maximum yield (mm)	Irrigation at maximum profit (mm)[b]	
				Low water fee	High water fee
Winter wheat	1997–98	$Y = -0.0632\ W^2 + 12.421\ W + 5417.8$	98.3	90.4	58.7
	1998–99	$Y = -0.0499\ W^2 + 19.371\ W + 5161.9$	194.1	184.1	144.0
	1999–2000	$Y = -0.0489\ W^2 + 23.013\ W + 5075$	235.3	225.1	184.2
Corn	1999	$Y = -0.0309\ W^2 + 12.449\ W + 8139.5$	201.4	186.9	172.3

[a] Y = grain yield (kg/ha); W = total irrigation water (mm)
[b] When calculating irrigation with maximum profit, the price of winter wheat is taken as 1.0 yuan/kg and the price of corn as 0.9 yuan/kg (present price), the low water fee as 0.1 yuan/m^3 and the high water fee as 0.5 yuan/m^3 (US$1 = 8.5 yuan)

Table 3. Critical soil moisture level (threshold) for winter wheat at various growth stages at Luancheng Station.

Growth stage	Seedling	Turning green to start of noding	Jointing	Booting	Heading to early milky filling	Maturing
Percentage over field capacity	60	55	65	60	60	50

Leaf water potential

The water status of plants is a more reliable indicator of water stress than soil water content because it reflects the influence of both soil and climate on the plant (Berliner and Oosterhuis 1987). According to Hsiao (1990), the most effective indicator of plant water status for irrigation scheduling is leaf water potential (LWP), which is related to transpiration rate. Figures 8 and 9 show the daily LWP and transpiration rate for winter wheat and corn. During the day, LWP decreased with increasing transpiration.

The transpiration rate fluctuated but there was a significant correlation between LWP and meteorological factors. Figures 10 and 11 show diurnal LWP and air temperature, radiation and vapour pressure deficit (VPD) for winter wheat and summer corn. LWP is highest before dawn; as air temperature, VPD and radiation increase, LPW decreases. At noon, LWP is relatively constant for several hours; it then increases as temperature, VPD and radiation fall. There is a linear correlation between LPW and temperature, VPD and radiation. The relationship can be described using the equations in Table 4.

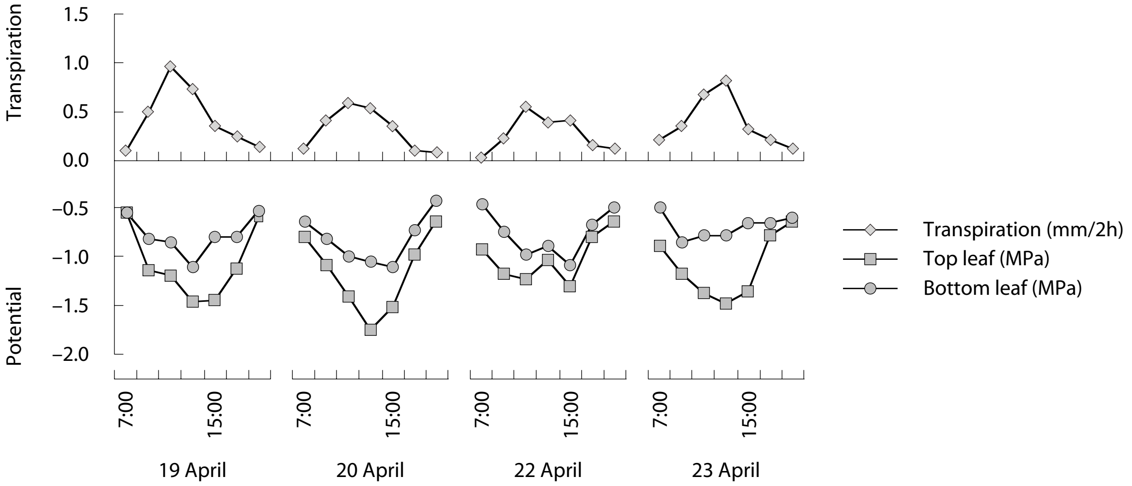

Figure 8. The diurnal change of leaf water potential with transpiration rate of winter wheat in 1996 at Luancheng Station.

