

Improving Agricultural Water Use Efficiency in Arid and Semiarid Areas of China

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Abstract

Water shortage in China, particularly in the north and northwest of China, is very serious. The region accounts for half of the total area of China, but has less than 20% of total national available water resources. While the water shortage in this region is severe, irrigation water use efficiency is only about 40%, with a typical agricultural water use efficiency of about 0.46 kg m⁻³. Excessive irrigation in Ningxia and Inner Mongolia has had a significant influence on downstream water users along the Yellow River. It is widely believed that an increase in the agricultural water use efficiency is the key approach to mitigate water shortages and to reduce environmental problems. This paper reviews water-saving agricultural systems and approaches to improve agricultural water use efficiency in the arid and semiarid areas of China. The paper will cover biological mechanisms of water-saving agriculture and water-saving irrigation technologies, including low pressure irrigation, furrow irrigation, plastic mulches, drip irrigation under plastic, rainfall harvesting and terracing. In addition, the paper addresses the compensatory effect of limited irrigation and fertilizer supplementation on water use efficiency and highlights the need to breed new varieties for high water use efficiency. Considerable potential for further improvement in agricultural water use efficiency in the region depends on effective conservation of moisture and efficient use of the limited water.

Media summary

Further improving agricultural WUE in arid and semiarid areas of China depends on effective conservation of moisture and efficient use of limited water.

Keywords

Water-saving, plastic mulch, terracing, limited irrigation, north and northwest of China.

Introduction

China is a country of both water scarcity and abundance because of the imbalance in the distribution, timing and location of precipitation. The total annual water resources available in China are 2,800 billion m³. With a population of 1.3 billion, the available water per capita water is less than 2,200 m³, one quarter the world average (Shan et al. 2000). Over 80% of the water resources are concentrated in the southeastern part of China where the arable area is only 35% of the country's total arable area of 95 million ha. In contrast, the water resources in the northern parts of the country account for less than 20% of the total, whereas arable land accounts for 65% of the total.

Of the total arable area, 50 million ha, or about 50 % of the total, is irrigated, mainly in the southeast where the water resources are more abundant. The water used in irrigation accounts for 80 % of the total water use in China, but as 80% of the food is produced on irrigated farmland, this water is important in feeding the large population (Yang et al. 1999). Dryland agriculture (crops and pastures) accounts for more than 70% of total farmland in northern and north-western China, including the vast rainfed areas to

the north of the Qinling Mountains and Huaihe River. Twenty five million hectares are located in the Loess Plateau, while the North China Plain has 16 million hectares of arable land and produces about 20% of the nation's food.

With its large population, China cannot maintain food security without irrigation. In northern and northwestern China where natural rainfall does not match the needs of crops in both quantity and temporal distribution, supplementary irrigation is used to increase yields and provide the food needs of the nation. However, excessive-use of diverted river flows and groundwater has caused severe environmental problems. For example, since 1972 the Yellow River in northern China has dried up in the winter months for several years to the extent that water did not reach the sea and in an extreme drought year failed to reach the sea for 7.5 months (MWR 2000). In the North China Plain where groundwater is the primary source of water for irrigation, the groundwater level has declined rapidly from about 10 m below the soil surface in the 1970s to about 30 m in 2001 (Zhang et al. 2003). Moreover, inefficient use of water is a notorious phenomenon in irrigation systems. It is estimated that in the North China Plain about half of the water is lost to leakage during transfer to farmers' fields (Liu and He 1996). Of the water reaching the field, losses of water are also substantial. Flood irrigation is predominant and more efficient irrigation systems such as sprinklers and drip irrigation is negligible.

China's population will increase by 12 million people annually over next half century. To support this growing population, food production has to be based on improving water use efficiency and further expansion of irrigation. Given the severe shortage of water resources in North China, the expansion of irrigated land is expected to be limited. Therefore, increasing water use efficiency in both irrigated agriculture and promoting dryland farming through water conservation and efficient use of rainfall will play significant roles in maintaining food security.

This paper reviews the current status of water-saving agriculture in northern China and highlights that further improvement in agricultural WUE in arid and semiarid areas of China depends on effective conservation of moisture and efficient use of limited water.

The climate and farming systems in northern China

Dominated by a continental monsoon climate, precipitation in north China is generally low and concentrated in a few months for the year. Annual rainfall gradually decreases from about 600 mm in the North China plain to 440 mm in the Loess Plateau (between Xi'an, Taiyuan, Yinchuan and Lanzhou in central China) to less than 300 mm in the northwest of China (Fig. 1). About 70 % of the annual precipitation is in the form of storms in the four months of June, July, August and September (Fig. 2).

