Multiple strategies for efficiently reducing water use while sustaining the current higher productivity of winter wheat in the North China plain

Qiaozhen Li[1], Chunying Xu[1], Xiuli Zhong[1], Xiaoying Liu[1], Shuying Li[2], Ennke Liu[2*]

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As one of the most important agricultural regions in China, the North China Plain (NCP) is threatened by a serious water-resource crisis due to excessive exploitation of groundwater reserves. The situation urges the region to meet the challenge of conserving groundwater while maintaining high crop production. In this review, firstly, water saving by means of cultivar improvement and reasonable cultivar adoption was discussed. Based on studies around key factors affecting cultivar water use and yield formation, some target traits to be genetically improved were indicated, including stomatal conductance, stomatal drought sensitivity, the traits restricting non-stomatal transpiration and nocturnal transpiration, early vigor, carboxylation efficiency, and harvest index. Also, the strategies were tentatively proposed for appropriately matching cultivars with specific stomatal traits to water availability of local areas. Secondly, irrigation scheduling in the NCP need to be further optimized to markedly conserve groundwater without causing larger yield loss. Irrigation frequencies of four times currently used in wheat could be reduced at least once, depending on soil water status at sowing, jointing, and grain filling stages. Finally, mulching soil surface with maize straw at appropriate amount after trifoliate stage of wheat is expected to bring about evaporation reduction and yield improvement.

Key Words: *Water saving; Yield loss; Cultivar improvement; Irrigation scheduling; Straw mulching*

INTRODUCTION

The North China Plain is one of the most important agricultural regions in China, supporting a population of over 300 million people. The rich soil and favorable climate are suitable for growing winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) as the most common double-cropping system. The NCP now supplies about 70% of China's wheat and 30% of its maize [1], with people in this densely-populated region relying on winter wheat as their major food supply and using the maize as animal feed. The annually average precipitation ranges from 470-910 mm [2], while the annual water consumed through evapotranspiration in a wheat-maize rotation averages over 800 mm [3,4]. The large difference between precipitation and evapotranspiration indicates that irrigation is essential for a high level of food production through this multiple-cropping system. With the typical continental monsoon climate prevailing in the region, the temporal distribution of annual rainfall is extremely variable. More than 70% of annual precipitation falls from July to September, the maize growing season, and less than 30% of the rainfall occurs in the wheat growing season. This meets only about 25-40% of the water requirements of wheat. As a result, more than 70% of the irrigation water used is for winter wheat. Due to the excessive exploitation of groundwater for irrigation from both shallow and deep aquifers, water resources in the region are now at crisis point, threatening the sustainability of the current agricultural production systems. Worse still, an increase in water demand for rapid development from other sectors is projected to aggravate the current deficit in the NCP over the next two decades [5].

Crop yield depends on both the amount of water available for growth and the efficiency with which the water is used in this water-limited environment [6,7]. The deepening water-resource crisis and the increasing yield requirement to meet the future food needs of a rising human population require synchronous realization of conserving the groundwater for ensuring sustainable crop production and maintaining the current higher yield. Since water in the field is consumed mainly through crop transpiration and evaporation from soil surface, the target could be achieved by genetic improvement of the cultivars, better matching cultivars to locations with particular water-resource availabilities, reductions of crop evapotranspiration through irrigation management and other practices preventing soil evaporation. To develop practicable and effective technologies for gaining higher yield and saving water is one of today's greatest challenges in the NCP. This review focuses on three themes:

1. Strategies of cultivar improvement for conserving water and maintaining high crop production, with special attention to winter wheat, the largest consumer of irrigation water in the NCP;
2. Optimizing irrigation scheduling to save water during the wheat-growing season, without markedly reducing yield; and
3. Straw mulching practice that have potential to save water by decreasing evaporation from the soil surface.

