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REVIEW PAPER

Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security

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Abstract

More than 70% of fresh water is used in agriculture in many parts of the world, but competition for domestic and industrial water use is intense. For future global food security, water use in agriculture must become sustainable. Agricultural water-use efficiency and water productivity can be improved at different points from the stomatal to the regional scale. A promising approach is the use of deficit irrigation, which can both save water and induce plant physiological regulations such as stomatal opening and reproductive and vegetative growth. At the scales of the irrigation district, the catchment, and the region, there can be many other components to a sustainable water-resources strategy. There is much interest in whether crop water use can be regulated as a function of understanding of physiological responses. If this is the case, then agricultural water resources can be reallocated to the benefit of the broader community. We summarize the extent of use and impact of deficit irrigation within China. A sustainable strategy for allocation of agricultural water resources for food security is proposed. Our intention is to build an integrative system to control crop water use during different cropping stages and actively regulate the plant's growth, productivity, and development based on physiological responses. This is done with a view to improving the allocation of limited agricultural water resources.

Key words: Crop production, deficit irrigation, food security, physiological response, water-saving agriculture, water sustainability.

Introduction

Globally, more than 40% of annual food production comes from irrigated land, and agriculture is the largest consumer of water, at 70% of all freshwater withdrawals (FAO, 2007). As water scarcity becomes more acute in many parts of the world, increasing the effectiveness with which agricultural water resources are used is a priority for enhanced food security. The world population is predicted to grow beyond 7.5 billion and food demand to increase by 50% by 2030 (FAO, 2012). Using present values of agricultural water-use efficiency (WUE), calculations suggest that water use in irrigation will increase by 30%, which can be as much as 750 km^3 of water. In addition to this, climate change will impact the extent and productivity of both irrigated and rain-fed agriculture across the globe, increasing crop water demand and decreasing crop productivity in many regions.

A significant challenge for agriculture is to provide the world's growing population with a sustainable and secure supply of sufficient, safe, nutritious food that meets dietary needs and food preferences for an active and healthy life. This will probably need be done using less farmland and reduced quantities of water (FAO, 2002). Agricultural water productivity (yield per unit of water used) must be improved.

Abbreviations: ABA, abscisic acid; APRI, alternate partial root-zone irrigation; ET, evapotranspiration; EUW, effective use of water; FPRI, fixed partial root-zone irrigation; GPP, gross primary productivity; PRD, partial root-zone drying; RDI, regulated deficit irrigation; RMB, Renminbi; VPD, water vapour pressure difference; WUE, water-use efficiency.

Increased global food security will be impossible if agricultural water-resource utilization is not sustainable (Biswas, 2008; García, 2008). China's population is currently over 1.3 billion and, despite social policies to limit population growth, is not expected to reach a peak until 2033 at around 1.5 billion. The country must feed 21% of the world's population with only about 6% of the global water resources and 9% of its arable land (Zhang, 2011). Arid and semi-arid areas account for 49% of the total land area of China, and the development of agriculture in many regions is limited by water scarcity. This is particularly the case for irrigated agriculture in arid areas, which will need an additional water supply to meet the challenge of producing more food in the coming decades (Molden, 2007; Li *et al.*, 2014).

WUE can be described and quantified by different terms and scales. Physiologically, photosynthetic WUE is the most basic at the leaf level, and instantaneous WUE ($\mathrm{WUE_{ins}}$, photosynthesis rate/transpiration rate, P_n/T_r) and intrinsic WUE ($\mathrm{WUE_{int}}$, photosynthesis rate/stomatal conductance of $\mathrm{CO_2}$, P_n/g_s) are the two common parameters. Furthermore, the trade-off between the amount of carbon assimilated and the amount of water transpired has been quantified at the leaf level (Lambers *et al.*, 1998; Katul *et al.*, 2000):

$$\mathrm{WUE_{ins}} = \frac{C_a \cdot (1 - C_i / C_a)}{1.6 \cdot \mathrm{VPD}} \text{ and}$$

$$\mathrm{WUE_{int}} = \frac{C_a \cdot (1 - C_i / C_a)}{p_a}$$

where, C_a and C_i are the ambient and inner leaf partial pressures of $\mathrm{CO_2}$ (hPa) respectively, and VPD(hPa) is the water vapour pressure difference ($e_i - e_a$) assuming that leaves and the atmosphere are at the same temperature. The constant 1.6 is the ratio of molecular diffusion coefficient for water vapour relative to that for $\mathrm{CO_2}$, and p_a is the atmospheric pressure (hPa).

However, the two parameters calculated according to measurement by the gas exchange method are both instantaneous values that can only explain short-term responses to environmental factors. At the ecosystem level, a measure analogous to $\mathrm{WUE_{int}}$ is:

$$\mathrm{WUE_i^*} = \frac{\mathrm{GPP}}{G_s}$$

where GPP is gross primary productivity and G_s is surface conductance derived from meteorological variables and the latent energy flux by inverting the Penman–Monteith equation.

Thus, inherent WUE (IWUE*) can represent $\mathrm{WUE_i^*}$, which can be described as the used daily GPP, VPD, and evapotranspiration (ET) data from 43 sites around the world at the ecosystem level (Beer *et al.*, 2009):

$$\mathrm{IWUE^*} = \frac{\mathrm{GPP \cdot VPD}}{\mathrm{ET}}$$

However, there are still some assumptions and limitations; for example, diurnal variations in GPP, ET, and VPD were neglected when exploring their linear relationship using daily data, but the relationship is non-linear under some particular environmental conditions (Katul *et al.*, 2000). A new underlying WUE was proposed and a hysteresis model supporting the GPP, $\mathrm{VPD^{0.5}}$ and ET relationship was also put forward (Zhou *et al.*, 2014):

$$\mathrm{uWUE} = \frac{\mathrm{GPP \cdot VPD^{0.5}}}{\mathrm{ET}}$$

The formation of crop yield is the result of the synergistic effect of multiple factors in the field. How can we express crop productivity and the physiological process in the long term and the response to breeding and other agronomic measures? As with crop level during the growth season, crop WUE ($\mathrm{WUE_c}$) is often used to quantify the crop water productivity responses to crop species, genotypes, and management practices as:

$$\mathrm{WUE_c} = B \times \mathrm{HI/ET}$$

where B is crop dry biomass, HI is harvest index, and ET is crop water used.

From an agronomic and genetic viewpoint, it has also been argued that the important determinant of plant production in arid areas is the effective use of water (EUW, defined as maximal soil moisture capture for transpiration, which also involves reduced non-stomatal transpiration and minimal water loss by soil evaporation) and not higher WUE under drought stress (Blum, 2009). Furthermore, at the farmland, irrigation district, and even regional levels, the seepage, water loss, and recycled water in the farmland and canal systems should be considered. A systematic and quantitative approach to improve the multiplicative WUE chain (E_{all}) from reservoir to crop yield was put forward by Hsiao *et al.* (2007) to quantify the integrative effects of agricultural water management, engineering, agronomical, and physiological processes clearly and fundamentally as follows:

$$E_{\mathrm{all}} = E_{\mathrm{conv}} \times E_{\mathrm{farm}} \times E_{\mathrm{appl}} \times E_{\mathrm{ET}} \times E_{\mathrm{tr}} \times E_{\mathrm{as}} \times E_{\mathrm{bm}} \times E_{\mathrm{Y}}$$

$$= \frac{W_{\mathrm{fg}}}{W_{\mathrm{V0}}} \times \frac{W_{\mathrm{fd}}}{W_{\mathrm{fg}}} \times \frac{W_{\mathrm{rz}}}{W_{\mathrm{fd}}} \times \frac{W_{\mathrm{ET}}}{W_{\mathrm{rz}}} \times \frac{W_{\mathrm{tr}}}{W_{\mathrm{ET}}} \times \frac{m_{\mathrm{as}}}{W_{\mathrm{tr}}} \times \frac{m_{\mathrm{bm}}}{m_{\mathrm{as}}} \times \frac{m_{\mathrm{Y}}}{m_{\mathrm{bm}}}$$

where E_{conv}, E_{farm}, E_{appl}, E_{ET}, E_{tr}, $\mathrm{E_{as}}$, E_{bm}, and E_{Y} are water conveyance, in the farm, application, consumptive, transpiration, assimilation, biomass and yield efficiency, respectively, W_{V0} is the ratio of the quantity of water (W) diverted out of the reservoir for the farm, W_{fg} is the quantity of water received at the farm gate, W_{fd} is the water at the field edge, W_{rz} is the water retained in its root zone, W_{ET} is the water in the root zone removed by ET, W_{tr} is the water taken up by the crop and transpired, m_{as} is mass of $\mathrm{CO_2}$ assimilated by photosynthesis, m_{bm} is plant biomass produced, m_{Y} is harvested yield.