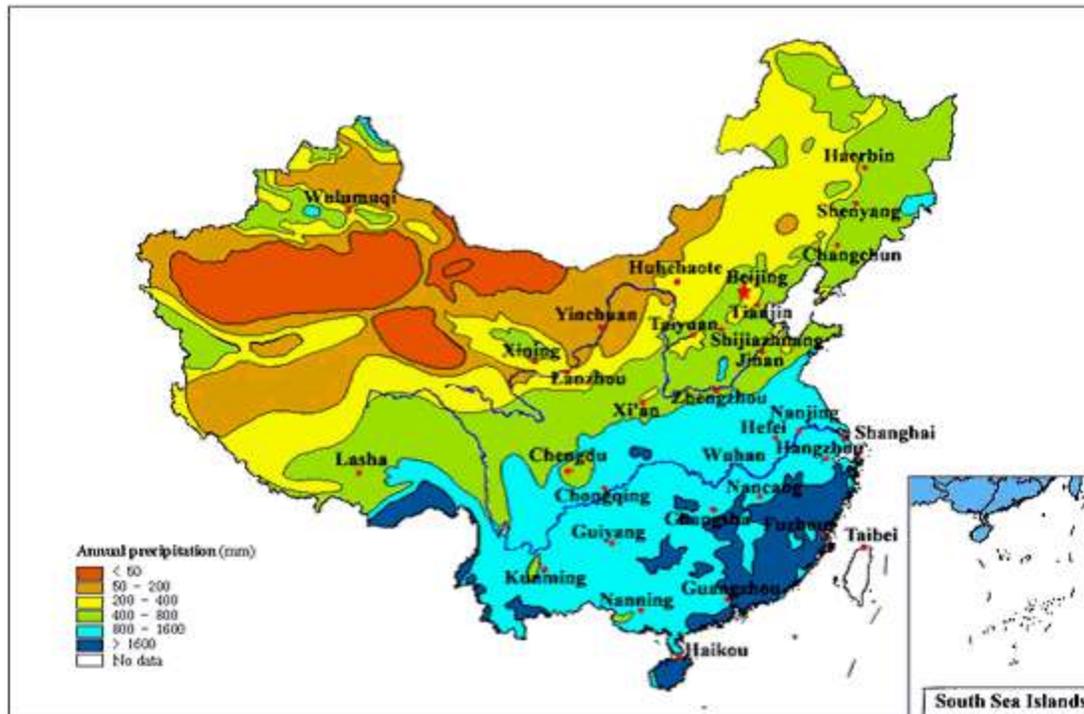


Figure 1. China's long-term mean annual precipitation distribution (source: China Meteorological Administration).

Winter wheat and maize are the staple crops in the North China Plain and the wetter part of the Loess Plateau. Winter wheat is usually rotated with maize each year. Wheat is usually planted in early October and harvested in early June. The maize is sown shortly before or immediately after the wheat is harvested. The annual rainfall is not enough to support two crops and therefore supplemental irrigation is usually applied to the wheat during spring and early summer and occasionally also to the maize if summer rainfall is deficient. The cropping system over much of the Loess Plateau is mainly a winter wheat monoculture with a three-month fallow during the rainy summer season. In the drier and colder areas winter wheat is replaced by spring wheat. Other rotations include double cropping with winter wheat followed by soybeans each year, spring wheat followed by field peas or millet every two years. In both the North China Plain and Loess Plateau, the soil is usually ploughed before sowing.

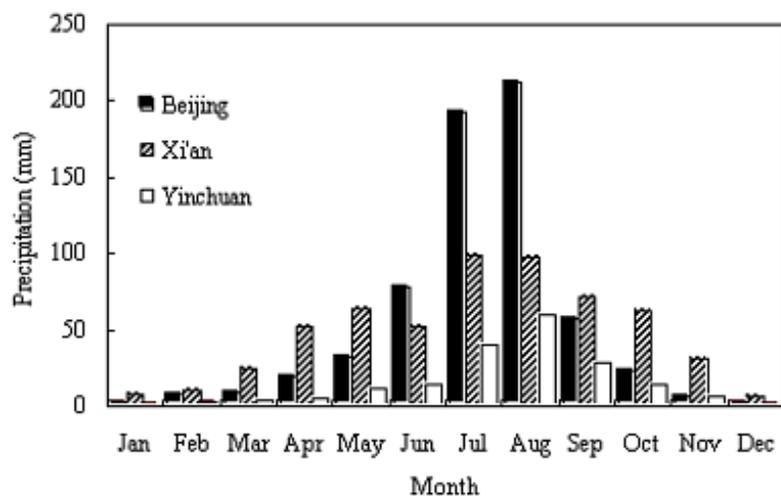


Figure 2. Distribution of rainfall at three selected locations in the north and northwestern part of China (over the last 30 years, the average annual rainfall in Beijing, Xi'an and Yinchuan was 644, 580 and 190 mm, respectively).

Water use efficiency of major crops

In the northern part of China, Xu and Zhao (2001) investigated the long-term crop yields, precipitation, and the amount of irrigation water applied in Fengqiu County. Their results showed that from 1949 to 1996, the water use efficiency (WUE) increased from 0.23 kg m^{-3} to 0.90 kg m^{-3} , mainly caused by the establishment of water conservation facilities, better soil management, extension of new crop varieties and a continuous increase in the use of nitrogen and phosphorus fertilizers. Duan and Zhang (2000) investigated the crop WUE from 4,422 irrigated sites/seasons located in 22 provinces. Their data indicated that the average WUE of the principal crops was 1.1 kg m^{-3} , and that from 1953 to 1986 the yield of wheat and WUE increased similarly. In the semiarid northwest part of China, Mu (1999) showed that the WUE of broomcorn millet (*Panicum miliaceum*) was about 0.74 kg m^{-3} in an agricultural technical demonstration trial. Table 1 summarises the differences of WUE of major crops in irrigated and dryland agriculture. However, the WUE of bushes and trees were much lower than that of crops in the gully regions of the Loess Plateau. Hu et al. (2001) showed that the average WUE of rosebushes (*Rosa davurica*) was about 0.23 kg m^{-3} , shrubbery was about $0.28 - 0.32 \text{ kg m}^{-3}$, grasses were about $0.26 - 0.41 \text{ kg m}^{-3}$, and locust trees (*Robinia pseudoacacia*) were 0.32 kg m^{-3} . However, on the north-facing sides of the gullies, the WUE of poplar (*Populus tremuloides*) and locust trees was 0.67 and 0.74 kg m^{-3} , respectively.