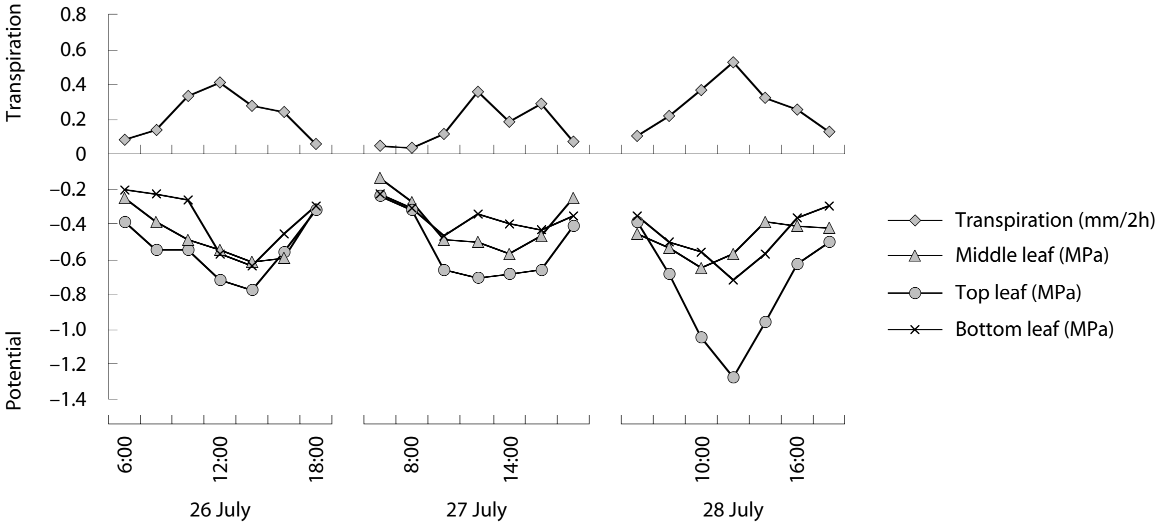

Figure 9. The diurnal change of leaf water potential with transpiration rate of summer corn in 1996 at Luancheng Station.

LWP has been used as an indicator for the crop water stress index (CWSI) (Sepaskhah and Kashefipour 1994) and to estimate evapotranspiration under water deficit (Kang et al. 2000). Figure 12 shows diurnal variation in LWP in well-watered and deficit-irrigated winter wheat. LWP was lower when soil moisture was lower. Early in the morning, the difference between LWP for well-watered plants and LWP for deficit-irrigated plants was greater than at any other time of the day.

During the evening, transpiration rate is low, so LWP can approach equilibrium with the effective soil water potential. At midday, transpiration is high and a leaf may lose water that cannot be immediately replenished even under well-watered conditions. Thus, variation in LWP between well-watered and water-deficit crops at midday may not reflect the true plant water status and predawn LWP appears to be the most effective indicator, a finding

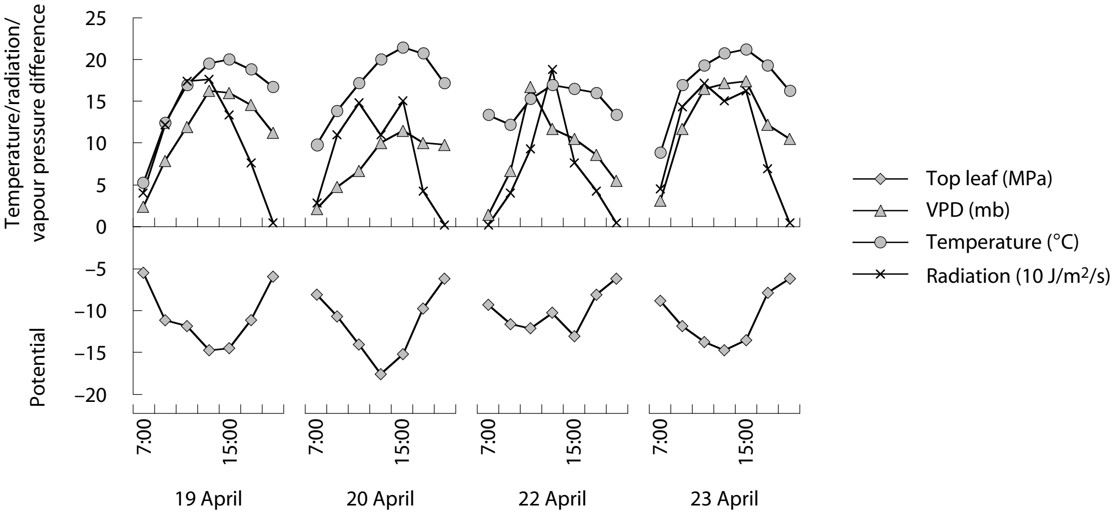

Figure 10. The diurnal change of leaf water potential with temperature, radiation and vapour pressure difference (VPD) of winter wheat in 1996 at Luancheng Station.

