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REGULAR ARTICLE

Biomass allocation and yield formation of cotton under partial rootzone irrigation in arid zone

Li-Song Tang · Yan Li · Jianhua Zhang

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Abstract Partial rootzone irrigation (PRI) means only part of the root system is exposed to watering at one round of irrigation while the rest part is left in drying soil. The method has been proved a water-saving irrigation without much reduction in yield. This study investigated how the biomass distribution and reproductive development of cotton are affected under PRI. A three-year field irrigation experiment was conducted with a 30% reduction in irrigation amount on cotton in an arid area of Xinjiang in northwest China. Three treatments included conventional furrow irrigation (CFI) as control, alternative furrow irrigation (AFI) and fix furrow irrigation (FFI). PRI decreased stomatal conductance on the days just after irrigation when cotton plants were not under water stress, but there was no difference in stomatal conductance among irrigation treatments when plants were under water stress on the days just before next irrigation. Non-hydraulic signals from the dried rootzone inhibited the stomatal opening under well watered condition, but the moderate water deficit developed in the shoots under PRI may have played a more important role in biomass allocation and yield formation. This moderate water stress reduced shoot biomass accumulation and increased root biomass. While the vegetative and reproductive parts of the shoot were reduced in the same proportion under the PRI, the final yield was much less reduced in PRI, indicating an increased reproductive efficiency of cotton. Furthermore, PRI advanced the development of the reproductive organs and led to earlier flowering. The early matured bolls produced seed-cotton yield with a higher market value. AFI plants consistently performed better than FFI in the 3 years. We conclude that AFI can be used as a better deficit irrigation method with positive regulative effects on stomatal opening and yield forming process.

Keywords Partial rootzone irrigation · Reproductive efficiency · Water stress · Stomatal regulation · Yield · Biomass distribution · Cotton

Introduction

As a new irrigation method, partial rootzone irrigation (PRI), or partial rootzone drying (PRD), has received much attention during last decade (Dodd 2009; Sadras 2009; Kirda et al. 2007; Zhang et al. 1998). Many researches have demonstrated that it has a very promising future in agriculture practice in the arid zone (De la Hera

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L.-S. Tang · Y. Li (✉)
Fukang Station of Desert Ecology,
Xinjiang Institute of Ecology and Geography,
Chinese Academy of Sciences,
818 South Beijing Road,
Urumqi, Xinjiang, China
e-mail: liyan@ms.xjb.ac.cn

J. Zhang (✉)
Department of Biology,
Hong Kong Baptist University,
Hong Kong, China
e-mail: jzhang@hkbu.edu.hk

et al. 2007; Du et al. 2006; Hu et al. 2009; Lei et al. 2009; Li et al. 2007; Liu et al. 2006; Wang et al. 2008, Zegbe et al. 2004). The major advantage of PRI is that it can deliver a reasonable yield while the amount of irrigation is significantly reduced (Kang and Zhang 2004; Zhang et al. 1998; Kirda et al. 2007). This is accomplished by taking advantage of physiological response of crops to PRI: When root system is divided into wet and dry soil, roots in drying part will produce chemical signals (such as ABA) to narrow stomatal opening while roots in wet part can supply water to support plant growth (Liang et al. 1996; Zhang and Davies 1989, 1990). However, when root signals were produced in drying part of root system, the transmission of root signals also was limited by water transport. Yao et al. (2001) showed amount of sap flux has a linear relation with soil water potential in a frequently irrigated pepper. Therefore, some of root signals may have accumulated in roots and be liberated by re-watering (Dodd et al. 2007). Alternation of wet and dry soil compartments is necessary to maintain the supply of root-to-shoot signals (and thus stomatal closure) throughout the crop growing season (Stoll et al. 2000).

Earlier researches have provided solid evidence showing that PRI could save irrigation water and increase water use efficiency (Zhang et al. 1998; Kang and Zhang 2004; Kirda et al. 2007). When irrigation amount was cut off by 30–50%, field experiments indicated PRI could maintained a quite reasonable even higher seed cotton yield comparing to regular irrigation method (Du et al. 2006; Tang et al. 2005, 2010). Meanwhile the maturing process of cotton was also been accelerated, and therefore not only the irrigation water use efficiency but also economical return of unit water were improved. (Tang et al. 2005). By reducing irrigation amount, PRI is actually a type of deficit irrigation (Geerts and Raes 2009; Romero et al. 2004; Sadras 2009). However, in the practice of PRI, irrigation water is concentrated to part of the soil or root system This means that half of the soil (wet side) could get much more water than that of conventional deficit irrigation. Obviously, this deficit irrigation is different from the conventional deficit irrigation, which gives water to all of the root system. This in turn will exert profound influence on crops: probably more than we expected from conventional deficit irrigation.