Table 1. Water use efficiency of major crops in irrigated and dry farmland in China

Crops		Average WUE (kg m^{-3})	
		Irrigated farmland*	Dry farmland**
Wheat (<i>Triticum aestivum</i>)	Winter wheat	1.32	1.01
	Spring wheat	0.80	0.52

Maize (<i>Zea mays</i>)	Spring maize	1.70	1.54
	Summer maize	1.74	----
Millet (<i>Setaria italica</i>)	Spring millet	1.10	0.61
	Summer millet	0.74	----
	Soybean	0.57	0.25
	Sorghum	1.91	0.48

* After Duan and Zhang (2000); ** After Mu (1999), Xin and Wang (1998).

At present, the rainfed WUE for grain yield in China is $2.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$, far behind that at experimental sites ($6\text{-}12 \text{ kg ha}^{-1} \text{ mm}^{-1}$) (Xin and Wang 1998; Wang et al. 2002) and the potential WUE of $20 \text{ kg ha}^{-1} \text{ mm}^{-1}$ obtained for rainfed wheat in a Mediterranean-climatic region of Australia (French and Schultz 1984). In recent years, experience in dryland farming demonstration counties has shown that grain yield can be increased by over 50% and yield per mm of rainfall by above $6 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (Shan 2003).

Improving agricultural WUE continues to increase as a topic of concern because of the demand for increased grain production in China. More than two-thirds of China's poverty-stricken people live in arid and semiarid areas. To solve the food and clothing problems of these people requires water-saving agriculture to be accelerated and grain and fibre yields to increase. However, farmers have only just begun to adopt water-saving practices and adoption has been low, possibly because farmers do not benefit directly by saving water. In addition, the current extension system charged with promoting the adoption of water-saving technologies or practices faces poor incentives and low budgets to carry out this work. In the semiarid areas attention has been focused on technical demonstrations aimed at increased yields in areas of low and medium yields (Shan et al. 2002). The system tends to promote technological solutions, developed at agricultural universities and research institutes rather than technologies and practices appropriate for low-income farmers. Although there are many places where the components of water-saving agriculture can be manipulated, such as water-saving irrigation and soil management, improvements in the water productivity of crops by physiological and genetic approaches has not yet been fully achieved.

Water-saving agriculture in China

The concept of water-saving agriculture

Water-saving agriculture refers to a farming practice that is able to take full advantage of the natural rainfall and irrigation facilities. The core problem that water-saving agricultural research has to solve is how to raise the water utilization rate and water use efficiency, that is to achieve a high yield on irrigated farmland with the minimum input of water and in rainfed agriculture to maximize rainfall use efficiency. What we stress here is that water-saving agriculture is not simply water-saving irrigation. It is a comprehensive exercise using every possible water-saving measure in whole-farm production, including the full use of natural precipitation as well as the efficient management of an irrigation network. In the north and northwestern part of China, water-saving agriculture includes the following three practices:

(1) Water-saving irrigation. This refers to the use of irrigated farming practice with the most economical exploitation of the water resources. Based on actual crop need, the irrigation management has to be improved so that the water supply to the crop can be reduced while still achieving a high yield. At the

same time, water leakage and evaporation from storage facilities and in transport have to be reduced to the minimum.

(2) Limited irrigation. Limited irrigation means that a soil water deficit is induced at non-critical stages of crop growth while supplemental irrigation is provided at critical stages of growth. It is a system of crop management in which dryland cultivation is integrated with a limited water supply in an irrigation network that is only able to supply part of the water needed for crop growth (Shan et al. 2000).

(3) Dryland cultivation. This refers to water-saving agriculture for areas beyond the reach of any irrigation network where natural precipitation has to be used effectively by collecting runoff or direct collection of rainfall and application to a crop to increase the yield.

Of the three, limited irrigation is becoming a new trend in water-saving agriculture. It is possible to develop water-saving information for the precise control of the timing and quantity of irrigation water, and thus limited irrigation can be expected to be a dominant form of crop cultivation in the future. The main purpose of all three kinds of water-saving agriculture is to increase the WUE of the system. In other words, it is to raise the following ratios to their maximum: soil-stored water content/precipitation volume; water consumption/soil storage of water; transpiration/water consumption; biomass yield/transpiration; economic benefit/biomass yield. The upgrading of these hydro-pedagogical and plant parameters are the key issues to be solved.

A water-saving agricultural system

A water-saving agricultural system refers to integrated farming practices that are able to sufficiently use natural rainfall and irrigation facilities for improved water use efficiency (Shan 2002). The scientific measures in a water-saving agricultural system includes spatial and temporal adjustment of water resources, effective use of natural rainfall, rational use of irrigation water and increased plant WUE (Figure 3). In agricultural practice, several factors need to be take into account, namely (i) the quantity, quality, spatial and temporal distribution of water resources, (ii) the establishment of cultivation practices aimed at reducing water consumption as a result of reshaping the existing farming structure and cropping system in line with the current distribution pattern of water resources, (iii) sufficient manpower and equipment for the research, development, production, supply and maintenance of water-saving materials, spare parts, instruments and facilitates, (iv) relevant laws and statutes concerning water management to be enacted, formulated and perfected, and (v) a special campaign to enhance the public's water-saving awareness (Deng et al. 2003a).