LITERATURE REVIEW

Improving the water use relating traits of wheat cultivars and reasonably matching cultivars to local water availability

Cultivar improvement of water use traits along with appropriate cultivar adoption has been considered as an efficient and economic pathway for conserving water. To reduce water use at the prerequisite of maintaining the current high level of crop productivity in the NCP, targets of cultivar breeding program and cultivar adoption strategies need to be proposed, based on the crop biomass-transpiration relation, the effect of water condition on accumulate distribution in late season, matching of crop cultivars to local areas with specific water availability.

[1]Key Laboratory for Dryland Agriculture of Ministry of Agriculture and Rural Affairs, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China;[2]Forestry and Grassland Bureau of Aohan Banner, Chifeng 024300, China

Correspondence: *Enke Liu, Forestry and Grassland Bureau of Aohan Banner, Chifeng 024300, China E-mail: liuenke@caas.cn*

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Crop biomass accumulation depends on stomotal transpiration: De Wit [8] proposed the famous function of crop biomass with transpiration, which is very solid and have stood the test of time up to now, namely:

$B=mT/E_0$

Where B is crop biomass

m is a crop constant

T is crop transpiration and

E_0 is free water evaporation.

Here E_0 is common in genotypic comparisons. m constant was also showed consistency among different species by comparison experiments, but substantial difference between C3 and C4 species, indicating the crucial effect of photosynthetic pathway. Therefore, for genotypic comparison, both m and E_0 can be removed from the function, and then B is the function of T. This function stipulated the determinant role of transpiration plays in crop biomass production, implying that any attempts to save water through reducing crucially important transpiration will unavoidably lead to biomass loss. Blum once stressed that breeding for maximized soil moisture capture for transpiration is the most important target for yield improvement under drought stress [9].

Accumulate distribution associates with late-season water conditions: Grain yield formation, however, not only depends on biomass accumulation, but also enormously influenced by accumulate distribution, Harvest Index (HI), as indicated by another famous yield function proposed by Donald and Hamblin, namely:

$Y=B \times HI$

Where Y is grain yield

B is crop biomass, and

HI is harvest index.

HI is influenced enormously by the water availability in the reproduction phase, though water requirement amount is not as large as vegetative phase. A severe restriction for grain filling by water deficit occurring in the terminal stage is likely to spoil an affluent biomass accumulation, leading to a large yield loss consequently. Conversely, a relatively smaller transpiration may result in a smaller biomass, but helps to conserve enough water for grain filling, and in turn gain a higher grain production. In the case of water-limited conditions, especially terminal drought occurs frequently, there is need to balance crop water use against the limited and known soil moisture reserve. This was strongly proved by the successful and widely cited case for dry land wheat grain yield improvement with selection for high WUE, which is derived from a lower stomatal conductance, under water limited conditions in NSW Australia [7]. Yield improvement was obtained by controlling water use during the earlier part of the growing season in order to avoid lack of soil moisture during reproduction.

Though crop biomass is determined by transpiration, the association of grain yield with transpiration depends on the water conditions of the whole growing period of the crops in the local areas. In the NCP, water resources unevenly distributes across different areas, from larger natural precipitation along with good irrigation system to drought rain-fed conditions. Therefore, there is great potential to gain water saving and higher yield by better matching cultivars with particular water use traits to locations with particular water-resource availabilities.

Stomatal trait improvement and cultivar matching to water availability of local area: Stomata, the main switch simultaneously controlling both transpiration and photosynthesis of crops; adjust its aperture constantly in response to environmental changes, as well known. High stomatal conductance confers both higher photosynthetic rate and higher transpiration rate, while low stomatal conductance restricts both water loss and photosynthetic assimilation [8-13]. Among different genotypes, stomatal conductance shows significant variability [14]. Furthermore, genotypes differ in the sensitivity of stomata to soil and air moisture alteration [13-17]. Sensitive genotypes strongly reduce stomatal conductance under relatively mild levels of drought, while less sensitive genotypes merely adjust stomatal conductance slightly under more severe drought [18,19]. Stomatal conductance has been considered as a crucial cultivar trait to be improved for realizing the duel goals of higher yield and water saving.