Typically in this literature, the numerator and denominator of the efficiency ratio for the overall efficiency ($\mathrm{E_{all}}$) under poor and good situations showed a 12–50-fold difference in WUE when the comparison is based on the upper limit values of the poor and on the mid-values of the good or between the mid-values, which indicated that there is much potential for improvement in different situations. Hence, deficit irrigation is practised when farmers have less water than the maximum ET needs, thus increasing WUE for E_{appl}, E_{ET} and E_{Y} mainly through applying most remaining water in the root zone, forcing crops to extract more water from the soil and improving harvest index by regulating vegetative and reproductive growth (Hsiao *et al.*, 2007).

There are three ways of dealing with water scarcity that limits food availability: (i) by increasing the supply of water and land above present levels; (ii) by improving water productivity either by enhancing yield or by EUW; or (iii) by importing water in the form of food (virtual water) to cope with regional water scarcity (Fereres *et al.*, 2011). In China, 63% of total water is used for agriculture, but there is substantial regional variation in these data. In north China, where there is extreme water scarcity and high productivity under most circumstances, the average water use may be 75%, but in arid areas such as north-west China, agriculture can use 90% of total water available since food production depends mainly on irrigation. Such a substantial commitment of water to irrigation causes significant problems for the natural environment, and the capacity for people to live normal lives and for communities to survive is called into question (Kang *et al.*, 2009).

How can we improve agricultural water productivity? Utilization of limited water resources can be made more efficient by implementing 'water-saving agriculture', which is an approach that includes more effective distribution of irrigation water, manipulation of water transport through the soil–plant–atmosphere continuum and an increased focus on increasing water availability for yield formation (Fig. 1). The central objectives are to take full advantage of any rainfall, efficient utilization of irrigation water, and improved crop WUE by integrative measures. In China, water-saving agriculture has been an effective way to cope with the ever-increasing food demands of the country. Water-saving agriculture is applied in China via a range of administrative policies. These are aimed at increasing the efficiency of agricultural water use. In practice, this is achieved by integrative technology systems including engineering, agronomy, and biology.

The engineering approaches include rational exploitation of water resources, rainwater harvesting and storage for agricultural use, utilization of brackish water or recycled sewage water, desalination of sea water or sea ice for irrigation, which can be implemented with canal lining, low pressure pipe conveyance, improved surface irrigation by shortening or narrowing borders or furrows, surge flow irrigation based on laser-controlled land levelling technology and sprinkler irrigation, micro-irrigation, drip irrigation under plastic film mulch, and subsurface irrigation (Du *et al.*, 2014). Meanwhile, agronomic approaches include crop rotation, water conservation through minimum tillage or no tillage, plastic film mulching or straw mulching, water-fertilizer coupling, use of superabsorbent polymers to increase the water-holding capacity of the soil, soil amendments, and anti-transpirants.

Although this is a wide range of innovative approaches, the most challenging and potentially promising approach is the exploitation of plant biology to deliver 'biological water saving' through physiological regulation of water productivity. This involves exploitation via plant improvement and/or crop management of our understanding of the control of stomatal opening, different root properties, and reproductive and vegetative growth. The aim of biological water saving is to decrease crop water consumption without an apparent yield reduction under conditions where water is in limited supply.

Plant physiological responses to deficit irrigation

Stomata are pores on leaf surfaces through which plants exchange CO_2, water vapour, and other constituents with the surrounding environment. In general, stomatal conductance depends on stomatal density and size, and more stomata will provide more pores for transpiration. Under the given conditions, water stress caused by deficit irrigation may result in stomatal closure and thus reduce transpiration rate. Many researchers have reported that stomatal density responds to various environmental factors and water deficit leads to an increase in stomatal density and a decrease in stomatal size, indicating an adaptation to drought (Zhang *et al.*, 2006; Martinez *et al.*, 2007). A study on a perennial grass (*Leymus chinensis*) showed that moderate water deficits had positive effects on stomatal number but more severe deficits led to a reduction (Xu and Zhou, 2008). Furthermore, research on peanut suggested that soil drying reduced stomatal aperture and stomatal conductance but increased WUE, and the response was different among different peanut genotypes under moderate or mild water stress (Songsri *et al.*, 2013). The research progress in determining the genes regulating stomatal density and the possibility of increasing plant WUE were reviewed by Wang *et al.* (2007). It appears that manipulating stomatal density may be a more amenable approach than manipulating stomatal behaviour in achieving a better plant WUE.

A supply of water to the plant is essential for crop growth. A minimum amount of cell turgor is required for cell expansion, while the activity of the cell cycle and cell production also requires a minimum water status. Water deficit during the growth and development of the plant affects different physiological, biochemical, and developmental processes that underpin yield formation in one way or another.

How can we develop an irrigation method to improve crop WUE from a physiological understanding? The major plant adaptive response to drought at the cellular level, which has a proven effect on yield under drought stress, is osmotic adjustment (Blum, 2005). Our experimental data on cotton also showed that deficit irrigation enables leaf turgor maintenance under the same leaf water potential, thus supporting stomatal conductance under lower leaf water status, and improves root capacity for water uptake (Du *et al.*, 2007). A primary response to variation in water availability is stomatal behaviour, and this will directly impact crop water status and carbon gain. Transpiration efficiency, which is WUE at the leaf level,

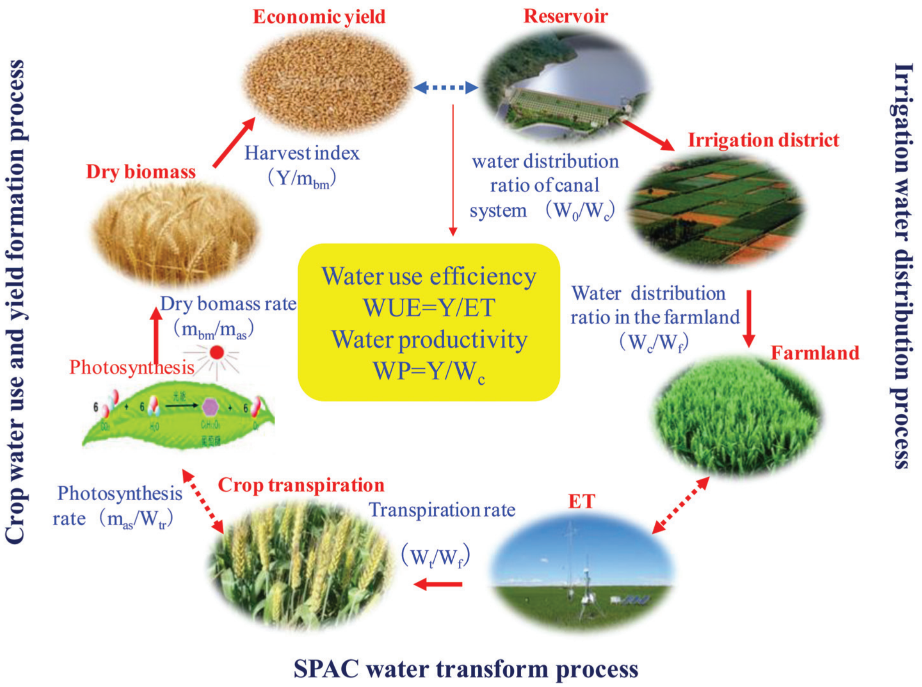

Fig. 1. Multiple processes of water use in agriculture for food security.

is determined by the delicate interplay between transient photosystem activity, substomatal cavity CO_2 concentration, and stomatal activity (Farquhar *et al.*, 1989). Furthermore, both reproductive and vegetative growth will be impacted by plant water status and carbon gain but can also apparently respond directly to soil water availability (Du *et al.*, 2010b). A positive and unique relationship between stomatal conductance to leaf water status has traditionally been considered evidence for stomatal control by a range of environmental factors and control of leaf water status by stomata. When a negative relationship is found, a mechanism that allows stomata to control leaf water status has been proposed (Jones, 1990).