Difference in duration and intensity of the water stress will result in different response from crops (Boyer 1982; Mc William 1986). Generally, water stress will result in decreased stomata opening, which will normally inhibit plant photosynthesis. Leaf expansion or growth is also known to be very sensitive and respond early to water stress (Boyer 1970; Hsiao et al. 1985). With increased duration and intensity of the water stress, the biomass allocation of plants will be changed (root growth will be favored as comparing to shoot) (Hsiao and Acevedo 1974; Brouwer 1983; Mingo et al. 2004), which make plants have less transpiring surface (leaf) and higher absorbing ability (root) (Connor and Jones 1985; Legg et al. 1979; Schulze et al. 1987; Sadras et al. 1991; Sadras et al. 1993). With increased duration or intensity of water stress, total biomass will be decreased, but certain part of the plant, such as root or reproductive part, may even get more biomass (Mingo et al. 2004). For instance, pervious work on PRI have shown that water stress may inhabit the overall growth of the crop, but the economic yield of the crop may not be significantly reduced (Tang et al. 2005, 2010; Zhang et al. 1998). Furthermore, inhibition of vegetative growth may have positive effects on quantity or quality of the yield in case of cotton, grapes and tomato (Loveys et al. 1998; Tang et al. 2005, Zegbe et al. 2004). Namely, harvest index may be improved significantly when the total biomass have been decreased by water deficit (Orgaz et al. 1992).

Under PRI, the reported WUE increases are usually calculated as total yield, not total biomass, divided by the sum of evapotranspiration or rainfall and irrigation. As yield is an accumulative effect over the whole growing season, attributing the WUE increases under PRI to decreased stomata opening alone could be rather problematic. In fact, previous studies have suggested that the room for improvement in biological efficiency of crop water use is very limited (Tanner and Sinclair 1983; Steduto et al. 2007). Under PRI, plant response should be at multi-scales and on many aspects: at organ, individual and field scales and on physiology, growth and allocation of photo-assimilates to different part of the plant. Although PRI has been proven to be a promising irrigation technique, few published works have analyzed how the biomass allocation, e.g., how different parts of the crop growth, especially the yield forming part, were affected by PRI.

Cotton is a major crop worldwide. It has become the most important cash crops in the arid Central Asia from the early part of the last century. In Xinjiang Province, northwest China (eastern part of the Central Asia), the planting area of cotton is around 1 million ha each year and is the most important crop in local agricultural production since 1990s. As a typical desert region with growing season precipitation much less than 100 mm, water consumption of crops is mostly from irrigation water. Runoff originated from the mountains is the only available water source for irrigation so that the development of local agriculture is limited by water resources, not by land area. In field practice of cotton production, excessive vegetative growth and shedding of buds, flower and bolls are key issues in maintaining high yield (Li 1979; Shi et al. 1987). Previous results have shown that PRI could not only save water, but also result in earlier flowering and maturing of cotton (Tang et al. 2005, 2010; Du et al. 2006). Furthermore, PRI (or PRD) has also shown a potential to regulate the vegetative and reproductive growth on grapevines (Dry and Loveys 1998).

Yield is the core of agriculture production. Therefore, how the biomass accumulation and yield formation are affected by PRI is the most important issues in evaluating the advantage of PRI. In this study, a field experiment for 3 years was conducted to investigate the effects of PRI on stomatal behavior, overall plant growth, biomass allocation, yield formation and water use efficiency (WUE). The objectives were to study the mechanism of cotton plant on maintaining reasonable yield when irrigation was reduced by 30% with PRI, therefore to explore how the growth dynamics of the various organs, specifically the reproductive or yield forming parts, are affected by PRI.

Materials and methods

Experimental set-up

The experiment site is at the Fukang Station of Desert Ecology, Chinese Academy of Sciences (44°17/N, 87° 56/E, 475 m a.s.l), which is located at the temperate arid zone in the hinterland of the Euro-Asia Continent. Annual average rainfall is about 160 mm and annual pan evaporation is about 1000 mm. The soil is a saline clay–loam with an average pH value of 7.8 and total salt content of 7.38 $g.kg^{-1}$(0–20 cm) and it has a slow water permeability of 200 $mm day^{-1}$ and the bulk density is approximately 1.45 $g cm^{-3}$. The field capacity, defined as the water content at −0.002 MPa, is about 0.312 m in the upper 1.0 m of the soil profiles (Li et al. 1998).