Although stomatal conductance determines the extent of water extraction, which further affects crop biomass, neither low stomatal conductance necessarily link to lower yield, nor water saving must be conflicting with higher yield. Virtually, in water-limited conditions, especially late-season water deficit occurs frequently, low stomatal conductance cultivar has the possibility of conserve soil water in earlier stages for grain filling to generate a greater yield [13,20-23]. In the NCP, due to the large variability in water resource conditions over the whole region, groundwater for irrigation can be conserved without markedly damaging yield through cultivar improvement and appropriate cultivar adoption. For the areas with larger natural precipitation and good supplemental irrigation, low stomatal conductance would be disadvantageous in terms of yield [7], instead, maximization of soil moisture use is crucial for higher yield. Also, after rain or irrigation, to increase transpiration is to reduce evaporation and to save water. Thus the trait of higher stomatal conductance as well as less sensitivity to drought is recommended for such areas. For the areas with medium precipitation and excessive exploitation of groundwater, where a compromise between higher yield and water saving are necessary, medium stomotal conductance along with medium drought sensitivity should be first preference. For areas where long term or serious drought seldom occurs, cultivars with low stomata sensitivity to soil drying and larger stomatal conductance when released from water stress after irrigation or rain may maximize water use and gain higher yield. For dry rain-fed areas, where terminal drought occurs frequently, lower stomatal conductance under no water stress and higher stomata sensitivity to soil drying may result in a relatively higher yield.

Other important traits of cultivar improvement for reducing water use or enhancing assimilate accumulation: Due to the close association of biomass formation with transpiration discussed above, to minimize the moiety of water that does not participate in photosynthesis undoubtedly helps to reduce water use without damaging yield anymore. Transpiration through cuticle is right a kind of non-stomatal transpiration without an associated benefit in CO_2 fixation. The trait of higher epicuticular wax deposition benefits eliminating this kind of water leak and increasing stomatal transpiration. Stomata leakiness at night, namely nocturnal transpiration, can also add to water loss without any advantage in CO_2 assimilation. The trait of complete stomatal closure in dark may prevent this kind of water loss. Therefore, to genetically improve these traits for restricting nocturnal and non-stomotal transpiration may minimize this moiety of water loss without any damage to biomass accumulation. Similarly, genetically improving biochemistry of photosynthesis, especially carboxylation efficiency, and harvest index can absolutely improve yield without consuming extra water.

In addition, evaporation from soil surface, which constitutes the majority of the non-productive water use, occurs mainly in the early stages of vegetative growth of both winter wheat and maize, when the crops have low leaf-area index. Soil surface shading by the crop canopy is crucial for reducing this water loss. Therefore, cultivars showing early-vigor may efficiently mitigate evaporation and ultimately, lead to increases in crop. However, early-vigor was also suggested to raise the risk of early exhausting soil water reserves in low-rainfall areas or when rainfall is less than normal in higher-rainfall areas [24]. The previous study reported that under terminal drought, constitutive traits controlling leaf water loss under well-watered conditions may lead to more water available for grain filling [13,18]. In the areas where crop depends on stored soil moisture, saving water at early growth stages is of great necessity, thus the use of early-vigor cultivars is not recommended to avoid early depletion of the stored soil water by their elevated transpiration rates. While for most areas in the NCP, water for crop growth is supplied by current-season rainfall or irrigation, cultivars having early-vigor are usually recommended and so commencement of a breeding program for early vigor is strongly advised.

