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Full Length Research Paper

Focus on agricultural biotechnology: Prospective for bio-watersaving theories and their applications in the semi-arid and arid areas

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Drought and water shortage have become a world-wide problem in recent years with the effect of global warming. Water-saving agriculture has become an inevitable direction of agronomical research, it has been developed from practices through agronomic water saving to engineering water saving and to the approaches in biological water-saving. The essence of biological water-saving should be the high-efficient use of water through biological ways, namely the "utilization and exploitation of physiological and genetic potentials of organisms so as to acquire more agricultural output and better economic and ecological benefits by utilizing smaller or same amounts of water or poor quality water". As a systematic approach, biological water-saving should not only be applied with priority in crop production, but also in other aspects of agriculture and industries such as husbandry, aquaculture, landscaping, sewage water management, water and soil environmental conservations. Therefore, biological water-saving represents the human effort in the construction of a resource-saving and environmental-friendly society.

Key words: Outlook, application, bio-water-saving, water use efficiency (WUE), drought, crop production, sustainable agriculture.

INTRODUCTION

The twentieth century has witnessed the great effort of mankind to strive for more food production, which has led to an unprecedented increase in grain production known as the First Green Revolution. As mankind entered the 21st century, the Blue Revolution – the Struggle in agriculture for better use of water resources – has just begun. Norman (2000), Nobel Peace Prize Laureate, said in 2000, "how can we continue to expand food production for a growing world population within the parameters of likely water availability? The inevitable conclusion is that mankind in the 21st Century will need to bring about a 'Blue Revolution – more crops for every drop' to complement the 'Green Revolution' of the 20th Century. Water use productivity must be wedded to land use productivity. Science and technology will be called upon to show the way". Water shortage has become an urgent problem in agriculture all over the world. Rapid expansion of cropped land and over-irrigation for high yield have led to the depletion of water resources in many parts of the world, such as the drying-up of lakes and rivers and declining ground water tables. The unsustainable techniques of agricultural development have greatly reduced the water that otherwise could be used for ecological maintenance. If such a water shortage develops into a crisis, it may have effects far more severe than the crisis in oil shortage that we

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have experienced thus far, or can be expected in the future.

Improving water use efficiency through biological approaches in combination with other water-saving methods and projects and developing a sustainable agriculture under limited water resources have become, and will continue to be the challenges for agricultural scientists in the future (Zhang and Zhang, 2007; Shao et al., 2006-2008). The current article reviews the theories, practices, progress and outlook of bio-water-saving with an emphasis on China.

UNDERSTANDING THE CONCEPT OF WATER-SAVING AGRICULTURE IN CHINA

Drought is a severe problem in the 21st century all over the world. Agriculture consumes the largest part of water, about 60-70% of the whole water consumption. How to use the limited water resource efficiently and keep a sustainable agriculture and economy has become a challenging issue for human beings.

From a historical view, China made many achievements in crop drought resistance and water-saving. For example, one of its greatest contribution was Qimin Yaoshu (Essential Techniques for the Peasantry), a monograph in agronomy written between about A.D 530s and 540s. In this great book large information was summarized about dry land-farming technical system with plough, harrowing and leveling as its core parts and drought prevention and moisture retention as its essential ideas, and also recorded upland rice production (Jia, 1963). These drought-resistant and water-saving techniques have been playing an important role in dry land farming in China since ancient time. China also made remarkable achievements in water-saving by hydraulic engineering during the 1950s-1970s, for instance, the construction of many dams and reservoirs and the control of Yellow River and the Huaihe River. In the 1980s, using fertilizers and the improvement of fertilizer performance and water productivity greatly increased crop yields in dry land areas. In the 1990s irrigation using water from rainwater-collecting tanks resulted in high rain water use efficiency. There have been three conceptual developments in dry land farming research in the semiarid regions of China: 1) attention from water deficiency to nutrient deficiency; 2) from water deficiency to the improvement of water productivity; 3) from drought resistance to the high water use efficiency (WUE) breeding (Zhang et al., 2004). The trend to shift from passive drought tolerance research to the active drought resistance and high WUE will inevitably occur in the future (Zhang et al., 2005). Similar research results and conclusions have been obtained in vast semiarid regions including Mediterranean (French et al., 1984), East Africa (Smaling et al., 1992), African regions to the south of Sahara (Rockstrom, 2001), desert steppe of West Africa (Breman et al., 2001), South India (Ahlawat et al., 1998) and West China (Li et al., 2001).