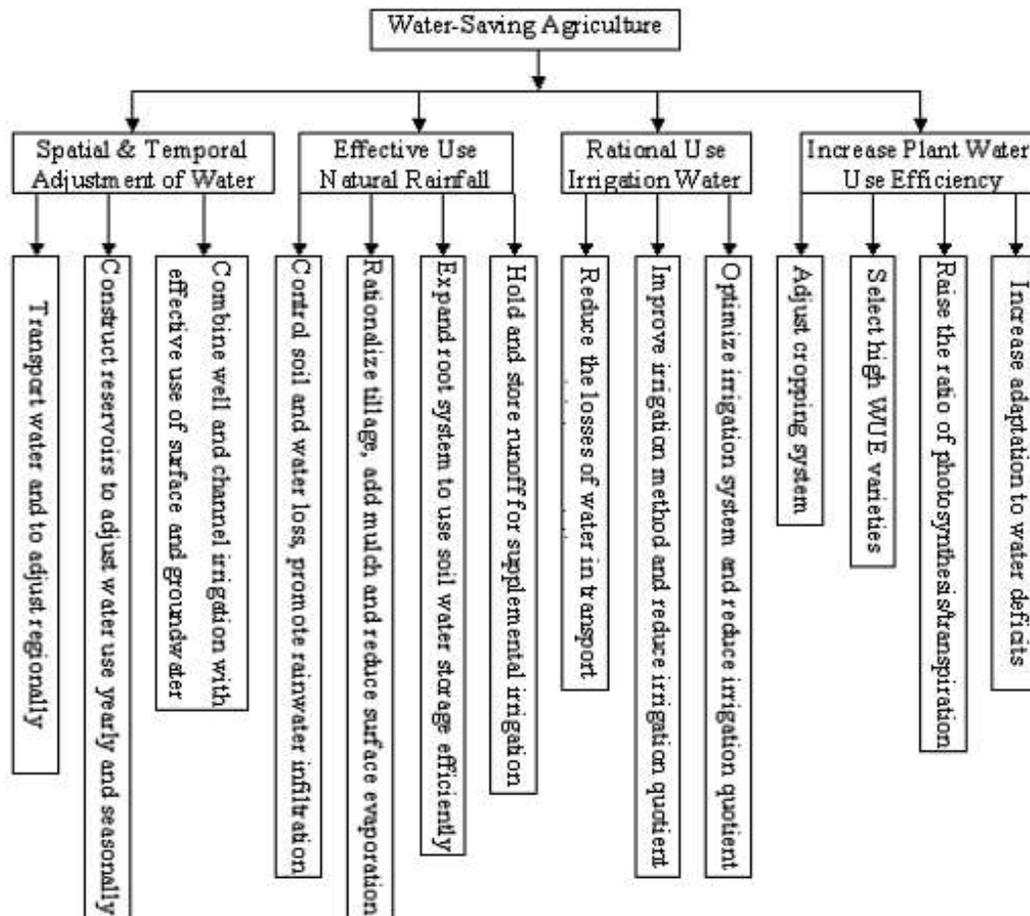


Figure 3. Components of a water-saving agricultural system and its regulating elements.

Besides water-saving irrigation networks and conservation tillage, a good understanding of factors limiting and/or regulating yield now provides researchers with a great opportunity to identify and select physiological and breeding traits that increase plant WUE and drought tolerance under water-limited conditions, thereby increasing plant WUE.

Some biological issues in water-saving agriculture research

In arid and semiarid environments, the response of plants to water deficits and the variable environment is complex because conditions vary in the frequency of drought and wet periods, the degree of drought, the speed of onset of drought, and the patterns of soil water deficits and/or atmospheric water deficits (Deng et al. 2003b). A crop's sensitivity to the different drought patterns varies during different growth stages. Drought tolerance in terms of yield is a complex trait at the whole plant or crop level with a range of adaptive pathways and physiological mechanisms in the varied types of 'drought' environments that occur. Biological water-saving aims to increase crop WUE and drought tolerance by genetic improvement and physiological regulation. Accordingly, there is a need to accurately understand the plant responses to water deficits on a real-time basis (Turner 1997; Richards et al. 2002).

Effect of water deficits on several physiological processes

Cell expansion is considered one of the most sensitive processes to water deficits. This leads to leaf expansion being very sensitive to water shortage and a reduction in leaf area being one of the key ways

in which a plant adjusts its water use (Passioura 2002). Reduced cell expansion also has an effect on the development of yield components, such as the inflorescence, or tiller initials in the cereals, leading to potentially small reproductive organs and reduced yield. This can be an irreversible effect that is difficult to overcome by re-watering. It can, however, be overcome to some extent by inter-organ compensation following re-watering, such as late tillering and more or larger grains per spikelet in cereals with fewer spikelets. However, meristematic tissues are generally positioned within the plant in a relatively protected environment as compared with that of a fully-expanded leaf and therefore it may take a severe stress for the meristem to lose its turgor.

Wang and Liu (2003) show that, under field conditions in northern China, there is a parabolic relationship between photosynthesis and transpiration, such that transpiration increases as photosynthesis increases but continues to increase when photosynthesis reaches a maximum so that ultimately transpiration efficiency decreases. At these levels, transpiration can be controlled without affecting the rate of photosynthesis. It is possible that measures for reducing stomatal conductance and preventing excessive transpiration could save water and improve WUE. Also, photosynthesis can vary at the same soil moisture content depending on the rate of drying (Deng et al. 1995). Under gradual soil drying conditions, wheat exhibited a higher photosynthetic rate than under fast soil drying conditions. In the former, osmotic adjustment increased by 0.13 MPa while under the latter process it remained constant. Osmotic adjustment allows for the maintenance of photosynthesis and growth by stomatal adjustment and photosynthetic adjustment (Turner, 2004). The study of Deng et al. (1995) showed that under mild and/or moderate soil water deficits, the decrease in the rate of photosynthesis was caused by stomatal closure or stomatal limitation, but not by a decrease in biochemical reactions. However, under severe soil water deficits, non-stomatal factors including some limiting enzymes could have been responsible for the decline in photosynthetic capacity (Du et al. 1998). Midday declines in photosynthesis have been shown to be induced by high vapor pressure deficits (VPD), and stomatal limitation was suggested as a major cause (Xu and Shen 1997). Under natural semiarid conditions, however, this decline usually resulted from soil water deficits that induced a decrease in leaf water potential at midday. Deng et al. (2000a) reported that both soil water deficit and high VPD simultaneously induced the midday depression in photosynthesis, which was interpreted as both stomatal and non-stomatal limitations being responsible for the decrease in photosynthesis in spring wheat in a semiarid environment.