Fully irrigated plants usually have widely opened stomata. Plants open their stomata for CO_2 uptake and carbon gain but will lose significant quantities of water at the same time (Kang and Zhang, 2004). A small narrowing of the stomatal opening can reduce water loss substantially with little effect on photosynthesis rate. Earlier research predicted that plants generally should have the capability to increase their WUE in this way, thereby maximizing their chance of surviving a period of drought, potentially without a great reduction in carbon gain and biomass accumulation. However, this may occur only when crops are aerodynamically well coupled to the atmosphere (Cowan, 1988). However, during critical growth stages, it is particularly important to maintain plant water supply and status (McLaughlin and Boyer, 2004); successful plants may be those that regulate their water loss as a function of the amount of available water in the soil (Jones, 1990). This suggests that plants must be able to 'detect' the degree of soil drying and then respond to it, for example by regulating their stomatal conductance. Early work in the laboratory (e.g. Zhang and Davies, 1989, 1990; Davies and Zhang, 1991; Mingo *et al.*, 2004; Dodd, 2013) has revealed that such a feed-forward mechanism may work through a range of chemical growth regulators such as abscisic acid (ABA), 1-aminocyclopropane-1-carboxylate (ACC), cytokinins, and plant mineral elements, which might act as 'signals' of the degree of soil drying. Some early suggestions were that synthesis of some growth regulators in roots may be a function of root water status, with 'root-sourced signals' moving to the shoots in the xylem stream to regulate shoot growth and physiology. However, there is now some doubt whether enough ABA can be synthesized in roots to attribute root signalling to root-sourced ABA (Christmann *et al.*, 2007). There are many reports of strong relationships between xylem ABA concentrations and shoot physiological and developmental responses (e.g. Tardieu *et al.*, 1992; Dodd *et al.*, 2008*a*, *b*; Dodd, 2009), and we must account for this extra ABA transport as soil dries. Many years ago, Hartung and co-workers reported that much shoot-sourced ABA can be transported to roots in the phloem and recirculated to shoots, apparently in quantities that are dependent on soil and root water status (Hartung and Slovik, 1991). In addition to this, Wilkinson and Davies (2010) showed that, while ABA in the xylem (which is always present, regardless of the soil water status) can be the regulator that is responsible for stomatal and growth responses to soil drying, extra hormone is not required to elicit a response. Alkalinization of the xylem sap, which often accompanies soil drying, will allow ABA arriving in the shoot increased access to sites of action on the guard cells, for example, thereby increasing the potency of the ABA-based root signal. Experiments with rootstocks and other tools have underlined the importance of root-sourced cytokinins and other hormones as components of root signals (Ghanem *et al.*, 2011). Root signals may substantially reduce water loss through stomata at a time when no water deficit is detectable in the shoots, and may be thought of as a first line of defence against soil drying. With prolonged soil drying, a second line of defence may operate through a progressive reduction in shoot turgor and water potential, perhaps starting with lower and older leaves. Massive amounts of ABA will be produced in these wilted leaves and be sent to the upper younger leaves and buds where water loss will be reduced even further (Zhang and Davies, 1989). It is important that plants maintain a minimum water status in their meristems for some growth and eventually for survival under a prolonged drought. With the decreasing availability of water in the soil, signals from the first and second lines of defence will increase in strength, and stomata will close further. Part of the root system in drying soil can respond to the drying by sending root signals to the shoots where stomatal behaviour may be impacted in such a way that water loss is reduced (Liang *et al.*, 1997).

Understanding the processes for regulating water use and yield as well as quality provide some opportunity for biological water saving in agriculture. We need to know how this biology can be manipulated to the advantage of farmers, via changing methods and degrees of water availability in plant root zones. Furthermore, key growth stages must be identified (Fig. 2).

Most plants grow in environments where water is frequently in short supply, and during this time, the demands of plants for water and photo-assimilates vary with the growth stage of the plant. The effects of water deficits depend on the timing, duration, and severity of the stress (Bradford and Hsiao, 1982). Soil water deficit at the seedling stage can substantially reduce the stomatal conductance leaf growth and leaf photosynthesis. However, such inhibition may not cause permanent injury because photosynthesis and growth can largely recover from all but the most severe stresses. Here, stomatal inhibition may be the main cause of a restriction in carbon gain (Cornic, 1994), while cell expansion may be limited by hydraulic and chemical influences. Cell division may continue under mild stress, and this 'stored growth' can cause leaves to grow faster after a soil-drying episode such that there may be no net loss of canopy development with time (Hsiao *et al.*, 1976). Soil water deficit may reduce water loss from plants through physiological regulation of stomatal conductance (Davies and Zhang, 1991). Therefore, the total water consumption can be reduced by both a temporary (or accumulative, depending on the degree of stress) reduction in leaf area and a reduced rate of transpiration.

Water stress can generate passive adaptation of plants to a condition of water scarcity, but a regulated deficit through a targeted irrigation treatment may be used as an active means of improving crop yield quality and WUE. The potential benefits of deficit irrigation given at different stage(s) of crop development have been tested on a broad range of crops. Regulated deficit irrigation (RDI), a concept raised in the 1970s, provides a controlled degree of soil drying at particular times in a season. In this way, the amount of irrigation water applied is reduced (Stewart and Nielsen, 1990), and this can therefore be a way of increasing water productivity (higher yields per unit of irrigation water applied). This technique has been used for controlling excessive vegetative growth (as an alternative to pruning, which may allow disease development of some crops). In a specific period of the growing season, irrigation time is limited in order to reduce the rate of canopy development. This can save water but have little impact on carbon gain and yield if the crop is not carbon limited. Penetration of more radiation to fruit developing in the canopy can greatly increase the quality of the fruit of some crops. The application of RDI can require less labour than a pruning operation and thereby increase profitability of the crop for farmers. After a period of water deficit, water is supplied

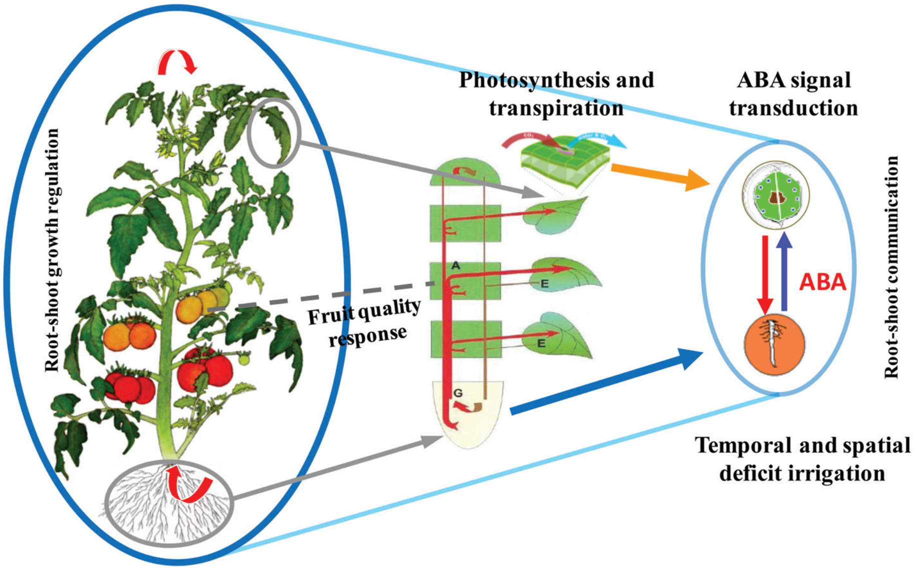

Fig. 2. Water-use process regulation by changing the drying and wetting method of plant root zones. The figure is modified from: Sauter A, Davis WJ, Hartung W. 2001. The long-distance abscisic acid signal in the droughted plant, the fate of the hormone on its way from root to shoot. *Journal of Experimental Botany* **52,** 1991–1997, by permission of the Society for Experimental Biology, and Davies WJ, Sally W, Loveys BR. 2002. Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist* **153,** 449–460, with permission.

again to the crop to ensure a reasonable yield of good quality.

Given that most countries in the world now face increasing water scarcity for at least part of their main cropping season, how to irrigate crops with a limited quantity of water without losing a significant amount of yield is a major issue: how can we increase productivity per unit of water used, thereby producing 'more crop per drop' (UNIS, 2000) of water used? Deficit irrigation methods based on physiological responses have been reported to improve WUE (Goodwin and Jerie, 1992; Boland *et al.*, 1993; Kang *et al.*, 2000*a*, *b*, 2002*a*, *b*). These were often explained either in terms of reduced soil surface evaporation and/or a trade-off of better water use for a proportionally smaller reduction in yield. Alternate partial root-zone irrigation (APRI) or partial root-zone drying (PRD) should produce more benefits than these. Early studies involving partially drying part of the root system also quantified the effects on the ABA contents of the roots, xylem sap, and leaves in either a horizontally split-root system in *Helianthus annuus* (Neales *et al.*, 1989) or a vertically split-root system with upper soil drying (Li and Zhang, 1994). These experiments were conducted using fixed PRD, and the roots in the dried part of the root zone experienced minor changes in soil water status. Much effort has been spent on developing efficient irrigation techniques such as RDI and APRI based on physiological response. Both methods can reduce transpiration and leaf growth while increasing WUE with only small decreases in yield while improving crop fruit quality (Dry and Loveys, 1998; Kang *et al.*, 1998).