It is believed that water-saving agriculture, proposed based on the concept of water-saving in irrigated agriculture, includes the high-efficient water use in dry land farming. In terms of the cores of high efficiency water use, both water-saving agriculture and dry land farming can be called as high WUE agriculture. High WUE agriculture refers to a new farming system that integrates high-tech system with economy and market and strives for high water use efficiency, high economic, ecological and social returns per unit water consumed (Zhang et al., 2005). For example, many countries like Israel have developed and adopted water-saving irrigation techniques such as water transmission through pipes and drip irrigation to improve water use efficiency on one hand, and produce agricultural products with high added value such as vegetables, fruits and flowers for international market on the other hand so that they have become the backyard of Europe (Yang, 2002). This is a typical high WUE agriculture. Therefore, we can say, water can be used as gold, and soil can be used like gold as well, book knowledge can be used really as gold. That is to say, promoting education and agricultural science and technology and improving farmers' scientific qualities and planting cash crops under limited water conditions can solve the problems of slow agricultural development, rural backwardness and farmers' low income in arid and semi-arid regions of China and in the other developing countries to a certain extent.

NEW TECHNOLOGY IN COMBINATION WITH PLANT BIOLOGY

Deficit irrigation strategies like regulated deficit irrigation or partial root drying have emerged as potential ways to increase water savings in agriculture by allowing crops to withstand mild water stress with no or only marginal decreases of yield and quality.

As a result, improving crop water-use efficiency (WUE) has been a matter of concern to researchers and agronomists in recent years. WUE is discussed either in terms of instantaneous measurement of the efficiency of carbon gain per water loss by plants or as the integral of such an efficiency over time (expressed as the ratio of biomass accumulation or harvested yield to water use) (Zhang et al., 2005). The WUE in the agricultural sector has been slowly improving due to the use of genotypes with increased WUE (Zhang et al., 2005) and due to adoption of innovative cultivation and irrigation practices (e.g. drip irrigation, use of irrigation calendars based on the depth of water table and soil salinity, reuse of wastewater) (Office of Technology Assessment, 1983; Chaves et al., 2003). Drip irrigation, mulching and protected cultivation have contributed to improve WUE in agriculture by significantly reducing runoff and evapotranspiration losses

losses (Shao et al., 2008). Mediterranean countries like Israel or Spain led developments in drip irrigation and cultivation under plastic in the past decades, but China has been strongly investing in these techniques. China has recently emerged as the world's largest producer of greenhouse vegetables and ornamentals (close to 2 million ha) and has about 15 million ha using plastic mulches (Yang et al., 2007). However, the use of drip irrigation remains too restricted suggesting that WUE can still be optimized by adoption of more efficient irrigation practices. Deficit irrigation strategies have the potential to optimize water productivity in horticulture. Nevertheless, the effects of deficit irrigation on yield or harvest quality are crop-specific. Knowledge of how different crops cope with mild water deficits is the basis for a successful application of deficit irrigation into practice (Yang et al., 2007).

Rice (*Oryza sativa* L.) is the most important staple in Asia, providing on average 32% of total calorie intake. To keep up with population growth and income-induced demand for food in most Asian counties, rice production must be increased by 56% over the next 30 years (Karaba et al., 2007). About 75% of total rice production comes from irrigated lowlands. In Asia, irrigated rice accounts for about 50% of the total amount of water diverted for irrigation, which in itself accounts for 80% of the amount of fresh water diverted. Fresh water, however, is becoming increasingly scarce because of population growth, increasing urban and industrial development, and decreasing availability resulting form pollution and resource depletion. Decreasing water availability for agriculture threatens the productivity of the irrigated ecosystem and ways must be sought to save water and increase the water productivity of rice. The high water demand of irrigated lowland rice mainly arises from keeping the field continuously submerged as a result of high evaporation and seepage and percolation in the fields. To reduce water use in irrigated lowland rice, systems of alternate wetting and drying or alternate submergence and nonsubmergence have been developed. It has been reported that alternate wetting and drying systems can maintain or even increase grain yield (Zhang et al., 2005). However, experimental evidence is still scarcely reported in international published reports. Furthermore, there are reports that alternate wetting and drying sys-tems often reduce, rather than increase, grain yield when compared with continuously submerged conditions. Obviously, it remains a major challenge to reduce water input without compromising yield and to optimize scarce water in rice production. For this objective, Yang et al. (2007) established an irrigation system to save water and increase grain yield, therefore enhancing water productivity by proper water management at the field level in irrigated lowland rice. The physiological mechanisms involved were also investigated. In their water-saving irrigation system, limiting values of SWP were proposed as irrigation indices. These values were related to specific growth stages, so that the wetting and drying could meet the growth and development of rice. Our results showed that the technique not only significantly reduced water input, but also increased grain yield, therefore enhancing water productivity. The technique was demonstrated and applied in eight different ecological rice-growing areas in China. Compared with the conventional irrigation that drainage was in mid-season and flooded at other times, the water-saving irrigation technique increased grain yield by 6.1 to 14.2%, reduced irrigation water by 25.4 to 38.2%, and increased water productivity (grain yield per cubic meter of irrigation water) by 26 to 47%.