Improving irrigation scheduling to conserve groundwater without markedly reducing yield

Reasonable supplemental irrigation can increase crop yield significantly, without excessive consumption of water [25]. Optimizing irrigation scheduling for winter wheat is thus an important practice for improving yield and saving water in the NCP. In recent decades, a number of studies have been carried out to clarify relationships between seasonal amounts of irrigation water with yield, water use efficiency and evapotranspiration so as to establish best irrigation scheduling [25-27]. A field experiment conducted by Zhang et al., [26] showed that in the NCP, of the four irrigation frequency treatments (from irrigation once up to four times during the season), the most frequent irrigation did not produce the maximum yield and WUE regardless of the year. Also, crop water usage under the treatment with maximum yield was significantly below the potential evapotranspiration value [26,28]. This implies that deficit irrigation is able to produce the relatively high grain yield and high WUE in the NCP. Other researchers have also shown that crops such as maize and wheat are well suited to deficit irrigation [29,30].

Wheat crop is not equally sensitive to water stress at its different growth stages [31], which has practical implications for irrigation scheduling [32,33]. In the Mediterranean region, wheat crops were most sensitive to soil-water deficit from stem elongation to booting, followed by anthesis, and milking. While in the US Great Plains, the critical growing stage for water response of winter wheat was from heading to the soft-dough stage [34]. In the NCP, it is reported that the greatest yield reduction took place when encountering drought stress at jointing-heading stage, two folds to that at filling stage [35]. Correspondingly, irrigation at jointing stage obtained the highest compensation effect, with the yield retrieval ability being 16.3-18.6% [36]. Similarly, Li et al., [37] found that irrigating at jointing or booting stage improved soil water status before anthesis and resulted in both higher grain yield and higher WUE, while irrigating at anthesis or milking stages brought about higher grain yield but not higher WUE. Appropriate timing of irrigation and water deficit creates a tool for scheduling irrigation for minimal yield reduction where a limited supply of water is available [38]. The majority of relevant studies support that supplemental irrigation at jointing stage is crucial to ensure a higher yield in the NCP.

The frequency of irrigation is another closely-related parameter affecting yield and water use of crops. In the NCP, winter wheat is usually irrigated about four times each season at a rate of 60-70 mm/application nowadays, at prewintering, jointing, booting and milking stages. The field experiment results of Zhang et al., [26] showed that three irrigations in a dry year, or one irrigation in a wet year, produced the highest grain productions and highest WUE. It has been suggested by several studies that pre-winter irrigation can be omitted [37,39,40]. For winter wheat, soil water stored before sowing is very important for high production [30]. Li et al., [37] reported that pre-sowing irrigation is important for saving water and ensuring high yields and WUE, and recommended a schedule of irrigation at pre-sowing, jointing and flowering. Sun et al., also stressed the indispensible role of pre-sowing irrigation, based on a field experiment with five different irrigation times, 75 mm of water amount each. They proposed that in the case of sufficient stored soil moisture at wheat sowing, irrigating once at jointing stage was appropriate to obtain the highest yield, grain quality, as well as water and nitrogen use efficiency. Yang et al., [27] used the DSSAT-wheat model to simulate water use by winter wheat in a 12-year period. The simulation showed that such a schedule of irrigation in mid-November achieved good growth of leaf area index and in mid-April prevented water deficit during ear growth and grain filling. In this way, 76 mm of evapotranspiration and 99.5 mm irrigation water can be saved without significant reduction in winter wheat yield. To conclude, irrigation frequency in the NCP can be at least reduced by one time (i.e, from four times to three times per season), depending on soil water status at sowing, jointing, and grain filling stages. In the areas with serious groundwater crisis, where water saving turns to be first priority, it is necessary to apply irrigation only once at jointing stage to save water and ensure the least yield reduction.

Reasonably utilizing maize straw to mulch soil surface for preventing water loss through evaporation

Due to the closer association between yield and transpiration, to reduce evaporation from the soil surface is to increase the fraction of available water for transpiration by plants, and in turn, is to save water and to improve yield [41]. Measuring evapotranspiration and soil evaporation by means of lysimeters, Bowen ratio and micro lysimeters, Wang et al., [3] found that of the average annual 850 mm crop usage in the NCP farmland, about 30% was from direct evaporation from the soil. The adoption of practices that reduce soil surface evaporation should contribute significantly to water saving in the region.