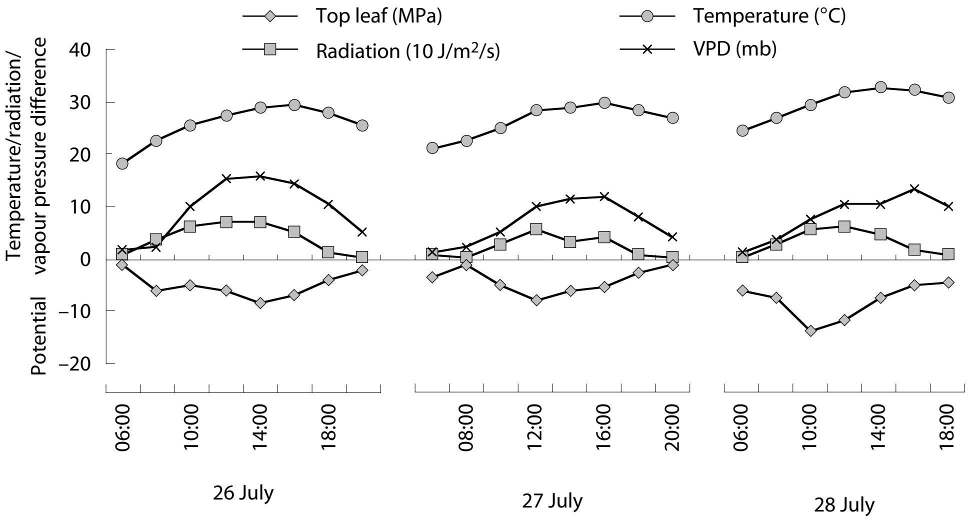

Figure 11. The diurnal change of leaf water potential with temperature, radiation and vapour pressure difference (VPD) of summer corn in 1996 at Luancheng Station.

that is consistent with other research (Nadler and Heuer 1997).

Table 5 shows the variation in LWP for winter wheat and summer corn at different levels of soil moisture, expressed as a percentage of field capacity. With decreasing soil moisture, variation in LWP usually increased. LWP can serve as an indicator of water stress for scheduling and control of irrigation.

Optimising the irrigation scheduling

Tables 6–10 show the results of different irrigation scheduling on yield, total water consumption and WUE for winter wheat and summer corn at Luancheng Station. Frequency and timing of irrigation affected grain yield and WUE, with irrigation important in improving yield. For example, in the 1999–2000 winter wheat season, when rainfall was scarce, the yield of the crop that was irrigated three times was almost 50% more than the crop without irrigation. However, the most frequent irrigation did not produce the maximum grain yield and gave the lowest (winter wheat) or almost the lowest (corn) WUE.

Because of the variation in rainfall, the frequency of irrigation needed to obtain maximum yield differed from one year to another. Generally a single

Table 4. Relation of leaf water potential to air temperature, radiation and vapour pressure difference in the absence of water stress at Luancheng Station.

Parameters	Winter wheat			Summer corn		
	Equation	*n*	*r*	Equation	*n*	*r*
Temperature (T, °C)	$\Psi L = 0.3279 + 0.0478T$	53	0.706	$\Psi L = 0.2012 + 0.01084T$	64	0.808
Vapour pressure deficit (VPD, mb)	$\Psi L = 0.7077 + 0.0384VPD$	53	0.762	$\Psi L = 0.1969 + 0.0592VPD$	64	0.812
Radiation (J/m^2/s)	$\Psi L = 0.733 + 0.00392R$	47	0.820	$\Psi L = 0.3666 + 0.01491R$	64	0.815

ΨL = absolute leaf water potential; *n* = number of measurements; *r* = correlation coefficient; mb = millibar; J/m^2/s = Joules per square metre per second

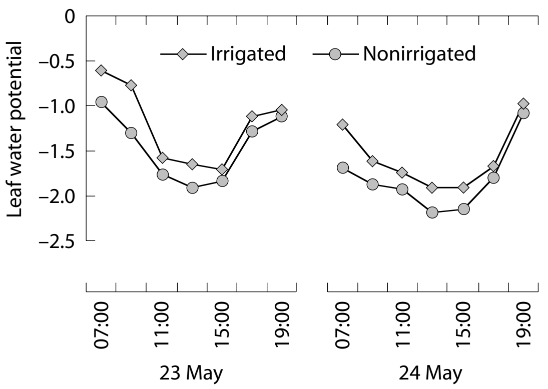

Figure 12. The difference of leaf water potential of summer corn under fully irrigated conditions and water-deficit conditions in 1996 at Luancheng Station.