How could this technique save irrigation water as well as increase grain yield and water use efficiency? They also observed that sensitivity of rice to water deficits varied with the growth stages. A mild soil-drying (SWP at −15 kPa) at most growth stages benefited rice plants. The result indicated that keeping the field continuously submerged would be not good for a high yield and much water could be saved from the conventional irrigation. In conclusion, the water-saving irrigation by controlling limiting values of soil water potential related to specific growth stages not only reduced water input, but also increased grain yield, therefore enhancing water productivity. High harvest index, maintenance in photosynthetic rates, reduction in leaf conductance, increases in cytokinin concentrations in roots and activities of key enzymes involved in sucrose-to-starch pathway in the grains may all contribute, at least partly, to high yield and high water use efficiency under the irrigation system.

Currently, our group stress on practicing water-saving agriculture to save water in rain-fed agriculture regions and the north China, in particular so as to produce more grain with limited water resources. But actually high WUE farming should be much more practiced in the regions of South China without facing water shortage, that is to say, such farming high-tech such as high-yield and super-high yield plants and animals with high economic return, intercropping, multi-storey farming, greenhouses, film-mulching farming, hydroponics and factory-style agricultural production should be adopted in these regions where water is not a factor limiting high grain yields to produce more high-quality agricultural products and achieve better economic, social and ecological returns. Meanwhile, we also place emphasis on high-efficiency exploitation of poor quality water resources by taking the road characterizing high WUE and high efficiency output.

In China, grains were traditionally transported from south to north, but since the 1980s when China began its agriculture reform, several large-scale grain transportations from north to south have occurred. This sufficiently proves the grain production capacity has been quickly declining in the south China but risen in north China to some extent. Therefore, we should rethink and reanalyze macroscopic changes in grain production and consumption in China. This will be helpful to understanding the stress on rehabilitating grain production and practicing high WUE farming in humid region, economically well-developed region and the regions that are backward, insufficient and low in grain production.

According to theories about virtual water (Allan, 1997; Cheng, 2003), virtual water and soil resources, virtual energy and virtual economy, the problems about inter-regional loss and gain in economic distribution resulting from the north-to-south grain transfer are practically the problems about inter-regional loss and gain in macro distribution and transfer of such resources as water resources, land resources in production and input energy, and consequently the problem is a problem closely related with sustainable development of water and soil resources and the development of high WUE agriculture in China. The north-to-south grain transfer, transferring insufficient but precious water, soil nutrient, sunshine, warmth and energy resources, and subsidies in the north to the south with sufficient water, light and warmth and a high yield potential, which is commonly known as "the land bestowed with rice and fish" and the "land of abundance". The consequences of such abnormal subsidy and resources transfer have not only severely discouraged the productive enthusiasm in major grain production regions in the north, but also resulted in severe depletion of agricultural water and soil resources in the north, thereby accelerating the crisis of water and soil resources and strangling the potential of sustainable agricultural development. This tendency will inevitably appear in the grain production bases in North China and northeast China plains (Zhang et al., 2005).

In China, agricultural development has gone through five major changes: 1) change from the primitive agriculture dominated with labor forces and animal powers to mechanical agriculture; 2) from organic agriculture and then the inorganic and organic combined (with a great deal of straws returned to soil) agriculture to the high output and commercial agriculture; 3) change from grain production-dominated agriculture to dominated by both grain and cash crop production, and to agriculture with well coordinated grain and cash crops and agro-product production (including animal raising and processing); 4) change from self-sufficient agriculture through domestic market-oriented agriculture to export-oriented agriculture, and 5) change from paddy field-dominated agriculture (needing standing water for a long time) through irrigated agriculture (regular irrigation) and then water-saving agriculture (regularly irrigated at a fixed water amount) to high WUE agriculture in south China, and the change from dry land agriculture through irrigated agriculture and then water-saving agriculture to high WUE agriculture in north China. With rapid development in water-saving agriculture, we have got more in-depth knowledge and understanding of efficient uses of macroscopic water resource and microscopic moisture, formed many new concepts and research directions, and in particular paid more and more attention to the concepts and indexes in raising water resource, water use rate, WUE as well as their related researches. We believe that in China, agriculture has been seen or will see three important stages, "comprehensive development with grain as the key link", "comprehensive development with money as the key link" and "harmonious development with water as the key link". Agriculture has been transforming and will transform from forestry and grassland agriculture through grain-production agriculture, grain-economy agriculture and then economic-grain agriculture to high WUE agriculture and forestry integrated agriculture (Borlaug and Dowswell, 2000; Zhang et al., 2006).