RDI is usually applied during the period of slow fruit growth when shoot growth is rapid. However, it can also be applied after harvest in early-maturing varieties. It is useful for reducing excessive vegetative vigour and also for minimizing irrigation and nutrient loss through leaching. The scheduling is applied by reducing irrigation rates only in those periods when fruit or crop growth is less sensitive to water, and irrigation reductions are often defined as a percentage of an optimal irrigation rate (Chalmers *et al.*, 1981; Girona *et al.*, 1993). Although the initial goal of RDI was to improve yield and/or quality, in arid and semi-arid regions, the focus is related primarily to the efficient management of limited water resources. Environmental problems caused by an excess of nitrogen leakage and irrigation sustainability are also addressed by this technique.

APRI has been proposed as a means of improving crop WUE with no (or reduced) losses in yield. APRI attracted considerable interest after it was first proposed (Dry and Loveys, 1998; Kang *et al.*, 1998; Davies *et al.*, 2000, 2011; Gu *et al.*, 2000). This irrigation method is relatively easy to apply in the field if alternative irrigation of part of the root system is possible. This is relatively straightforward at low cost, with some manufacturers of irrigation piping selling irrigation piping where two lines are welded together with offset drippers. The concept of elevating the transport of hormones from one part of the root system while the wetter soil around the other part of the root supplies water is derived from earlier split-root studies (Blackman and Davies, 1985; Zhang and Davies, 1987) and requires parts of the root zone to be dried and wetted alternately (Kang and Zhang, 2004). The novelty of this method is that a root signal from the drying roots can reach the shoots where physiological processes such as stomatal behaviour and leaf growth can be controlled (Zhang and Davies, 1990). However, Dodd (2007) showed that it is important not to dry the soil excessively because some xylem transport from dry roots is required to allow chemical signals to exert physiological control. Although PRD/APRI and RDI are rational in theory, it is difficult for farmers to optimize their application, particularly in anything other than row crops (e.g. in cereal production in the field). The timing of RDI and the degree of soil water deficit, and the timing and method of APRI are still needed to be investigated on cereals in different climates, cereal varieties and planting conditions. Even the control equipment in the field still needs to be optimized before it can be concluded whether it is practical in all conditions. Nevertheless, Dodd's group have gone some way to providing an understanding of how different degrees of soil drying and timing of rewatering can impact the transport of growth regulators (Dodd, 2007). In a particularly interesting paper, Martin-Vertedor and Dodd (2011) related the number of cereal roots in drying soil to the intensity of an ABA signal and the degree of limitation of leaf growth. In a meta-analysis across a range of horticultural and agricultural crops, Dodd (2009) showed a positive impact of PRD on WUE compared with a control where the same amount of water was applied indiscriminately across the whole root system. This is strong evidence that long-distance chemical signalling in a range of crops can be exploited to enhance water productivity in agriculture.

Deficit irrigation studies in China to improve WUE in agriculture

Since drought tolerance varies considerably by genotype and by phenological stage, deficit irrigation requires precise knowledge of the crop response to drought stress for each of the growth stages (Kirda *et al.*, 1999). Many regions of China are suffering from water scarcity, with overuse of water in agriculture causing serious environmental problems in some regions. The impacts of RDI have been researched on a range of field crops in China in the arid north and north-west China under the support of the National Natural Science Foundation and programs from the Ministry of Science and Technology and other ministries. The research showed that crops that are less sensitive to water deficits, such as fruit trees, cereals crops, and greenhouse crops, can adapt well to various deficit irrigation practices (see Tables 1–3).

Deficit irrigation methods on cereal crops: maintaining yield with less water

In general, cereal crops contribute significantly to food security. There is some potential to practice RDI on cereal crops in the arid north and north-west of China. Most experiments on field crops such as maize, wheat, and sorghum have shown that RDI can maintain a similar yield level under mild water

Table 1. *Details of recommended deficit irrigation and compared irrigation methods on field crops in China*

Plants	Study no.	Details of recommended deficit irrigation and compared irrigation methods	Location and time	Reference
Maize	1	Alternate partial root-zone furrow irrigation compared with conventional furrow irrigation	Minqin, Gansu, 1999–2000	Kang *et al.* (2009)
	2	Controlled soil water at 40–50% θ_f at the seedling stage plus a further mild soil drying (55–65% θ_f) at the stem-elongation stage, compared with 60–80 and 65–85% θ_f, respectively	Changwu, Shaanxi, 1996–1997	Kang *et al.* (2000*a*)
	3	Controlled soil water at 60% θ_f compared with 65% θ_f at the seedling to stem-elongation stage	Xinxiang, Henan, 2007	Du *et al.* (2010b)
Wheat	4	Irrigation controlled at the lower limit of soil water content at 60%, and 45% θ_f at seedling, 45% θ_f at grain-filling stage, and 75% θ_f at other stages, compared with 75% θ_f at all stages	Changwu, Shaanxi, 1995–1998	Kang *et al.* (2002*a*)
	5	Irrigation water amount of 60 mm compared with 75 mm at seedling to tillering stages	Wuwei, Gansu, 2004	Kang *et al.* (2009)
	6	Irrigation controlled at the lower limit of soil water content as 80, 70, and 70% θ_f, compared with 90, 85, and 85% θ_f at sowing, seedling and jointing stages	Yanzou, Shandong, 2007–2008	Han *et al.* (2009)
	7	Controlled soil water at 50–55% θ_f compared with 65% θ_f at the planting to seedling stage with three varieties	Xinxiang, Henan, 2006–2007	Du *et al.* (2010b)
	8	Controlled irrigation times as four with the irrigation water amount of 30 mm per time, compared with irrigation times as two with the irrigation water amount of 60 mm per time at stem-elongation and heading stages	Luancheng, Hebei, 2003–2007	Du *et al.* (2010b)
Sorghum	9	Alternate partial root-zone furrow irrigation at jointing and heading stages with irrigation water amount of 37.5 mm compared with traditional block irrigation of 67.5 mm for each irrigation	Xiuwen, Shanxi, 2011	Cao *et al.* (2011)
Potato	10	Alternate partial root-zone furrow irrigation only using half the irrigation water amount compared with traditional furrow irrigation with three varieties	Huhehot, Inner Mongolia and Qinwangchuan, Gansu, 2009–2010	Xie *et al.* (2012)
	11	APRI only using 70% irrigation water amount compared with traditional subsurface drip irrigation	Xinxiang, Henan, 2008	Huang *et al.* (2010)
Bean	12	Mild deficit (60–65% θ_f) at seedling and jointing stages compared with full irrigation (70–75% θ_f) at all stages	Qinwangchuan, Gansu, 2006	Ding *et al.* (2007)
	13	Alternate partial root-zone furrow irrigation compared with conventional furrow irrigation with same upper and lower limit of soil water content	Shenyang, Liaoning, 2010	Xu *et al.* (2011)
	14	Alternate partial root-zone furrow irrigation compared with conventional furrow irrigation; the irrigation water amount after planting is three-quarters of the control treatment	Changchun, Jilin, 2009–2010	Zhang *et al.* (2011)
Peanut	15	Two-thirds of the water was applied using alternate partial root-zone furrow irrigation compared with conventional furrow irrigation with the same upper and lower limits of soil water content	Shenyang, Liaoning, 2011	Xia *et al.* (2013)

θ_f, field capacity.

stress during earlier stages, with WUE enhanced significantly (Fig. 3). Experimental research on maize showed that soil drying at the seedling stage plus further mild soil drying at the stem-elongation stage is the optimum deficit irrigation strategy for maize production in this semi-arid area (Kang *et al.*, 2000*a*). The similar results on maize in Shanxi and Shaanxi, cotton in Xinjiang and Gansu, and wheat in Shaanxi and Gansu also suggested that RDI should be applied at the early growth stage (Kang and Cai, 2002). The degree of water deficit can reach 45–50% of field capacity, which has no serious effect on crop yield and can improve crop WUE by 20–29% on maize and 61–66% on wheat, respectively (Kang *et al.*, 2000*a*). A study carried out on winter wheat in the North China Plain showed possible water savings of 25–75% by applying RDI at various growth stages, without significant loss of yield and profits (Zhang *et al.*, 2005, 2013). It was also found that the maximum grain yield of winter wheat will be gained at 84% of maximum ET, and that a reduced irrigation frequency is better for both grain yield and WUE in drought years. Timing of the deficit and its severity should also be modulated according to the drought tolerance of different wheat varieties. For the variety that is sensitive to drought, water deficit at the seedling to stem-elongation stage is the best choice for improved WUE, and its increment also decreased with deficit stage postponed. However, for the variety with higher drought resistance, water deficit in the later

Table 2. *Details of recommended deficit irrigation and compared irrigation methods and responses of fruit quality on fruit trees in China*

The relative fruit quality parameter is the ratio of fruit quality under the recommended deficit irrigation method to that under the conventional method. There was significant difference for data with an asterisk under the recommended deficit irrigation method compared with the control.