Shortage of assimilates and sometimes nitrogen availability is a major cause of arrested grain growth during drought stress. Drought stress during cereal grain development reduces the duration of grain filling. If the rate of grain filling is not increased, the final grain weight is reduced. An increased grain growth rate under drought stress depends on the supply of assimilates. During stress the supply of assimilates decreases due to the inhibition of current photosynthesis. An alternative source of assimilates is the water-soluble carbohydrates stored in the stem. These reserves are readily utilized for grain filling and their availability may become a critical factor in sustaining grain filling and grain yield under drought stress (Ren et al. 2003).

It seems that the order in which crop physiological processes are affected by drought are growth, stomatal movement, transpiration, photosynthesis and translocation (Shan and Chen 1998). These observations permit irrigation scheduling to be designed to reduce the water supply and at the same time minimize losses in crop yield.

Drought sensitivity at the different crop growth stages

Many studies (Mary et al. 2001; James et al. 2001) have looked at the yield losses associated with drought at different stages of plant development. Villareal et al. (1999) showed that crown root initiation and anthesis are the two stages at which yield losses from drought stress can be the most critical in wheat. Current research (Trethowan and Pfeiffer 2000) is aimed at identifying different plant traits that would allow wheat varieties to withstand the different types of drought. Liang et al. (2002) demonstrated that alternately drying and rewatering had a significant compensatory effect that could reduce transpiration and increase WUE significantly under drought conditions.

In the North China Plain and Loess Plateau, winter wheat was found to be sensitive to water stress from stem elongation to heading and from heading to milking (Table 2). Limited irrigation and supplemental irrigation are recommended at these growth stages. On the Loess Plateau, Kang et al. (2002) found that periods of mild soil water depletion in the early vegetative growth together with severe soil water depletion near maturity was optimal for limited irrigation of winter wheat in this 540 mm rainfall region. Deng et al. (2002) showed that in the Guyan County of the Ningxia Uh Autonomous Region of China, a single irrigation of 600 m³ ha⁻¹ (equivalent to 30% of the volume of irrigation water required for a full cropping season and the maximum yield) applied at the jointing stage yielded up to 75% of the yield of the fully-irrigated wheat. This amounted to a 2.8 kg increase in grain yield per cubic meter of water. The optimum time for limited irrigation in spring wheat was at the jointing stage, before the water deficit became critical. It seems essential to make a distinction between the critical growth stage at which yield is greatly reduced by drought from the one at which supplemental irrigation results in the highest yield improvement.

Table 2. The sensitivity index of winter wheat to water stress during individual growth period in the North China Plain and Loess Plateau

	Sowing to tillering	Tillering to re-greening	Re-greening to jointing	Jointing to heading	Heading to milking	Milking to maturity
North China Plain	0.080	0.010	0.083	0.183	0.126	0.009
Loess Plateau	0.116	0.115	0.111	0.315	0.245	0.001

Adapted from Zhang et al. (1999) and Shangguan et al. (2002).

Varietal responses to water deficits

While the current interest in research at the molecular level is important, it should accompany research on water relations at the whole plant level. The success of crops in producing yield depends primarily on the success of leaves in controlling water loss and the effectiveness of roots in taking up water. Tolerance of dehydration depends on characteristics at the biochemical or molecular level, such as osmotic adjustment, the water conductivity in tissues, and the manner in which the water deficit affects enzyme-mediated processes. Clearly, both avoidance and tolerance of water deficits will contribute to successful crop production under semiarid conditions. Avoidance of severe water deficits requires coordination at the whole plant level between the control of water loss from transpiring shoots and water absorption through root systems.

Using gas exchange methodology and the stable isotope ¹³carbon, Zhang and Shan (1998) demonstrated that the WUE of modern wheat cultivars is irrigated varieties > varieties of both irrigated and dryland > dryland varieties. Zhang et al. (2002) showed that in the evolution of wheat from 2n→6n, the WUE at the whole plant level increased with the increase in ploidy, which in turn increased with an increase in the size of the root system, whereas the root/shoot ratio of wheat decreased with the increased ploidy level under both drought and irrigated conditions. This suggests that early wheats had excessive root proliferation at the expense of shoot growth, thereby reducing WUE, and the increase in ploidy has resulted in an increase in shoot and grain growth and an increase in wheat WUE at the whole plant level. These results suggest that use of breeding to increase the water-saving potential of wheat is possible.

A deep root system is synchronous with more water uptake from the soil and better performance under drought. It may, however, be that the root systems of cultivars grown in a given region are already adequate and further improvement may not be required. Information on whether the current cultivars

extract all the available soil water is required to establish this. If soil water remains after harvest then genetic improvement in rooting depth and/or distribution may be required. This trait is, of course, difficult to measure. The simplest way to increase rooting depth and root distribution of crops is to increase the duration of the vegetative period. This may be achieved by sowing earlier or delaying flowering by using a late cultivar.