From the broad sense of water conservation and high efficient use of water, water and soil conservation may be the fundamental form of the concept of water-saving agriculture or high water / soil use efficiency agriculture in China. It includes more than dry land agriculture, irrigated agriculture and ecological environment improvement and presents an obvious intention to form a new academic discipline. This new discipline not only aims to take biological and engineering measures to fully conserve and make efficient use of water in farm fields and non-farm fields, but also involves conserving and making efficient use of resources such as soil nutrient; it aims not only to resist drought but also to prevent flood so as to coordinate and improve water resources circulation and ecological environment. Nowadays, the concept of water and soil conservation has been gradually understood and accepted at home and abroad (Wu et al., 2003; Zeng et al., 2005). Biological water-saving shall be the foundation and core of water and soil conservation and of water-saving agriculture (Zhang et al., 2007; Shao et al., 2006-2008).

In irrigation regions, water-saving engineering techniques such as canal system of field irrigation and irrigation equipment have been widely extended. So far the irrigated land area has accounted for half of the total cultivated land in China. These have all greatly improved the utilization ratio of river and rainwater resources and hence played an important role in stabilizing grain production in China. Since agricultural and engineering water-saving measures were taken to improve the water resources utilization ratio, and as fresh water resources have been in short supply and polluted and the climate has been becoming drier, it is necessary to employ modern agricultural and new biological techniques to carry out in-depth research on biological water-saving measures to breed and extend new drought-resistant water-saving breeds of living organisms so as to produce more food and more dollars for every drop of water. This is the ultimate way for the development of water-saving agriculture (see the website listed in References).

On the condition that China can stably produce 400 to 500 million tons of grain (Lu, 2005), its agriculture should be oriented for stable grain production and profit-making. It can better solve the problems concerned with farmers, countryside and agriculture only by practicing high WUE agriculture and developing export-oriented ago-products with high added value. Under the new situations, the term “green revolution” should mean two things: one is to greatly increase grain yield and the other is to produce more pollutant-free, high-quality and high-price “green foods”. We should launch a “blue revolution” centering on utilizing limited water resources at high efficiency in Northwest China and North China that have limited water resources to complete sustainable development of “green revolution” and thus produce more grain. On the other hand, we should launch a “blue revolution” aiming to improve the economic value of water use to produce more pollutant-free, high-quality and high added value “green foods” in South China and Eastern coastal areas Of China that have rich water resources such as river water, ocean water, sea water and slightly brackish water. In the meantime, we should conduct a “white revolution” with milk cow as the key link in the grassland regions and the areas with welled development agriculture (Zhang, 2002). Nowadays as water resources are becoming increasingly insufficient and water quality is deteriorating, agriculture with high water use efficiency is the key for China to develop modern agriculture and join the outside world.

Now, China still stresses on developing water-saving agriculture and the first goal of water-saving agriculture is to raise the utilization rate of water resources, which is mainly realized by engineering water-saving from the macroscopic point. However, only engineering and biological measures are combined and then true water-saving can be realized. Thus, the second aim of water-saving agriculture is to increase crop water use efficiency and yields. Although crop water-saving breeding is a newly emerged term, remarkable achievements have been obtained in the past practice of crop drought-resisting and water-saving breeding. The real problem is that we have not previously paid closer attention to it so that the theoretical researches about it have relatively lagged. If it has high agronomic WUE, but no good economic returns, it will not have any developmental hopes. Hence, the third target of water-saving agriculture is to improve its economic return, i.e., economic water use efficiency, while trying to improve its biological water use efficiency. And because plants consume the largest part of water the study of value water use efficiency of plants will gradually attrac-ted more and more concern in the future. The fourth target of water-saving agriculture is to further improve the water use efficiency of animals and microbes through in-depth researches on biological water-saving. The fifth target of water-saving agriculture is to attract people’s attention to ecological WUE of plants as the environment problems will become worsen in many regions in the future (Zhang et al., 2004).

Agronomic water-saving has developed for thousands of years. Now China is not economically strong enough to practice engineering water-saving in a large area. Living things have a wide genetic diversity thus capable of adapting to various environments, but their exploitation is still not enough. Biological water-saving is simple, easy, cheap to carry out and able to produce good results and high added value. For example, biological products produced under arid conditions are usually good quality, suffered less pest injuries as green foods. Therefore, all agronomic and engineering water-saving measures should be combined and adopted in biological water-saving, which will be the ultimate objective of water-saving agriculture.

NEW DEVELOPMENT OF THE CONCEPT OF BIOLOGICAL WATER-SAVING

The development of biological water-saving has experienced three stages: water-saving through crop physiology (Shan et al., 1991), water-saving through crop genetics and physiology (Shi, 1999). Water saving trough biological technology includes water-saving by animals, plants and microbes (Zhang et al., 2007; Shao et al., 2007). Scientific development trends in biological water-saving science indicate that biological water-saving has become a systematic engineering. The concept of biological water-saving is still expanding. It not only should be given the first priority position in crop production and in particular grain production in agriculture and be placed in an important position in vegetable, fruit and flower productions; but also it has a great water-saving potential through animal breeding. Besides, it has significance in landscape planting, sewage control, water and soil conservation and environment control.