Plants	Study no.	Details of recommended deficit irrigation and compared irrigation methods	Location and time	Relative fruit quality parameters	Reference
Apple	1	Moderated water deficit irrigation (water amount at 60% of US Class A pan-evaporation) during 10 June to 10 July; 80% in other growth period, compared with 80% in whole stages under micro-sprinkler irrigation	Changping, Beijing, 1999–2000	–	Huang *et al.* (2001)
	2	Half irrigation water amount was applied using alternate partial root-zone block irrigation compared with conventional block irrigation	Shexian, Hebei, 2004, 2006	No significant difference in TSS, fruit firmness, fructose, and TA	Cheng *et al.* (2008)
	3	Control irrigation water amount of two-thirds during sprouting to bloom flowering compared with conventional block irrigation	Shexian, Hebei, 2004–2006	No significant difference in TSS, fruit firmness, fructose, and TA	Cheng *et al.* (2008)
	4	Half irrigation water amount was applied using alternate partial root-zone drip irrigation compared with conventional drip irrigation; the alternate cycle was 2–4 weeks	Yantai, Shandong, 2006–2007	1.05–1.07* (fruit firmness); 1.09–1.10* (TSS); 0.90–0.96* (TA)	Liu *et al.* (2010c)
Pear	5	Controlled soil water content at 40–60% θ_f for 25–80 d after full blooming, compared with conventional block irrigation above 60% θ_f during all stages	Handan, Hebei, 1998–2001	1.08* (TSS); 1.28*–1.72* (fructose); 1.27* (TA); 1.10*–1.17* (K)	Cheng *et al.* (2003)
	6	Moderated water deficit irrigation (water amount at 60% of US Class A pan-evaporation) in slow fruit enlargement stage, 80% in cell division and slow fruit growth period, compared with 80% in all three stages under drip irrigation	Korla, Xinjiang, 2009–2010	1.00–1.04 (TSS); 0.55*–1.24* (TA); 1.01–1.10* (fructose)	Wu *et al.* (2012)
	7	Alternate partial root-zone block irrigation (300 l of water per plant per irrigation) compared with conventional block irrigation (500 l of water per plant per irrigation); the low limit of soil water content is 60% $\theta_{f.}$	Yongnian, Hebei,2004–2005	–	Zhao *et al.* (2007)
	8	Alternate partial root-zone block irrigation (50 mm per plant per irrigation) compared with conventional block irrigation (60 mm per irrigation); the low limit of soil water content is 60% $\theta_{f.}$	Yongnian, Hebei, 2006–2007	1.08–1.14* (TSS); 0.92–0.95 (TA); 1.04–1.06 (fruit firmness)	Zhao *et al.* (2008)
Peach	9	Moderated water deficit irrigation (water amount as 60% of US Class A pan-evaporation) in slow fruit enlargement stage, 80% in cell division and slow fruit growth period, compared with all 80% in three stages under drip irrigation	Haidian, Beijing, 1997–1998	–	Li *et al.* (2001)
	10	Half irrigation water amount was applied using APRI compared with conventional drip irrigation; the alternate cycle is 2–4 weeks	Haidian, Beijing, 2004–2005	–	Song *et al.* (2008)
	11	Alternate partial root-zone drip irrigation compared with conventional drip irrigation; the irrigation water amount was 70% of the control treatments	Yangling, Shaanxi, 2001	–	Gong *et al.* (2004)
Table grape	12	Half irrigation water amount was applied using alternate partial root-zone drip irrigation compared with conventional drip irrigation with the same irrigation cycle	Wuwei, Gansu, 2004–2006	1.15–1.42* (Vc); 1.01–1.04 (TSS); 0.87*–1.00 (TA)	Du *et al.* (2008)
	13	Two-thirds irrigation water amount was applied using alternate partial root-zone furrow irrigation compared with conventional furrow irrigation with same irrigation cycle	Wuwei, Gansu, 2004–2006	1.26*–1.38* (Vc); 0.96–1.01 (TSS); 0.82*–0.91* (TA)	Du *et al.* (2013)

Table 2. *Continued*

Plants	Study no.	Details of recommended deficit irrigation and compared irrigation methods	Location and time	Relative fruit quality parameters	Reference
	14	The limit of irrigation was controlled at 40% θ_f during the sprout and heading period	Shihezi, Xinjiang, 2009	–	Liu *et al.* (2010*a*)
Wine grape	15	Controlled soil water content of 65–70% θ_f under conventional drip irrigation (CK); the irrigation water amount was 26 l per plant; 18.2–20.8 l per plant is recommended for three varieties (Cabernet Sauvignon, Cabernet Franc and Pinot Noir)	Yinchuan, Ningxia, 2011	1.02–1.10 (TSS); 0.93–0.97 (TA); 1.02–1.11* (fructose); 1.20*–1.31* (tannins); 1.01 (total phenols); 1.04–1.08* (anthocyanins)	Fang *et al.* (2013)
Jujube	16	Moderate water deficit (half water of CK) at bud burst to leafing stages, compared with full irrigation (90 mm per stage) using block irrigation method	Dali, Shaanxi, 2005–2006	1.15–1.31* (fruit firmness); 1.03–1.05 (Vc); 0.90–1.04 (TSS)	Cui *et al.* (2008)
Litchi	17	APRI (half water of CK) compared with conventional irrigation; the irrigation method was micro-sprinkler	Haikou, Hainan, 2007	No significant difference in TSS, TA, and anthocyanins	Zhou *et al.* (2008)

θ_f, field capacity; CK, control treatment; TSS, total soluble solid content; TA, titrated acid content; Vc, vitamin content.

stage is better for its WUE improvement. Moreover, for the variety with moderate drought resistance, stem elongation to booting is the better stage for water deficit to improve WUE (Du *et al.*, 2010b).

Experiments with pot-grown maize showed that, compared with conventional watering, alternative irrigation on half the root zone reduced water consumption by 35% with a total biomass reduction of only 6–11% (Liang *et al.*, 1997; Kang *et al.*, 1998). Experiment with hot peppers under drip irrigation also showed that APRI reduced water used for irrigation by about 40% (Kang *et al.*, 2001). Another experiment, where APRI was applied to a vertical soil profile (Kang *et al.*, 2002*b*), showed that water consumption was reduced by 20% (moderate soil drying) and 40% (severe soil drying) by extending the watering intervals. It was concluded that alternative watering in the vertical soil profile is an effective and water-saving method of irrigation and may have the potential to be used in the field.

In the field, photosynthesis rate, transpiration rate, yield, WUE, soil water distribution, irrigation water advance, and uniformity were assessed over 4 years for maize irrigated with APRI in an arid area with a seasonal rainfall of 77.5–88.0 mm, and conventional furrow irrigation was used as a comparison. The results showed that there was no significant difference in photosynthesis rate between different irrigation treatments when plants received the same amount of water. Luxury water consumption was reduced, without necessarily reducing the rate of photosynthesis substantially. The most surprising result in this experiment was that APRI maintained a high grain yield with up to a 50% reduction in the amount of irrigation. As a result, WUE for applied water was increased substantially (Kang *et al.*, 2000*a*, *b*). In another trial of APRI, wheat under ridge planting and furrow irrigation was compared with conventional furrow irrigation. The yield of APRI plants increased by 15.5–18.5% compared with control treatment at the same irrigation water amount of 225–300 mm, and one-third to one-half of the water was saved under the same yield level (Lian, 2006). Furthermore, APRI can also significantly reduce nitrate nitrogen accumulation in deeper soil layers (Xue *et al.*, 2008; Xu *et al.*, 2009). Earlier research also showed that APRI had the highest nitrogen fertilizer recovery with minimal mineral nitrogen residue left after maize harvest (Kirda *et al.*, 2001, 2005). For other field crops such as potato, bean, and peanut, deficit irrigation strategies still have great potential on improving WUE with less water and similar yield levels (Fig. 3).