DISCUSSION

Straw mulching was proposed to have good potential in reducing evaporation [26,42,43]. Experiments conducted for the wheat-maize double cropping system in the NCP demonstrated that mulching reduced soil evaporation loss by 40 mm in winter wheat season and by 43 mm in summer maize season [26]. Li et al., [44] found that straw mulching could increase the contents of soil organic carbon and its components including microbial biomass carbon， potential mineralized carbon， and particulate organic carbon. However， Chen et al., [45] reported that mulching the soil surface with summer maize straw created unfavourable growth conditions for winter wheat, resulting in yield reduction. Thereafter, Yan et al., found that mulching soon after winter wheat sowing and mulching at trifoliate stage brought about a yield reduction by 8.6% and 2.0%, respectively. They thus suggested that straw mulching need to be applied not earlier than trifoliate stage of winter wheat to avoid negative effect on grain production. Thus mulching time should be taken into account when apply straw mulching. In the north eastern China, Zhang et al., [46] reported that straw mulching caused harvest index reduction by 20% in comparison with the conventional management. They attributed the decrease in harvest index to overuse of soil water before anthesis， which resulted in severe water stress during grain filling stage. Inconsistently, Chang et al., [47] found that straw mulching increased grain yield and water use efficiency of winter wheat by increasing whole water use amount, and tilting the water use ratio in favour of late season growth. Thus the effect of straw mulching also depends on the water conditions of local areas. It could be compromised in some areas of north western region where terminal drought being apt to occur. Differing from north western region, winter wheat in the NCP seldom suffers from severe terminal drought. Mulching soil surface with maize straw after trifoliate stage at appropriate amount is hoped to bring about yield improvement and evaporation reduction [48-57].

CONCLUSION AND PROSPECTIONS

National food security and regional water crisis urgently requires the NCP to conserve irrigation groundwater while ensuring the current higher crop productivity. Cultivar improvement, reasonable cultivar adoption, as well as diverse agricultural practices may contribute greatly to realizing the dual goals of water saving and higher yield.

Stomatal adjustment, simultaneously regulating photosynthesis and transpiration, closely associates with water use and assimilate accumulation. Stomatal conductance and stomatal sensitivity to drought stress, which show significant genotypic variability, are considered primary traits to be improved genetically for synchronously saving water and maintaining the higher yield production level. Through adopting cultivars with specific stomatal traits, it is expected to maximize transpiration and minimize evaporation in the meanwhile, or to inhibit transpiration for compromising higher yield and water saving in serious water crisis areas. Over the whole NCP, irrigation groundwater might be significantly conserved without causing markedly yield reduction by appropriately matching cultivar stomatal traits to local water availability. In addition, genetically select some traits for restricting nocturnal and non-stomotal transpiration may minimize this moiety of water loss without any damage to biomass accumulation. And genetically improving biochemistry of photosynthesis, especially carboxylation efficiency, and harvest index can gain higher yield without consuming extra water. Also, early-vigor is a target trait to efficiently prevent evaporation in early development stage.

Irrigation scheduling in the NCP need to be further optimized (better timing and better amount) through field experiments combined with model simulations in order to markedly conserve groundwater without causing larger yield loss. Irrigation frequencies of four times per winter wheat season currently used in the NCP could be reduced at least once, depending on soil water status at sowing, jointing, and grain filling stages. In the areas with serious groundwater crisis, it is necessary to apply irrigation only at jointing stage to save water and to minimize yield reduction.

Soil evaporation accounts for about one third of the total water consumed in the winter wheat-summer maize double cropping system of the NCP. Practices such as straw mulching could benefit reducing water wastage by evaporation, though the effect depends on mulching time and water conditions of local areas. In the NCP, mulching soil surface with maize straw at appropriate amount after trifoliate stage of wheat is expected to bring about evaporation reduction and yield improvement.

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