Therefore, we think that biological water-saving, or more exactly, biological high efficiency water use, should be defined as “to produce more agricultural output and higher economic and ecological returns by utilizing and exploiting physiological and genetic potentials of living organisms (including animals, plants and microbes) with limited or same amounts of water or poor quality water resources”.

Biological water resources

Biological water resources refer to the total quantity of water resources contained within the bodies of organisms. As to the estimation of biological water resources, the files of UN Water Conference in 1977 indicated that the global biological water resource reserve is 0.112 (KM^3), accounting for 0.0001 (%) of the total water reserve and 0.003 (%) of fresh water reserve (United Nations, 1977). Hereby, organisms are also a bank of fresh water resources, like forests, grassland and agricultural produce all reserving large quantities of water. Compared with the above mentioned other water resources, biological water resources are especially precious, which are the only source of our food. And water is the blood of the biosphere and the decisive factor of the sustainable development of environment (Malin, 2005).

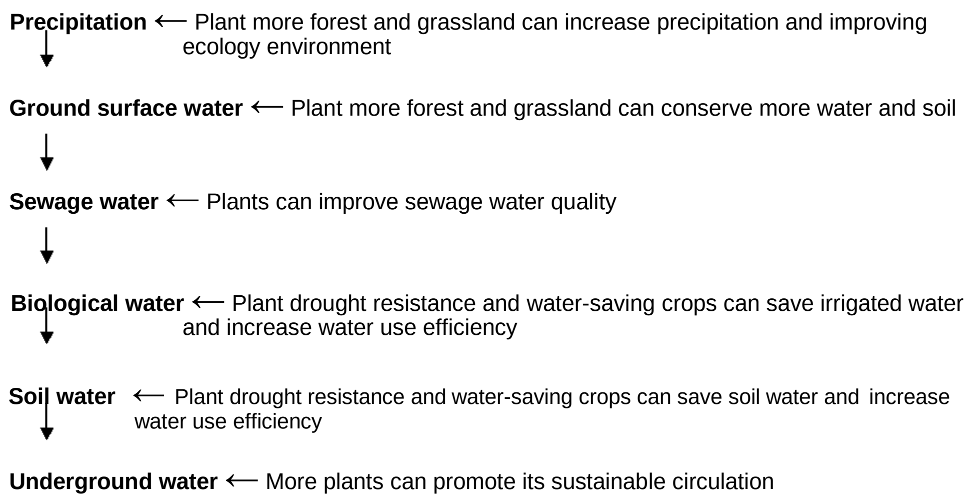

Figure 1. Bio-water saving and water conversation and conservation.

Although biological water resources are relatively small in comparison with other types of water resources, it has close relationship with the living environment of us human beings. Biological water is one of the central joints in the conversion of various water resources. Therefore, there are still large research space and development potentials for biological water.

The direction of biological water-saving

The scarcity of freshwater is a difficult problem in the world. It is the common choice for the countries to develop water-saving society and improve the higher efficient use of water resource. The improvement of plant intrinsic WUE is one of the important connotations for agricultural water-saving except engineering water-saving, agronomical water-saving and management water-saving. Furthermore, this is the key and potential for the further improvement in water-saving and production increase (Shan et al., 2006).

We consider that biological water-saving includes three levels of implication in agronomic term: one is to reduce water and soil loss by organism mulching; the second is to reduce irrigation and soil water depletion, namely, water-saving; the third is to improve WUE so as to produce more food and economic benefits by every drop.

STUDIES ON THE TRANSFORMING SYSTEM OF SIX KINDS OF WATER RESOURCES WITH BIOLOGICAL WATER TRANSFORMATION AS THE CORE

Before 1980s, many studies focused on “transformation of three kinds of water” (rainwater→ ground surface water→underground water); in 1990s more research focused on “transformation of four kinds of water” (rainwater→ground surface water→soil water →underground water) (Liu, 1994); in 2000s more studies focused on “transformation of five kinds of water” (rainwater→ground surface water→soil water→plant water →underground water) (Kang et al, 1994; Wei et al., 2000). We think that now the research should be carried out on the “transformation of six kinds of water” (the precipitation—ground surface water—sewage water—biological water—soil water—underground water) (Figure 1). All kinds of human activities and industrial and agricultural productions change clean water into vast amounts of sewages in rural and urbane areas. As a result, Sewages have become a resource that must be recycled and then used. Therefore, sewage disposal has become a world-wide problem (Bao, 2005). Living things can not only conserve water and soil, but also decontaminate sewage, for example, sewage water can be cleared by many plants like reed and other animals and microorganisms. Therefore, biological water-saving can play an important role in the transformation of six kinds of water.