Deficit irrigation methods on fruit trees: improving WUE and fruit quality

Deficit irrigation was applied successfully to fruit trees to balance the vegetative and reproductive growth with acceptable yield and improved fruit quality. Fruit trees are well suited to RDI and APRI strategies because of their deep root systems, and water can be applied with precision to individual plants (Table 2 and Fig. 4). In some earlier cases, experiments on apple and peach trees showed that RDI saved 17–20% of water while shoot growth was reduced, but the tree yields showed no significant differences (Huang *et al.*, 2001; Li *et al.*, 2001). Experiments on pear also showed that controlled soil drying reduced shoot growth by 15–25%, and the fruit diameter and fresh weight were not affected by deficit applied during the fruit growth stage. There is no significant effect of RDI on fruit size, soluble solid content, and yield at harvesting stage (Cheng *et al.*, 2003). Our study on pear-jujube trees also suggested that deficit irrigation can be applied for a fixed period with a controlled degree of soil drying to reduce irrigation water and restrict excessive vegetative vigour. This treatment maintained or slightly increased the fruit yield and thus WUE was significantly increased. During the bud burst to leafing stage, moderate soil water deficits did not have an effect on fruit quality but significantly saved irrigation water and increased fruit yield and thus enhanced WUE by 5–23%. Low water deficit during the fruit growth stage and low, moderate, and severe water deficits during the fruit maturation stage had no significant

Table 3. *Details of recommended deficit irrigation and compared irrigation methods and responses of fruit quality on greenhouse crops in China*

Crops	Study no.	Details of recommended deficit irrigation and compared irrigation methods	Location and time	Relative fruit quality parameters	Reference
Tomato	1	Slight water deficit irrigation (soil water content as 55–65% θ_f at bloom and fruit setting stage and 75–85% θ_f at fruit development stage, compared with 65–75 and 75–85% θ_f, respectively, under drip irrigation	Yangling, Shaanxi, 2006	No significant difference in TSS, Vc and TA	Guo *et al.* (2007)
	2	Alternate partial root-zone furrow irrigation at vegetative growth stage and whole root-zone irrigation at fruit growth stage, compared with conventional furrow irrigation at both stages	Yangling, Shaanxi, 2008	No significant difference in appearance and nutritional quality; the mean nitrate content in the fruit was reduced significantly by 3.1%	Wu *et al.* (2009)
	3	Controlled soil water content at 70–85% θ_f, low water (60% irrigation water amount of CK) at flowering and fruit-set stage and middle nitrogen (0.30 g kg^{-1}) under APRI	Yangling, Shaanxi, 2011	1.13*–1.37* (TSS); 1.06–1.25* (deoxidized sugar); 1.32*–1.50* (lycopene); 0.71–0.79* (TA); 1.03*–1.05* (Vc); 1.39*–1.55*(nitrate content)	Liu *et al.* (2013)
Eggplant	4	Irrigation time interval of 10 d, mild deficit (80% water of full irrigation) at seedling and mature stage, i.e. 12 and 20 mm, full irrigation at flowering and fruit-set stage, i.e. 25 mm per time using drip irrigation	Xinxiang, Henan, 2011	No significant difference in TSS and fruit firmness	Wang *et al.* (2012)
	5	Half water was applied using alternate partial root-zone furrow irrigation compared with flood irrigation for full irrigation	Yangling, Shaanxi, 2004	–	Du *et al.* (2005)
Cucumber	6	Controlled soil water content at 60–90% θ_f at flowering stage and 65–90% θ_f at fruiting stage, compared with 70–90% θ_f at both stages	Yangling, Shaanxi, 2006	1.40* (deoxidize sugar); 1.31* (total soluble sugar); 1.03* (Vc); 1.05*(soluble protein)	Chang *et al.* (2007)
	7	Alternate partial root-zone furrow irrigation (the upper limit of soil water content was 85% θ_f) compared with conventional furrow irrigation	Yangling, Shaanxi, 2007	–	Du *et al.* (2010*a*)
	8	Alternate partial root-zone furrow irrigation compared with conventional furrow irrigation; the irrigation water amount after planting was 65% of the control treatments	Shunyi Beijing, 2008–2009	1.22*–1.26* (soluble protein); 1.08–1.16* (Vc)	Cao *et al.* (2010)
Nectarine	9	Half water was applied using alternate partial root-zone furrow irrigation compared with flood irrigation for full irrigation	Tai'an, Shandong, 2002–2003	0.80*(fruit firmness); 1.16*(TSS)	Bi *et al.* (2005)
Cantaloup	10	Alternate partial root-zone drip irrigation (the upper limit of soil water content was 85% θ_f) compared with conventional drip irrigation(the low limit of soil water content was 100% θ_f)	Yangling, Shaanxi, 2012	1.14* (TSS); 1.25* (Vc); 1.31* (soluble protein)	Zhao *et al.* (2013)
Strawberry	11	Controlled half of the root zone irrigated to 100% θ_f and the other half maintained under drying conditions; irrigation was shifted from one side to the other side of the root zone when volumetric soil water content (θ) at the drying side decreased to about 50% θ_f, compared with whole root zone irrigated to 100% θ_f.	Taian, Shandong, 2007–2008	–	Wang *et al.* (2009)

θ_f, field capacity; TSS, total soluble solid content; TA, titrated acid content; Vc, vitamin content.

effect on the fruit weight and fruit volume but reduced fruit water content slightly, which led to a much reduced percentage of rotten fruit during the post-harvest storage period. Such an RDI strategy also shortened the fruit maturation period by 10–15 d and raised the market price of the fruit (Cui *et al.*, 2008, 2009).

Yield, WUE, and the fruit quality response of table grape subjected to three drip irrigation treatments were examined in

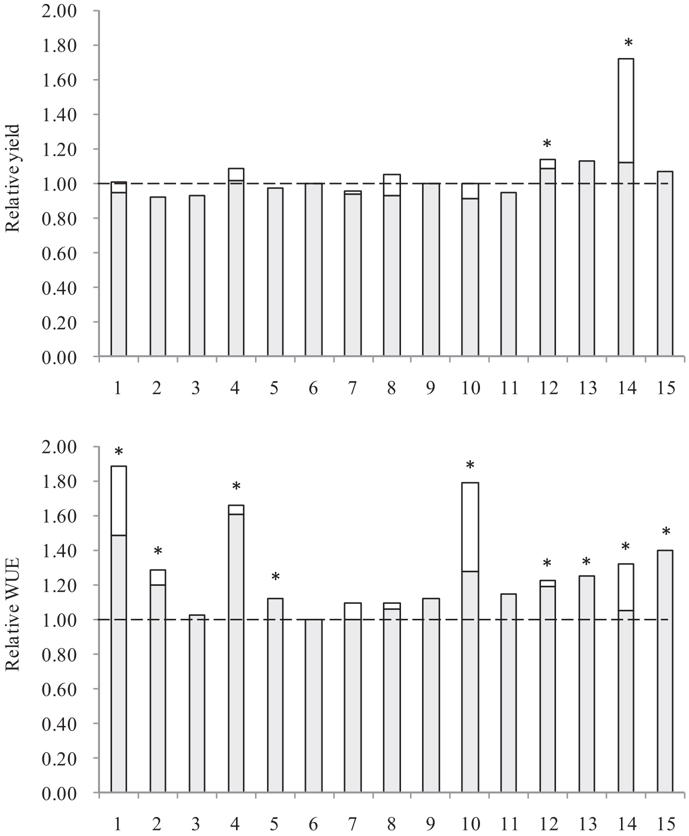

Fig. 3. Relative yield and WUE of recommended deficit irrigation methods on field crops in China. The relative parameter is the ratio of yield and WUE under the recommended deficit irrigation method to that under the conventional method. AN asterisk indicated a significant difference for the data under the recommended deficit irrigation compared with the control. The fraction of the conventional method is given for each column. Shaded and unshaded columns indicate the relative parameters minimum and maximum data since the experiments were conducted for two or more years. Study numbers and details are listed in Table 1.