Interaction of water and nutrients in WUE

According to our recent research results (Deng et al. 2003a), the contribution of nutrients can improve WUE and biological water-saving as shown in Figure. 4. The nutrients that are found to be most limiting in the loess hilly region of China are nitrogen (N) and phosphorus (P) (Shan and Chen 1993). Most of the soils in the Loess Plateau region of China are calcareous, especially on the eroded tops of hills. The deficiency is really a problem of high pH and runoff (Wei et al. 2000). The increased yield and WUE from added N was observed in several dryland areas where crops were grown on the same land for several years (Shan and Chen 1993). Liu et al. (1998) indicated that the maximum yield and highest WUE were achieved under the optimum fertilizer input of 90 kg N ha⁻¹ and 13 kg P₂O₅ ha⁻¹ in the semiarid field conditions of loess hilly area in Ningxia. Increased fertilizer application was positively correlated with grain yield and WUE of spring wheat, with correlation coefficients of 0.96 and 0.89, respectively. Increasing the level of fertilizer significantly increased the number of fertile spikelets, kernels/spike and kernel weight. The number of fertile spikelets was particularly sensitive to fertilization, whereas kernel number and weight were more affected by plant density. Fertilizer applied in spring wheat improved the development of the root system and especially enhanced root growth in the cultivated 0-20 cm soil layer. The increased root system in the fertilized plants was able to improve crop water use and nutrient absorption and hence crop yield and WUE was increased.

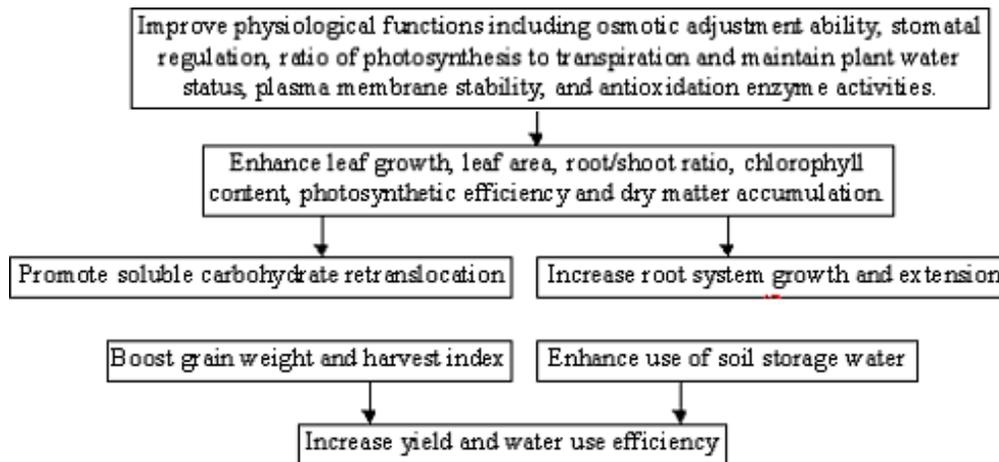


Figure 4. Compensatory effects of crop plants adapted to moderate water deficit.

Water-saving agricultural practices

Water-saving irrigation

Due to increased water scarcity, the irrigated area is unlikely to expand in the dryland region of northern China. Supplemental irrigation, the combination of dryland farming and limited irrigation, is an ideal choice for improving crop yields in this region (Bai and Dong 2001). Good irrigation scheduling requires the timing of irrigation and the amount of water applied to match actual field conditions. This requires information on soil-moisture conditions at the time of irrigation and, when using irrigation, close cooperation among farmers to be effective. Further, water-saving irrigation depends on adopting water-saving techniques in the transportation and application of the water.

On-farm WUE can be improved by moving to a more efficient irrigation system. There are three main types of irrigation systems available: border or furrow flood irrigation, sprinkler irrigation and drip irrigation with drip irrigation being more efficient than sprinkler irrigation and sprinkler irrigation being more efficient than border/furrow irrigation. An investigation into the irrigation of maize showed that 210 mm of irrigation applied by border irrigation under a mulch of wheat straw gave a grain yield, total evapotranspiration and water use efficiency of 8000 kg ha⁻¹, 390 mm and 2.2 kg m⁻³, respectively (Zhang et al. 2002). Increasing the amount of irrigation by 270 mm increased the yield to 8834 kg ha⁻¹, but WUE decreased. Straw mulching reduced the total evaporation by 50 mm showing that wheat straw mulching can reduce the amount of irrigation required by maize in the North China Plain (Zhang et al. 2002). Irrigation of cotton in Xinjiang indicated that the flowering and budding stages were the most suitable times to supply limited irrigation water, thus significantly improving the WUE by 57 % (Hu et al. 2002). In the northern part of China, Liu et al. (2003) reported that the yield and WUE of winter wheat under sprinkler irrigation conditions was increased by 28% and 48% and 636 m³ ha⁻¹ water was saved compared with that under border irrigation conditions. Zhang and Cai (2001) conducted a cotton irrigation experiment that demonstrated that irrigation under the surface of a plastic mulch is an effective way to protect soil evaporation and that a mild water deficit during the budding stage could significantly enhance lint yield and improve water use efficiency. These examples show that water-saving irrigation can really save water and need to be used at a regional scale. However, to improve the standard of irrigation design and irrigation efficiency requires (i) enforcement or regulation – requiring irrigation to be designed to a standard, and (ii) education – informing water users of the benefits of good design to encouraging them to expect a high standard of design from irrigation equipment suppliers (Zhou 2003).

Soil management

Terracing and contour farming

With frequent farming activities and a high degree of cultivation, sloping land with an angle of 10-25 degrees is highly susceptible to soil erosion. Cultivation on such slopes can lead to erosion of 0.43 cm and 48 t ha⁻¹ of fertile topsoil (Wei et al. 2000). Changing such sloping land into contour terraces prevents water and soil erosion, raises land quality and grain yield. Sloping land with an angle of 6-10 degrees can be improved by planting crops along the contour using a 0.5-m deep and 1-m wide trench or ridge to conserve soil and water, improve soil fertility and facilitate sustainable development. In the semiarid Loess Plateau, the building of level terraces has enhanced water infiltration, raised the rainfall utilization rate and created high-yielding farmland while also conserving the soil and water. Combined with other agricultural techniques, it had played a major role in increasing the productivity and sustainability of the region (Deng et al. 2000b).