Water resources are flowing resources and act in a cyclic system. Thus, we must strengthen the researches about timely and highly efficient water use by living things. If water is not timely and fully used by them, that means water extravagance. If there was a reservoir carrying no living things, then its water would not be ecologically dead; if it carries living things, it can be used for fish raising and irrigation, and then its water is ecologically and economically active. It is a future development trend to make use of living things to improve poor quality water resources. Academics and oceanographer in China (Zeng, 2000) advocated “blue revolution” and “farming fishes in sea”, namely seeking foods from sea. In this aspect, there is a high potential in high-efficiency water use to be exploited in the coastal areas of China.

In 1980s, some famous Chinese scientists, represented by Qian (2000) brought forward “sand industry”, which is a good example in high efficiency biological water use (Liu, 1995). In deserts and newly reclaimed lands, autogenous wild grasses firstly appear, then certain ecological effects occur and animal raising creates economic benefits later on. Although plants are major consumers of water resources, plants can bring about great ecological and economic benefits through water consumption and transformation. In the desert part of the semi-arid area in China, Psammophytes along with other various approaches to efficiently utilize limited rainwater and soil water should be greatly expanded in order to improve ecological environments for human welfare. There are many people who have emerged as the desert-controlling paradigms in many regions of Shaanxi, Gansu, and Ningxia provinces in China. In wild deserts, they have planted trees that form ecological forests that do not have previous examples in history and the scientists of the institution of botany, Chinese Academy of Sciences are making effort to improve and construct grasslands through natural recovery in the grassland region of Inner Mongolia, China. These have attracted high concern in the desert-controlling field of the world and the government of China. In such arid areas, such as Qinhai and Lanzhou of Northwest China, the annual rainfall is only 100-200 mm, and the annual evaporation is at least 2-5 times the rainfall, amounting to 1000 mm; but, the farmers still grow crops on sand-mulched lands, for instance, seed-use watermelon, which achieving a good economic return, and this fully demonstrates that high-efficiency biological water use is feasible, realistic and important under limited water conditions. It follows that so long as desert control is scientifically conducted it will produce the effects that plants expand while deserts retreat so as to improve desert environments and help desert-related economic development (Zhu, 2004), just as what the examples in high efficiency water use has shown.

TO RESTRUCTURE CROP PRODUCTION AIMING AT BIOLOGICAL WATER-SAVING

Although fallow can reduce nutrient and soil water consumption, but under certain circumstances, planting and burying green manure plants in soil can increase soil fertility, maintain fertility, or planting such minor crops as legume, buckwheat and oil sunflower can also result high efficiency water use, certain economic return. The practices to plant such cold-resistant crops as spinach, *Brassica chinensis*, and *B. chinensis var. oleifera* on fallow lands in central Shaanxi of China and the regions of South China in autumn and winter are the examples in high efficiency water use. In humid regions and seasonally dry regions of South China such drought-tolerant crops as upland rice, maize, sorghum and wheat can be planted in the place of rice and potato can be planted on autumn- and winter-fallowed lands after rice harvesting (Lin, 2005), which is an approach in high-efficiency biological water use.

In cold zone of north China, many regions have been conducting the studies about expanding winter wheat northward because of global warming (Gao et al., 2005) in order to utilize soil water and other resources in autumn and winter, and to conserve water and soil, reduce sandstorm occurrence and improve ecological environment. Therefore, restructuring the distribution and planting systems of different plants and breeding and extending water-saving drought-resistant plant varieties will make biological water-saving and high-efficiency water use have great potentials to be exploited.

PHYSIOLOGICAL REGULATION AND GENETIC MODIFICATION TO IMPROVE CROP WUE

Our long-term research has indicated that drought-resistance and water-saving is the means for crop to survive and reproduce under arid and semi-arid climatic environments, and the goals in crop production are high WUE and high yield (Chaves et al., 2003; Karaba et al., 2007; Shao et al., 2005-2008). Although drought-resistance and water-saving are complex problems in plants, human beings have still made many remarkable achievements in crop breeding and production and will continue to advance in these respects. In semi-arid areas, drought-resistance, water-saving and high yield are not in severe conflict under some condition, some drought-resistant crop varieties with high yield and good quality; and super-high yield varieties can be bred to raise the efficiencies of water, solar energy and nutrients. WUE can integrate drought-tolerance and high yield in one body (Zhang, 1998) and is a quantificational comprehensive index in drought-resistance and water-saving research, including many aspects such as drought-resistance, drought-tolerance, water-saving high-efficiency water use and high-efficiency output; now it have gradually been becoming an important indicator to assess crop drought resistance and water-saving (Zhang, 2003, 2006; Shi, 2005; Uri, 2005; Su et al., 2007).

In recent years, we have carried in-depth studies about the physiology, genetics, breeding, evolution, gene mapping and molecular marker of wheat in WUE (Zhang et al., 2000; Zhang et al., 2002), showing that wheat has increased the WUE of its leaves, individual plants and population through evolution to some extent (Zhang et al., 1998) and its WUE-related traits are genetically controlled are possible to be genetically and culturally improved. Under arid and semi-arid conditions, the WUE of wheat ranges between 0.1 and 1 kg/mm, and the WUE of maize ranges from 0.2 to 2 kg/mm, and as a result the WUE difference between the two is tenfold. On condition that the annual rainfall is 500 mm, wheat may have a yield of 7,500 kg/h and maize a yield of 15,000 kg/ha. This suggests that the concept of “one kilogram water for one kilogram grain” has been outdated by variety improvement, farming and fertilization practices and so on.