The field experiment was conducted from 2005 to 2007. The experimental field was 100 m×200 m in size and divided into 10 m×20 m plots for the application of the treatment. A buffering belt of 5 m width was set aside between the plots. Three treatments were applied: conventional furrow irrigation (CFI), where every furrow was evenly supplied with water at each irrigation event; fixed furrow irrigation (FFI), where irrigation was fixed to only one of the two neighboring furrows; and alternative furrow irrigation (AFI) where the two neighboring furrows were alternately irrigated in succession. Six replicates for each treatment were assigned randomly in the field.

Fertilizer was applied as $(NH_4)_2HPO_4$ at 450 $kg ha^{-1}$ and mixed in the top 20 cm soil before sowing. More dressing with urea was applied in later June according to irrigation timing (Tang et al. 2010) at 300 $kg ha^{-1}$ in furrows that were irrigated afterwards. Cotton seeds (Gossypium hirsutum cv Xin K4) were sown on May 1st, 2005, April 28th, 2006 and May 2nd, 2007 into rows (35 cm between rows and 10 cm within the row). Three rows of cotton were planted between two furrows. The width of furrow was 70 cm. Figure 1 shows the plantation of cotton rows, and the dry side and wet side are signed to number 1 and 2 for AFI and FFI. It should be noticed that wet and dry side are shifted in AFI. Except for irrigation, the rest of the field management was the same for all the plots and followed the local commercial practice. The timing and amount of the irrigation for CFI strictly followed the local commercial practice. The irrigation amount was exactly the same for each year due to the stable dry weather from year to year. Briefly, irrigation was provided when there is the sign of substantial midday leaf wilting (over 50%). For FFI and AFI, the irrigation timing was the same but the amount was only 70% of that for CFI. The irrigation water was

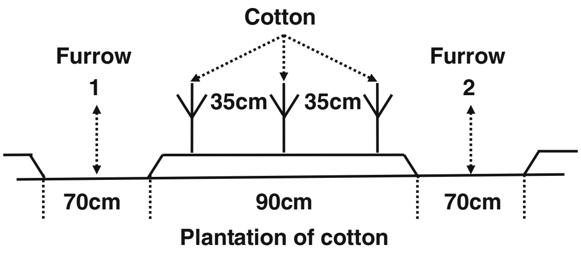

Fig. 1 Front view of the cross section perpendicular to the crop row and the furrow. 1 and 2 indicate dry and wet furrow. The wet and dry sides are shifted alternately in AFI; meanwhile the FFI has fixed wet and dry sides

delivered by the pipes with a diameter of 10 cm and the amount of irrigation was controlled with a flow meter installed at the discharging end of the pipes. Further details on the irrigation timing and the amount were given by Tang et al. (2010).

Measurements and sampling

Leaf water potential (LWP) was measured with a pressure chamber (3000 Plant Water Status Console, Soil Moisture Equipment Corp., Santa Barbara, CA, USA) on the plants of the central rows between the two furrows. Diurnal variations of leaf water potential were monitored on the third day after irrigation when the soil was still wet (allowed 2 days for the plants to recover) and the day right before the irrigation. The interval of measurement was 1 h in the morning and afternoon and 2 h for the noon when leaf water potential was relatively stable. Each measurement was done with ten replicates on fully expanded youngest sunlit leaves. Stomatal conductance of the leaves was measured with a portable porometer (LI-1600, LI-COR Inc., Lincoln, NE, USA) on the plants of the central rows between the two furrows. Ten youngest mature leaves that were fully exposed to sunlight were chosen at each measurement for each treatment. Diurnal variations of stomatal conductance were monitored 2 days after irrigation when the soil was still wet and 1 day right before the irrigation. For each measurement, the leaf temperature, relative humidity and incoming photosynthetic photon flux density (PPFD) were recorded.

For the monitoring of the leaf area per plant, ten cotton plants of average size from each treatment were marked and the maximum leaf length and width of all leaves on the plants were measured continually, with the first measurement done on the thirtieth day after sowing and the interval was 10 days. The product of max width and length of leaf was converted into leaf area by a very good relationship with leaf area obtained by scanning and calculating the leaf area with graphic processing software (CIAS 2.0, CID, Inc., WA, USA). Monitoring of cotton shoots growth was done on the same ten marked cotton plants as leaf area monitoring, besides, the plant height, number of buds, flowers and bolls of each plant were measured every 5 days.