Mulching

In the North China Plain and Loess Plateau, it has been shown that mulching with crop residues can improve water use efficiency by 10–20% through reduced soil evaporation and increased plant transpiration (Table 3). Mulching with crop residues during the summer fallow can increase soil water retention (Feng 1999). Straw mulching can be easily implemented by local farmers and has been extended in the provinces of Hebei, Gansu, Shaanxi, Ningxia, Qinghai, Inner Mongolia and Shandong because material is easily accessible, low cost and does not contaminate the soil. Combined with N, P and potassium (K) fertilizers, mulching of residues can improve yields by at least 1500 kg ha⁻¹ (Sun and Wang 2001).

Table 3 The effect of mulching on soil evaporation, grain yield and water use efficiency of wheat and maize.

Crop	Treatment	Evapotranspiration (mm)	Soil evaporation (mm)	Grain yield (g m ⁻²)	WUE (kg m ⁻³)
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Winter wheat	Mulching	367	75	714	1.94
	No mulching	390	117	669	1.72
Maize	Mulching	386	86	712	1.84
	No mulching	431	129	666	1.55
Summer fallow	Mulching		39		
	No mulching		107		

Adapted from Zhang et al. (2003) and Zhao et al. (1996).

Plastic film has also been widely used to mulch the soil surface and promote crop growth during early growth when temperatures are low. Several methods of using plastic film have been adopted, including sowing wheat and rice through holes in the plastic, sowing maize and wheat in rows in the furrow with plastic between the rows, and mulching two subsequent crops with same plastic film. Wang et al. (2004) conducted a field experiment in a loess soil in central Shaanxi Province to identify the effects of rainwater harvesting on WUE and yield of winter wheat. They used ridge-furrow tillage, the ridge being mulched by plastic for rainwater harvesting in the furrows. They demonstrated that mulching significantly increased the harvesting of rainwater and significantly increased yield. Biomass and grain yield in the mulched plots were 39.5 % and 28.9 % higher than in the corresponding treatments without mulching. The highest WUE of 4.4 kg m⁻³ for biomass and 2.2 kg m⁻³ for grain yield was achieved when N fertilizer was added and plant density was kept low.

Fertilization

Besides drought, another factor constraining productivity in dryland farming areas is soil infertility. A 15-year field experiment at the Changwu Ecological Station indicated that N is important in improving WUE and soil water use, while P plays an important role in increasing not only total soil water use but also water extraction from deep soil layer (Dang 1999). Table 4 summarized data showing that N increased water use efficiency by 20% in the region. The main ways to increase soil fertility include increasing the percentage of legume and green manure crops, and combining this with the use of inorganic fertilizers. The key is to adopt fertility-enhancing rotations such as a grain crop with a summer green manure crop, a grain-oilseed-legume rotation or grain-legume intercropping, grain-grass intercropping or wheat-potato intercropping in order to fully use resources like light, heat and water to achieve increases in yield and incomes. Increased use of chemical fertilizer in dryland farming has already doubled grain yields and hence WUE.

Crop residue mulching together with the incorporation of the residues increases soil organic matter and improves fertilizer use efficiency. Field experimental data in the North China Plain demonstrated that in a corn-wheat rotation, the grain yield of the field in which all the corn and wheat straw was retained in the field and incorporated into the soil was higher than that of the field in which only the wheat straw was retained in the field and incorporated into the soil (Zhang et al. 2001). The experimental results showed that the total water consumption of the two crops would be 780 mm and the water use efficiency would be 1.9 kg m⁻³ if the farmer retained and incorporated all the straw into the soil and added nitrogen fertilizer and animal manures (Zhang et al. 2001). In Ningxia, He et al. (1999) conducted experiments to clarify the effects of water and N and K fertilizer and animal manures on WUE of potatoes. The results showed that both N and water supply very significantly increased WUE. K and animal manure increased WUE significantly whenever one of them was deficient (He et al., 1999). Xu and Zhao (2001) reported that in

northern China, the crop WUE increased steadily over 10 years from 0.22 to 0.90 kg m⁻³ due to technological developments. The increase in WUE was mainly caused by the establishment of water conservation measures, soil improvement, the adoption of new crop varieties and the continuous use of increasing amounts of N and P fertilizers. Fertilizers have a great potential to further increase of the efficiency of water use, especially for crops that grow in autumn when the water supply is plentiful.

Table 4. Effect of nitrogen on water use efficiency (kg m⁻³) in dryland of north and northwest part of China.

Crop	N-	N+	Place	Data source
Winter wheat	0.271	0.472	Hebei, North China Plain	Shan et al. (2000)
Spring wheat	0.773	0.883	Shaanxi, Loess Plateau	Ren et al. (2003)
Winter wheat	0.643	0.834	Henan, Central China	Zhong et al. (2000)
Winter wheat	0.260	0.670	Changwu, Loess Plateau	Dang (1999)
Potato	0.956	1.142	Guyuan, Loess Plateau	He et al. (1999)