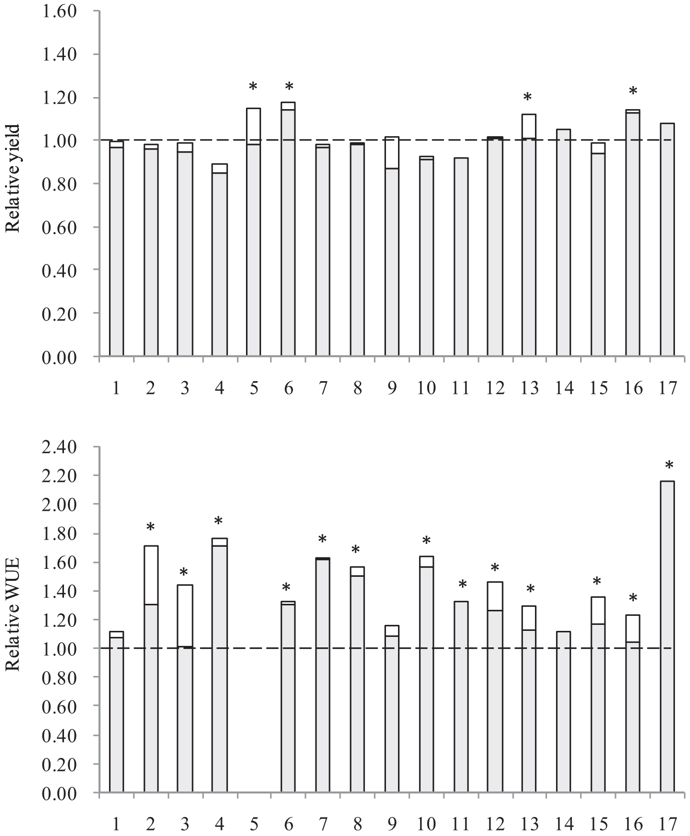

Fig. 4. Relative yield and WUE of recommended deficit irrigation method on fruit trees in China. See Fig. 3 for details. Study numbers and details are listed in Table 2.

Wuwei, Gansu province, in northwest China. The three treatments were: (i) conventional drip irrigation, irrigated on both sides of the root system as the control; (ii) alternate drip irrigation, irrigated with 50% of the control, alternatively on the two sides of the root system during consecutive watering and (iii) fixed drip irrigation, irrigated with 50% of the control, only and always on one side of the root system. The results showed that improved WUE, earlier fruit maturity, and better quality of table grape could be achieved by alternate drip irrigation without detrimental effects on the fruit yield in arid areas (Du *et al.*, 2008). Mineral potassium and iron elements in fruit and anthocyanins in the pericarp, which have better effects on the prevention of hypertension, were found to be much higher under APRI than under conventional drip and furrow irrigation (Zhou, 2000). The experimental research on wine grape conducted in Yinchuan, Ningxia province, showed that quality parameters of fructose and tannins were improved significantly (Fang *et al.*, 2013). In a pear orchard in Yongnian county, Hebei province, 60% irrigation water was applied under APRI and fixed partial root-zone irrigation (FPRI) compared with conventional irrigation, and showed that yield and fruit weight were maintained at similar levels but WUE was improved by 62–63% under APRI (Zhao *et al.*, 2007). However, in another research study on lychee using an APRI strategy in Haikou, Hainan province, the data showed that, in tropical areas, half of the irrigation water under APRI could maintain a similar yield and fruit quality (Zhou *et al.*, 2008).

Deficit irrigation methods on greenhouse crops: improving yield, WUE, and fruit quality

Greenhouses may be used to overcome shortcomings in the growing qualities of a piece of land, such as a short growing season or poor light levels, and thereby improve food production in marginal environments. Much research has recently suggested that deficit irrigation on greenhouse crops can improve or maintain yield with a higher WUE and better fruit quality (Table 3 and Fig. 5). Tomato is one of more popular vegetables as well as an important source of antioxidants such as lycopene, phenolic, and vitamin C in the human diet (Toor *et al.*, 2006). Our experiments in arid regions of north-west China from winter 2008 to spring 2009 and from winter 2009 to spring 2010 showed that one-third and two-thirds of full irrigation at the seedling stage did not significantly influence greenhouse tomato fruit growth; in addition, total yield and fruit quality, water consumption, and total yield were decreased by the application of one-third of full irrigation at the flowering and fruit

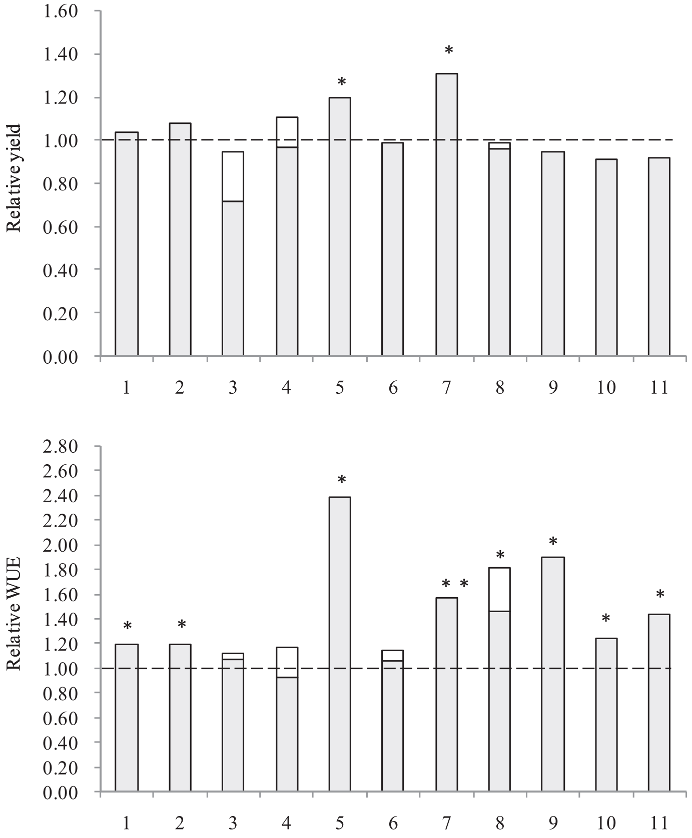

Fig. 5. Relative yield and WUE of recommended deficit irrigation method on greenhouse crops in China. See Fig. 3 for details. Studies number and details are listed in Table 3.

development stage and one-third or two-thirds of full irrigation at fruit maturation stage. However, the fruit contents of total soluble solids, reducing sugars, organic acids, and vitamin C, as well as fruit firmness, sugar/acid content ratio, colour index, and WUE, were significantly increased (Chen *et al.*, 2013). Experimental research conducted in Yangling, Shaanxi, showed similar results in the greenhouse (Liu *et al.*, 2013); however, earlier experiments of RDI and APRI on tomato in the same sites showed no significant difference on total soluble solids, vitamin content, and organic acids (Guo *et al.*, 2007; Wu *et al.*, 2009). An APRI experiment on eggplant in the greenhouse showed that 25.35% more yield and 25.39% more WUE were gained under APRI than under FPRI at the same irrigation level (Du *et al.*, 2005). Furthermore, the RDI experiment of eggplant under drip irrigation showed that 80% water supply at seedling and mature stage could improve the yield and WUE, while 60% water supply at blooming stage improved the appearance quality of eggplant with significant reduction of yield and WUE (Wang *et al.*, 2012). The experiments on cucumber also tested the same effect on yield, WUE and fruit quality (Chang and Zou, 2007; Cao *et al.*, 2010).

Experiments with nectarine also showed that when compared with conventional irrigation, APRI and FPRI can inhibit growth of new shoots and advance the maturity of fruits, which means higher price and more benefit to the farmers. The average fruit single weight and firmness obtained with APRI and FPRI treatments are reduced, but the yield is not influenced, and total soluble solid content was increased. Compared to the conventional irrigation treatment, 50% of water was saved in APRI and FPRI and therefore WUE was increased. Compared with FPRI, the average fruit weights, yield, total soluble solid content and WUE were all increased with APRI. Fruit firmness was not increased (Bi *et al.*, 2005). Furthermore, alternate partial root-zone drip irrigation on cantaloupe in the greenhouse also suggested that yield was improved with significant enhancement of soluble solid content, vitamin C, and soluble protein (Zhao *et al.*, 2013). APRI on strawberry in the greenhouse also showed that half the amount of water could maintain the yield at the same level (Wang *et al.*, 2009).

In the last 3 years, a farmer field school was organized in the Shiyang River Basin, north-west China. This was intended to train farmers in water-saving agriculture. Local farmers were invited to the Shiyanghe experimental station, which belongs to China Agricultural University, to learn more about deficit irrigation and its impact on the environment. The use of the technique was extended to 4133 ha in this region during 1999–2002 and has even extended to cereal crops in Inner Mongolia, Shaan Xi, Xiniang and Ningxia provinces in arid north-west China in recent years. The research interests of APRI strategy focus mainly on water–fertilizer coupling and the processes impacting fruit growth and quality (Zhou *et al.*, 2007; Song *et al.*, 2008; Liu *et al.*, 2010*a*, *b*; Chai *et al.*, 2011; Nong *et al.*, 2012; Du *et al.*, 2013; Li *et al.*, 2013; Zhou *et al.*, 2013; Zhu *et al.*, 2013; Wang *et al.*, 2014). The aim of the research is to assess how root hydraulic conductivity changes in different parts of the root zone, how the ability of roots to take up water and nutrition changes for different parts of the root system, how the major nutrients are distributed in the plants, and how the stomatal adjustment and changes in root uptake capacity can regulate and improve WUE and fruit quality under APRI. It is necessary to reveal the crop-to-crop response differences due to APRI to understand the variations of root and trunk sap flow, transpiration rate, ET rate, water cycle, and balance in the field under APRI. Based on the above understanding, deficit irrigation protocol was designed to increase fruit quality and WUE (see Fig. 6) for food security.