Malse et al. (2005) of Australia published a paper in Nature which told that they adopted $\delta^{13}C$ as the representative trait of WUE, then positioned the QTL controlling transpiration efficiency on the ERECTA marker of the second chromosome and thereafter cloned from Arabidopsis ERECTA gene, a gene encoding a putative leucine-rich repeat receptor-like kinase that can change both leaf stomatal number and leaf structure, and regulate the flowering time, and is proved to regulate plant transpiration efficiency and consequently to have a bright prospect in improving crop drought resistance and using water at high efficiency.

Some people call living things that have a high water requirement as “water pigs”, like as buffalo, rice and clover; living things that have a low water requirement as “water misers”, like as camel, cactus and millet. Water pigs can be transformed into water misers through natural evolution and artificial improvement (Perry et al., 2001). For example, rice can be transformed into upland rice and Shanghai Agricultural Gene Center of China bred hybrid upland rice characterizing drought-resistance, water-saving, high quality and good quality (Yu et al., 2005). In particular, modern molecular, genetic and transgenic techniques can be employed to transfer drought-resistance and water-saving genes among different species to breed new varieties of living things with drought resistance, water-saving, good quality and high yield, which represent an important research direction in biological water-saving. In 2000, Elumalai, an American scientist, reported that HVA1 gene of barley was transformed into wheat and the offspring of the transgenic wheat got their WUE and drought-resistance greatly-improved (Chaves et al., 2003; Karaba et al., 2007; Shao et al., 2007, 2008).

Therefore, there exists a great potential to be exploited in improving the use efficiencies of soil water, rainwater and irrigation water through variety and soil fertility improvements and farming practice optimization. With their long-term efforts the scientists and experts in crop genetics, breeding and production may be able to raise the maximum yield potentials of such C3 plants as rice and wheat to caught up with and even surpass the yields of some varieties of such C4 plants as maize and sorghum, which may fully demonstrate the potentials and importance of WUE improvement in crops. On the production level of 9,000 kg/ha, the field WUE of wheat (grain yield/ unit water consumed) is higher than that of maize and then that of rice because different crops have different water requirements.

The developmental trends of dry land crops with high yields reveal that in China wheat yield is 2 250 kg/ha on poor dry land making up 50% of its total dry land, 3 750 kg/ha on mid-yield dry land making up 20-30% of its total dry land, 6 000 kg/ha on fertile dry land accounting for about 15% of its total dry land and about 7500 kg/ha on breeding land and demonstration land making up the rest 5% of its total dry land. In the region of China where the rainfall stands at 500 mm, the average yield of wheat on dry land did not reach 750 kg/ha in 1950 and now ranges within 2250-3750 kg/ha. The yield of wheat on dry land reaches 7500 kg/ha in arid area of Laizhou, Shandong province (Lin, 2005), showing that there is great potentials to be exploited in high-yield breeding and production of dry land crops. In addition, with water-saving and drought-resistant varieties with high yields extended and adopted the crop yield still can reach 7500 kg/ha even though hybrid rice is planted in the place of rice, wheat adaptable to both dry land and irrigation land is planted in the place of wheat adaptable to irrigation land or irrigation is conducted 1-3 times instead of 5-10 fives during growing period. In particular, the successful breeding, extension and adoption of maize, rice and wheat varieties with super-high yields, that is, raising water use efficiency by improving crops, are of important significance and indicate a great potential to be exploited in increasing grain yields in China.

It is shown that in China great progresses have been made in dry land wheat breeding on the one hand and there exists a great potential to be exploited in high-yield breeding and culture of dry land crop on the other hand. It is our belief that in China, as the conditions in wheat production is improved and the fertilizer input in wheat production is increased, wheat yield will averagely reach 3 000 kg/ha or more on dry land and even 3 750 kg/ha on 50% of the dry land in the middle of this century. Therefore, raising WUE by improving crop is of important significances in continuous increasing the grain yield of China brought to the persistent increase in China’s food production.

Plants genetically and physiologically differ significantly in drought resistance and high water use efficiency, just as “someone can gain weight even by drinking water”. Wheat and other crops can be classified into 4 WUE types of which type 1 is characterized by low water consumption and low yield and low WUE, and consequently referred to as so-called “three-low” type; type 2 is characterized by moderate to low water consumption, middle to high yield and higher WUE, for instance, Xifeng 20, Chang 6878 that are planted in the region of winter wheat in north China; type 3 is characterized by medium to high water consumption, the highest yield and the highest WUE, such as Shijiazhuang 8 and Linfeng 615 that are the varieties of wheat adaptable to both dry land and irrigation land that are extended in the dry land area of Huanghuaihai Region in China; and type 4 is characterized by high water consumption, low yield and low WUE. We hope to breed new drought-resistant and water saving varieties with high yields that belong to types 2 and 3 (Zhang et al., 2006).