Water harvesting

In an area with annual rainfall less than 350 mm water harvesting can be used to collect rainfall for use as supplementary irrigation for agricultural production. On sloping and terraced land, water retention facilities are built to collect the natural rainfall so that in the case of a serious drought the water can be used to increase soil moisture by drip irrigation. Due to the limited volume of water that can be stored, the technology is usually used together with other water-saving measures such as sowing the plants with a small amount of water at the time of planting, plastic mulching, root-zone drip irrigation, and under-mulch irrigation. To build one water cistern with a capacity of 50 m³ needs an investment of around \$US50. It can provide supplementary irrigation water for 0.13 ha of land and ensure a yield over 4500 kg ha⁻¹. If the water is used in the production of cash crops like water melon, greenhouse vegetables and fruit trees, it will provide an even greater economic benefit to the farmer. To raise the rainwater utilization efficiency and to meet the demand of poverty alleviation and social-economic development, the Gansu Research Institute for Water Conservation carried out systematic experiments in the Dingxi area of China and in 1995 set up many pilot projects to demonstrate the benefits of water harvesting. The project has successfully solved the drinking-water problem for 1.3 million people and their 1.2 million livestock. Since 1997, a water catchment and irrigation project has been established to supply water for supplemental irrigation for use with highly efficient water-saving methods. The results have proved to be very successful and have changed the basic agriculture of the area. (Zhu and Li 1998). Water harvesting and its utilization have become a strategic measure for social and economic development in this semi-arid region, providing an effective means of alleviating poverty and allowing a breakthrough in dryland farming.

Challenges and perspectives

Improving agricultural WUE continues to be a topic of concern because drought is an important factor limiting grain production worldwide. Greater yield per unit of water is one of the most important challenges in water-limited agriculture. The WUE of Chinese agricultural production is surprisingly low. About 97% of farmers in the irrigated areas of north and northwest China still use traditional furrow or border (flood) irrigation methods, with an annual water demand of about 7,320 m³ ha⁻¹. In contrast, sprinkler or drip irrigation, which account for only 3% of the irrigated area, uses 3,250 m³ ha⁻¹ or less. More than 70 % of

the irrigated land in China does not apply any kind of water-saving measure (Jin and Young 2001). Therefore, large-scale water-saving crop production systems need to be established in the near future if China is to continue to feed its growing population.

Also in China, precipitation is far from being fully utilized. In northern China, with a yield of about 2.7 t ha⁻¹ rainfall use efficiency is only about 55% even on demonstration farms/regions (Shan and Chen 1998). In the southern hilly area of Ningxia Uh Autonomous Region, with 450 mm of annual precipitation, the spring wheat yield was 0.75-2.25 t ha⁻¹, with water use of 280 mm, which is about 20% to 60% of the annual rainfall (Shan 1998). These figures show that there is still considerable potential for further improvement in agricultural WUE. To increase the rainfall utilization rate, a comprehensive approach including prevention of water loss and soil erosion, reduction in soil evaporation, use of underground water storage and a steady increase in the proportional use of water by crops must be adopted (Figure 4). Increases in crop productivity can be achieved by combining water and soil conservation and the use of drought-tolerant varieties.

Agricultural WUE is broader in scope than simply the use of agronomic and biological solutions and must be considered on a watershed, basin, irrigation district, or catchment scale. The main pathways for enhancing

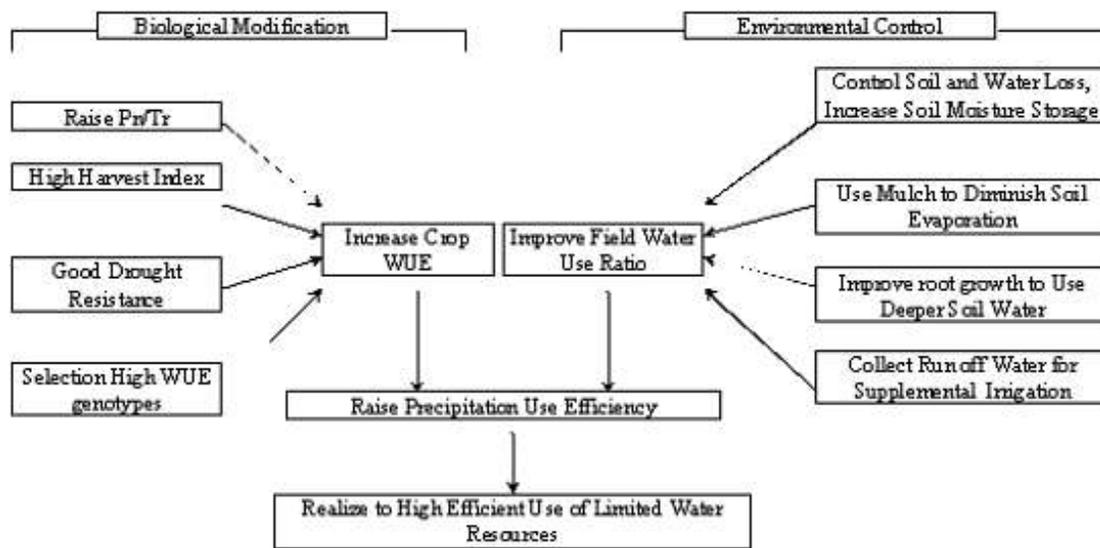


Figure 4. Water-saving approaches to improve agricultural WUE in the North and Northwestern China (Pn: photosynthetic rate, Tr: transpiration rate).

WUE with limited irrigation are to increase the output per unit of water (engineering and agronomic management aspects) (Zhang et al. 1998), reduce losses of water to unusable sinks, reduce water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects) (Howell, 2001). At present engineering technologies for water-saving agriculture, such as prevention of channel leakage, water delivery with low-pressure pipe, sprinkler and drip irrigation systems have been advocated and adopted. However, some solutions such as advanced surface irrigation techniques, water-saving irrigation scheduling and optimized water allocation in irrigation areas, and irrigation forecasting technology have not been widely advocated or adopted. Further study on new technologies for water-saving agriculture, such as combining biological water-saving measures with engineering solutions is also necessary (Deng et al. 2003b). Promoting water-saving agriculture is not only able to increase water use efficiency, but can also facilitate the structural adjustment needed by agriculture (Shan 2003).

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