A sustainable strategy of agricultural water resources for food security in China

Deficit irrigation requires more accurate and real-time allocation of agricultural water resources, especially in arid areas. Sustainable water management for food security needs to include: (i) the optimal allocation of water resources; (ii) high efficiency of agricultural water use; (iii) prevention and control of water pollution; and (iv) countermeasures to combat extreme climate disasters and other considerations.

Improving agricultural WUE is a strategic requirement for food security. If China is to deliver the Government's proposed increment of 50 billion kg of grain between now and 2020, over this period annual agricultural water use must

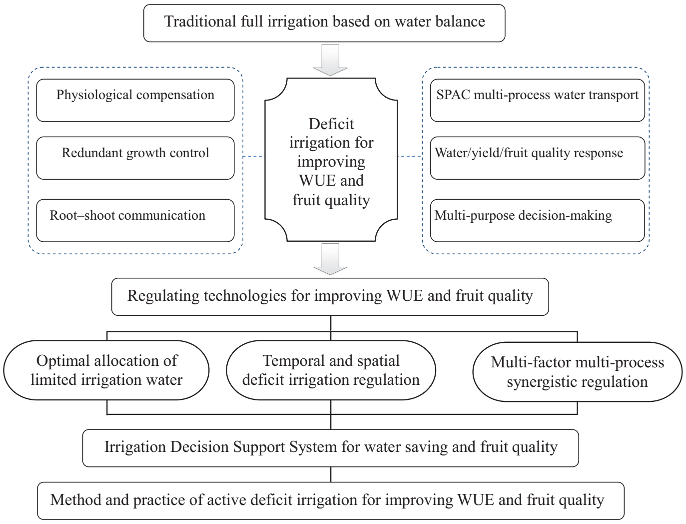

Fig. 6. Research frame of deficit irrigation for improving fruit quality and WUE. SPAC, soil–plant–atmosphere continuum.

be kept constant or even maintained at a reduced level. The WUE of farming in China is still far lower than that of developed countries, with an irrigation water effective use ratio of about 0.5 and an irrigation water productivity of 1.1 kg m^{-3}, Both of these figures are far lower than the values of 0.7–0.8 and 2.5–3.0 kg m^{-3} achieved in advanced countries. Meanwhile, the agricultural irrigation in China is still relatively extensive and the water-saving irrigation area ratio is only 42% of the whole irrigation acreage in China. According to a survey conducted by the Ministry of Water Resources, if the irrigation water effective use ratio improved from 0.5 to 0.7, approximately 60–70 billion m^3 of water would be saved; and even if the irrigation water productivity increased only from 1.1 to 1.5 kg m^{-3}, about 100 billion m^3 of water would be saved to produce the same cereal yield.

In recent years, the Ministry of Water Resources of China put forward an agricultural water management strategy for ‘increasing grain yield and water-saving’ in north-east China, ‘limiting groundwater abstraction for saving’ in North China Plain, ‘water-saving with high efficiency’ in north-west China, and ‘water-saving with drainage reduction’ in south China. Research and the extension of efficient irrigation technology have developed rapidly in China. On the North China Plain, winter wheat yield increased significantly when crops received 3600 m^3 hm^{-2} from microspray irrigation technology, with a WUE of 1.7 kg m^{-3}, while WUE under traditional border irrigation is 1.5 kg m^{-3} (Zhang *et al.*, 2013). Maize production in north-east China has reached 15000 kg hm^{-2} under drip irrigation; the average yield increment is 6000–7500 kg hm^{-2} compared with yields under conventional cultivation and surface irrigation. Fifty percent of the irrigation water is saved by using drip rather than sprinkler irrigation, and 86% is saved if drip irrigation is used rather than surface irrigation.

There is a clear economic benefit of using drip irrigation in addition to the water-saving benefit. According to the survey data in north China, 8550 Renminbi (RMB) hm^{-2} of irrigation is required for the total cost of water supplies, irrigation equipment, plastic film, and conventional cultivation management for drip irrigation. If calculated on the basis of maize yield of 15 000 kg hm^{-2} and a local price of 1.2 RMB kg^{-1}, the income will be 18 000 RMB hm^{-2}, and the net income will be 9450 RMB hm^{-2}; compared with the average net income of conventional maize, the efficient water-saving technology provides 6000 RMB hm^{-2} in benefit to the local farmers.

Optimizing water transport and distribution in the irrigation canal system is also necessary for achieving water-saving irrigation at the scale of an irrigation district or catchment. With the extension of high and new technology in agricultural water management, digital canal system management greatly promotes the practice of precision scheduling of water resources and precision irrigation. In order to meet the requirement of optimizing water distribution in canal systems, there is a need to apply computer and information technology to control water volume flow in real time. In order to optimize management of a canal system, automation of engineering control equipment, advanced systems software, and decision-making support are all needed in the large irrigation districts in north China.

A sustainable strategy for management of agricultural water resources involving deficit irrigation based on physiological responses of crops needs to: (i) either reduce ET without yield reduction or improve yield with a similar ET; (ii) construct a compensatory mechanism for agricultural water-saving for farmers; (iii) improve water-saving efficiency by rural land circulation and scale operation;(iv) develop advanced practical water-saving technologies and economical, reliable, and durable equipment and facilities in the field; (v) construct and improve the system for water-saving technology extension and service; (vi) strengthen basic research on water-saving irrigation under changing environmental conditions; and (vii) establish national ET monitoring and an agricultural water-saving experimental research network.

The application of deficit irrigation in a saline environment is another problem that should be addressed. Deficit irrigation under saline conditions is still a very difficult issue in terms of balancing soil salinity and water shortage. There are some references indicating that deficit irrigation is the greater risk of increased soil salinity due to reduced leaching (Schoups *et al.*, 2005; Kaman *et al.*, 2006; Raine *et al.*, 2007; Geerts and Raes, 2009). Only when irrigation water volumes required for leaching are considered would it be a sustainable strategy, especially in arid areas. An experiment of RDI to reduce soil salinization in an apple orchard concluded that potential reductions in soil salinization because of the lower amounts of added salts were only experienced under natural salt leaching arising from high precipitations and that, otherwise, irrigation should be increased to control root-zone salt accumulation (Nasr and Ben Mechlia, 2002). Another experiment evaluating root-zone salinity distribution in an olive orchard showed that, since PRD supplied half of the irrigation water amount, it added fewer salts to the soil than the full irrigation treatment, and these salts were leached during the wet season keeping soil salinity to levels that were not harmful to the olive trees (Ghrab *et al.*, 2013). Furthermore, an experiment conducted from 2008 to 2012 in a peach orchard in the Middle Ebro Basin of Spain found that soil salinity and sodicity did not increase during the 5-year study period because of salt leaching by precipitation (Aragüés *et al.*, 2014). More effort is still needed to coordinate soil salinity control and water productivity improvement. Other negative effects of long-term deficit irrigation on yield reduction, the regional water cycle, and its accompanying processes should also be considered.

Conclusion remarks

Because of the rapid depletion of water resources and the increasing impact of climate change, conventional irrigation practices can no longer be sustained in many areas in China. Methods that may cut down irrigation are of considerable interest and should be explored further. Deficit irrigation methods have been assessed systematically by the irrigation community in different parts of the world and are now used widely in crop and fruit production in many countries, Much of this work is still relatively empirical, but through these efforts we have gained a good appreciation of what are the most drought-sensitive developmental stages of many important food crops.

Cowan (1988) and others have argued that plants have evolved mechanisms to maximize carbon gain and growth in environments where rainfall is unpredictable. This suggests that crop plants should be able to regulate their water use according to the water availability in the soil. Our understanding of the theoretical basis of active regulation of WUE has now increased to the point where physiological control mechanisms might be exploited to tune deficit irrigation methods for different crops and different environments. Such tuning might deliver increased WUE, yield, and crop quality. Further gains can be achieved if we also include in our manipulations accurate and real-time assessments of water availability that allow effective allocation of water resources.

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