For the monitoring of the biomass allocation of cotton shoots, ten plants of approximately average size were cut at the soil surface from each treatment. After then, the shoot of each plant was divided to vegetative (stem and leaf) and reproductive (bud, flower and boll) parts and both parts were oven dried till constant weight at 80°C. The sampling interval was also 5 days.

Due to measurement destruction to root, root sampling was done once only at the time of first harvesting of each year. Root system of ten plants at approximately average size was washed out with water jet for each treatment. The root system was then separated into dry and wet part (Fig. 1), with overall root length, number of secondary roots were measured and counted in situ. After the measurement, all pairs of roots and corresponding shoots were oven dried under 80°C and root-shoot ratio was calculated as the dry weight of root divided by that of the shoot.

To evaluate seed cotton yield per boll, 30 opening bolls were sampled randomly from each treatment at each harvesting. The average yield per boll was then calculated. For final yield (seed cotton) assessment, blocks (2 m×2 m) at the center of each plot were sampled and harvested by four hand-pickings from the middle of September to the end of October, following local commercial practice in harvesting. The harvested seed cotton was sun-dried to constant weight and the yield per unit area was calculated. The total amount of water consumption is calculated as irrigation plus rain fall of the growing season in each year. As groundwater level is around 4–5 m, it is not considered as a source of plant water uptake. After then, overall water use efficiency (kg.m^{-3}), as suggested by Molden (2003), is calculated as total seed cotton yield divided by the sum of rainfall and irrigation.

Data treatment

The study was carried out in a typical arid zone. Weather condition is rather stable from year to year: with high temperature and radiation during the cotton growing season that is occasionally disturbed by rain fall. For the 3 years, the amount of irrigation was exactly the same and intervals of irrigation were almost the same (Tang et al. 2010). Analysis of the 10 years' precipitation data revealed that most of the rainfall events (90%) were ≤5 mm, and only very few of rainfall events (1%) were ≥10 mm (Wang and Tang 2009), which explains why the amount and intervals of irrigation are almost the same for the 3 year (Tang et al. 2010). Having considered the very limited variation in weather condition from year to year, stomata and plant growth data of different years were pooled together by the irrigation cycles or growing season to simplify the presentation.

Statistics analysis

Data were analyzed by a complete randomized model using the GLM procedure of SAS software Version 8.0 (SAS Institute, Cary, NC, USA). Treatment means are separated by Tukeys Studentised range test at $P \leq 0.05$. For the comparisons of fitted lines, the slopes and intercepts of these lines were tested by F test**.**

Results

Figure 2 shows the relationship between leaf water potential (LWP) and stomata conductance on days before and after irrigation for each irrigation cycle of the 3 years. Each paired data are mean of ten replicates and measured at the same time. During days just after irrigation, all plants have high LWP and high stomata conductance (upper side of Fig. 2). The values of R^2 are 0.84, 0.85 and 0.84 for CFI, AFI and FFI, respectively, indicating good relationships between LWP and stomata conductance for all treatments. The significant difference in regression lines (Fig. 2) between CFI and PRI (AFI and FFI) indicated that plants of CFI have higher stomata conductance than PRI when they have same LWP. This suggests that factors other than LWP are regulating stomata conductance, which is likely to be non-hydraulic signaling such as root to foliage translocation of ABA.

On the days just before next irrigation, all plants were under water stress. The values of LWP and stomata conductance were very low for all treatments (Fig. 2), but the correlation between LWP and stomatal conductance were still good (R^2=0.76, 0.82 and 0.80 for CFI, AFI and FFI respectively). Data show that for a given LWP, plants of all treatments have almost the same stomata conductance (Fig. 2), which indicates that LWP is the main factor controlling of stomata conductance under such condition.

Figure 3a shows that FFI had significantly higher total root length than CFI and AFI. Detailed data show that root distribution of FFI is non-uniform between sides while CFI and AFI had nearly uniform root distribution. After measuring total root length, the numbers of secondary laterals on main root, which indicates the branching of the root system, were also counted. Figure 3b shows that in AFI, plants have relatively identical branching of secondary laterals in both sides as plants in CFI. While in FFI, most of secondary laterals developed in the wet side. The overall number of secondary laterals in AFI was similar as in CFI, but in FFI less secondary laterals were found, indicating that long term soil drying had hindered the root development in the dry side of FFI.