Table 5. The variation of leaf water potential at different levels of soil moisture with full irrigation at Luancheng Station.[a]

Soil moisture	Difference in leaf water potential (kPa)	
	Winter wheat	Corn
80	0.1–0.2	0.1–0.2
60	0.3–0.45	0.3–0.4
45	0.5–0.67	0.45–0.6

[a] 0–50 cm soil moisture (percentage over field capacity)

irrigation in a wet year, two in a normal year and three in a dry year produced the maximum grain yield for winter wheat. For corn, three irrigations in a dry year produced the highest grain yield. Because the three seasons when corn was grown had less rainfall than in normal years, no results were obtained for wet or normal years. However, previous experiments suggested that for corn no irrigation was required when rainfall was high during the growing season (around 400 mm) and a single irrigation at seedling stage was sufficient in normal years.

Analysis of variance showed a significant difference in the effects of irrigation frequency and timing on yield and rate of water use. For example, in the 1998–99 season of winter wheat, five treatments were tested, all but two of which included two

Table 6. Yield, water use efficiency and total water consumption of different irrigation treatments for winter wheat at Luancheng Station, 1996–97.[a]

Number of irrigations	Timing of irrigation	Total irrigation (mm)	Total water consumption (mm)	Yield (kg/ha)	Water use efficiency (kg/m^3)
1	21 Nov	67.5	364.7	5500.6	1.51
2	21 Nov, 22 Apr	144.4	428.6	6900.8	1.61
2	21 Nov, 29 Apr	153.5	434.5	6164.3	1.42
3	21 Nov, 27 Mar, 22 Apr	171.4	428.9	6494.3	1.51
3	21 Nov, 27 Mar, 29 Apr	200.1	475.9	6308.6	1.33
3	21 Nov, 27 Mar, 7 May	186.7	460.0	6503.3	1.41
3	21 Nov,27 Mar, 14 May	193.7	476.1	6219.8	1.31
3	21 Nov, 18 Apr, 14 May	194.8	470.1	7170.0	1.53
3	21 Nov, 29 Apr, 22 May	176.7	413.2	6236.6	1.51
4	21 Nov, 27 Mar, 22 Apr, 14 May	252.5	474.7	6503.3	1.37

[a] All treatments were irrigated before over-wintering on 21 November

Table 7. Yield, water use efficiency and total water consumption of different irrigation treatments for winter wheat at Luancheng Station, 1997–98 season.

Number of irrigations	Timing of irrigation	Total irrigation (mm)	Total water consumption (mm)	Yield (kg/ha)	Water use efficiency (kg/m^3)
0	–	0.0	299.4	5413.8	1.81
1	15 April	84.7	333.7	6088.2	1.83
2	25 Mar, 21 Apr	95.0	338.4	5954.9	1.76
2	25 Mar, 20 May	151.3	366.0	5958.0	1.63
3	25 Mar, 21 Apr, 20 May	175.9	375.6	5650.7	1.50
3	7 Apr, 21 Apr, 20 May	166.6	389.8	6066.0	1.56

irrigations with 160 mm of water. Due to differences in the timing of irrigation, there was about 10% variation in WUE and yield. The results indicated that irrigation scheduling can be optimised for high yield and WUE.

Table 11 shows the irrigation scheduling for winter wheat that was developed from information about sensitivity to water stress, supplemental water available (200–250 mm annually) and experimental results. A single irrigation at the seedling stage is usually sufficient for summer corn, because the crop grows in the rainy season. Such irrigation would not exceed the amount of water available and would stop the decline in the groundwater table.

Table 8. Yield, water use efficiency and total water consumption of different irrigation treatments for winter wheat at Luancheng Station, 1998–99 season.