Considering genetic improvement of drought-resistance and water-saving crop varieties, the three measures can be taken as follows: 1) to strengthen the screening and exploitation of various drought-resistant germplasms with high WUE; 2) to introducing and domesticating new plant species and crop varieties with drought resistance and high WUE from arid and semi-arid areas of China and foreign countries; 3) to breeding new drought-resistant and water-saving crop varieties with high-quality and high yield by employing biotech including conventional breeding methods and transgenic techniques.

Now in-depth research on the physiological and genetic mechanisms of high WUE crops should be carried out on the levels of growth, development, morphology, structure, tissue, cell, molecule, gene metabolic regulation, genome, genetic engineering, breeding and improvement in the following aspects: (1) drought resistant mechanisms; (2) high WUE mechanisms, such as molecular biology mechanisms in aquaporin and WUE regulations; (3) the mechanisms to increase the harvesting indexes (HI) of crops; (4) the coordination among drought resistance and high WUE and high yield; (5) the mechanisms to couple high use efficiencies of water and nutrients; (6) high efficient use and transport of water and light. Thus, biological water-saving should be stressed in future. The research about biological water-saving need to be reinforced and a project to study the mechanism and application of biological water-saving or the mechanism and application of the improvement in crop WUE should be organized, which will be of important significance to the developments of water-saving agriculture and sustainable agriculture.

Conclusion

In nature, plants also have to cope with the interaction of multiple stresses that often arise concomitantly with drought, and ultimately involve oxidative stress (Stanhill, 1992; Richards et al., 2002; Li and Peng, 2003; Inter Academy Council, 2004; Liang, 2006; Shao et al., 2008). Protective responses at the leaf level must then be triggered in response to stress to prevent irreversible damage to the photosynthetic machinery. The molecular understanding of mechanisms involving stress perception, signal transduction, and transcriptional regulation of stress tolerance, may help engineer tolerance to multiple stresses in crop plants. Application of TFs may provide a more adaptive function in improving tolerance, either through protection or repair mechanisms. Advances in the molecular biology of stress responses in tolerant organisms are introducing the potentials of stress tolerance genes in agricultural programmes, not only to ensure survival but also to ensure productivity under drought environments.

The researches about biological water-saving contain wide ranges of diverse contents; have a weak basis and later starting so that they have a great potential. The technology of biological water-saving will be the ultimate aim in saving water and increasing crop yields. It also can be seen that biological water-saving is the ultimate aim not only in saving water in agriculture but also in constructing a resource-saving and environment-friendly society. Bio-water-saving has been listed as one of the national key research fields of China and one of the key research fields in which related organizations and some provinces of China hope to make breakthrough, but although biological water-saving is in the ascendant, it will have a long way to go as well.

It is believed that it is the main task to construct and expand the agriculture characterized by biological water-saving as well as construct and promote the cities characterized by biological water-saving and it is the ultimate goal to construct a society by biological water-saving. The construction of the agriculture characterized by biological water-saving involves two respects: one is crop planting characterized by biological water-saving and the other is animal raising characterized by biological water-saving. Crop planting characterized by biological water-saving is the main research field to be studied, whereas it is imperative to study animal raising characterized by biological water-saving. Crop planting characterized by biological water-saving is the core of water-saving agriculture ranking the highest in importance. As to crop planting characterized by biological water-saving the first is to construct and expand field crop planting characterized by biological water-saving and the second is to construct and expand vegetable crop planting characterized by biological water-saving.

As urban and township developments are ongoing quickly, the problem about the water consumption of land-scape planting and magnitude of sewage disposal has attracted the attention from all the society and become one of the key problems critical to urbane construction and sustainable development. Therefore, the two keys to construct and promote the cities characterized by biolo-gical water-saving are to construct and promote land-scape planting, sewage disposal and environment con-servation characterized by biological water-saving. It would have significant reality meaning and long history influences that will have realistic significance and pro-found historical influence. Therefore, efforts should be made to transforming landscape planting characterized by high water consumption into landscape planting cha-racterized by water-saving as early as possible so that urbane landscape planting will embark on a sustainable and healthy road.

Biological water-saving is a systematical engineering that can play an important role at the different parts of the ecosystems. Besides the agriculture and cities characterized by biological water-saving will be constructed, the techniques of biological water-saving should be employed to reinforce the environment control and improvement and the development and exploitation of poor quality land and water resources for water and soil conservation in particular in non-farming and mountainous areas so as to construct a ecosystem and a society both of which will be characterized by biological water-saving.

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