Number of irrigations	Timing of irrigation	Total irrigation (mm)	Total water consumption (mm)	Yield (kg/ha)	Water use efficiency (kg/m^3)
0	–	0	323.0	5325.8	1.65
1	16 Mar	80	366.4	7023.8	1.92
1	3 Apr	80	338.2	6697.5	1.98
1	24 Apr	80	370.4	7058.3	1.91
2	4 Mar, 24 Apr	160	444.2	7592.0	1.71
2	11 Mar, 24 Apr	160	438.4	7422.5	1.69
2	17 Mar, 6 May	160	399.0	6915.0	1.73
2	17 Mar, 14 May	160	403.9	7344.6	1.82
2	21 Nov, 24 Apr	160	400.3	6923.0	1.73
2	31 Mar, 5 May	160	442.5	7296.0	1.65
4	21 Nov, 31 Mar, 24 Apr, 5 May	240	478.5	6937.5	1.45

Table 9. Yield, water use efficiency and total water consumption of different irrigation treatments for winter wheat at Luancheng Station, 1999–2000 season.

Number of irrigations	Timing of irrigation	Total irrigation (mm)	Total water consumption (mm)	Yield (kg/ha)	Water use efficiency (kg/m^3)
0	–	0	282.9	5103.8	1.80
1	6 Apr	60	325.0	6180.8	1.90
2	2 Dec, 6 Apr	120	374.6	6810.0	1.82
2	25 Mar, 25 Apr	120	414.2	7092.9	1.71
3	2 Dec, 18 Apr, 10 May	180	432.6	7593.2	1.76
4	2 Dec, 6 Apr, 25 Apr, 15 May	240	487.7	6937.8	1.42

Discussion

For winter wheat, this study found that, in wet, normal and dry years, respectively, at a rate of 60 mm per irrigation, one, two or three irrigations of the crop were sufficient to obtain maximum profit and WUE. As winter wheat in this region is generally irrigated between three and five times each season, such an irrigation schedule could substantially reduce the use of groundwater. The amount of irrigation necessary for maximum profit was less than that required for maximum yield.

Table 10. Yield, water use efficiency and total water consumption of different irrigation treatments for corn at Luancheng Station, 1997, 1998 and 1999 seasons.

Year	Number of irrigations	Timing of irrigation	Total irrigation (mm)	Total water consumption (mm)	Yield (kg/ha)	Water use efficiency (kg/m^3)
1997	0	–	0	220.93	4114.5	1.86
	1	17 July	60	275.21	5611.1	2.03
	2	17 July, 14 Aug	120	349.36	5859.0	1.68
1998	0	–	0	290.40	5233.7	1.80
	1	16 July	60	364.60	6659.0	1.83
	2	16 Jul, 14 Aug	120	370.97	7118.4	1.92
1999	0	–	0	301.45	8155.5	2.52
	1	18 Jul	60	341.33	8794.5	2.58
	2	18 Jul, 7 Aug	120	355.46	9034.5	2.54
	3	18 Jul, 1 Aug, 23 Aug	180	402.73	9565.5	2.37
	4	18 Jul, 1 Aug, 23 Aug, 8 Sep	240	447.89	9280.5	2.07

Table 11. The optimised irrigation scheduling for maximum yield and water use efficiency of winter wheat with different types of seasonal rainfall under limited irrigation.

Type of seasonal rainfall[a]		Growth stage					
		Sowing to recovering	Jointing	Booting	Heading to milky filling	Maturing	Total (mm)
Dry	Average rainfall (mm)	30.7	3.5	6.3	12.9	6.4	59.8
	Simulated irrigation (mm)[b]	60	60	0	60	0	180
Normal	Average rainfall (mm)	52.3	10.9	17.4	16.3	8.1	105.0
	Simulated irrigation (mm)[b]	0	60	0	60	0	120
Wet	Average rainfall (mm)	67.9	17.4	22.8	34.2	12.1	154.4
	Simulated irrigation (mm)[b]	0	0	60	0	0	60

[a] Seasonal rainfall was analysed using the data from 1951 to 1999 in Luancheng County

[b] ‘Simulated irrigation’ is the irrigation amount used in the simulation model

In addition to irrigation scheduling, WUE can be improved by methods such as reducing soil evaporation. In the piedmont of Mount Taihang, about 30% of total water consumption in growing winter wheat and summer corn resulted from soil evaporation. Total soil evaporation was about 273 mm, equivalent to the amount needed for more than four irrigations of the crop. If this evaporation was reduced by even 50%, at least two irrigations of the crop could be saved. Thus, there is great potential for improving farmland WUE by reducing soil evaporation in the region, perhaps by the use of straw mulching.

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