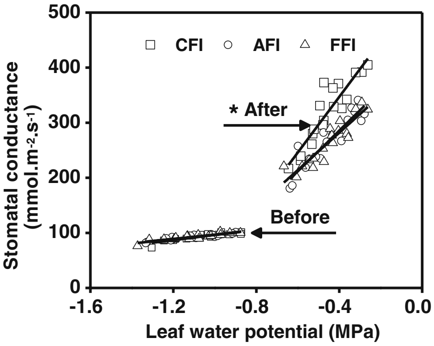

Fig. 2 Relationship between leaf water potential and stomatal conductance 1 day before and 2 days after one round of irrigation. CFI, AFI and FFI are conventional furrow irrigation, alternative furrow irrigation and fixed furrow irrigation respectively. Due to similar meteorological conditions, points are pooled data from measurements of 2005, 2006 and 2007. Each point is mean of 10 samples and points are fitted with linear regression curves. For the comparisons of fitted lines, the intercepts and the slopes of these lines were tested by F test and the asterisk indicates significant differences at $P_{0.05}$ level: On the third day after irrigation: CFI: y=505.19×+548.97, R^2=0.84. AFI: y=369.5×+433.41, R^2=0.85. FFI: y=339.07×+417.45, R^2=0.84. For the slopes: F=3.71, P=0.0316, indicate significant differences among slopes of the lines. For the intercepts: F=39.80, P<0.0001, indicate significant differences among slopes of the lines. On the day before irrigation: CFI: y=47.22×+143.56, R^2=0.76. AFI: y=36.812×+133.23, R^2=0.82. FFI: y=40.648×+137.49, R^2=0.80. For the slopes: F=0.88, P=0.4208, indicate non-significant differences among slopes of the lines. For the intercepts: F=0.67, P=0.5162, indicate non-significant differences among intercepts of the lines

Reduction of irrigation water significantly depressed the shoot growth of cotton plants in AFI and FFI (Fig. 4). Figure 4a shows a quite fast increase of leaf area during the vegetative stage and the early period of the reproductive stage. Significant difference among treatments started at the beginning of reproductive stage. During the mature stage and later days of reproductive stage, all plants kept a rather stable leaf area. The height of cotton plant in all treatments have a similar growth trends as leaf area, but height maintains a slow increase even during mature stage (Fig. 4b). Reproductive organ includes buds, flowers and bolls,

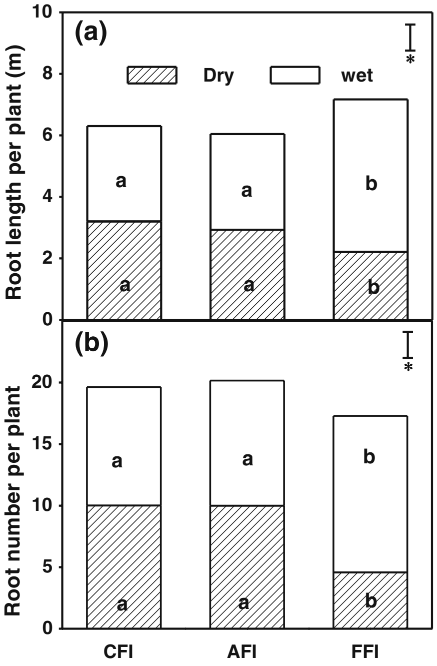

Fig. 3 Distribution of root length (**a**) and number of secondary laterals (**b**) at depth of 0–40 cm in the cotton field. The root system was separated into dry and wet part according to Fig. 1. *Vertical bars* are the minimum significant difference (MSD) by Tukey's Studentised range test and the asterisks show significant differences at $P_{0.05}$ level

with bud growing into flower and flower into bolls. It can be seen from Fig. 4c that once the reproductive stage begins, the number of reproductive organ increases sharply, with significant differences among treatments. From the later days of reproductive stage, bud or flower and even boll shedding started and the number of reproductive organ decreased remarkably, but that of CFI was still higher number than AFI and FFI. Overall, Fig. 4 indicates that the growth of cotton plant is significantly affected by PRI.

Figure 5 shows the dynamics of dry matter allocation in cotton shoot under different treatments. As a consequence of water stress, vegetative growths of shoot were gradually reduced in AFI and FFI, and the average dry matters of vegetative shoot were lower than that of CFI (Fig. 5a). Dry matter of vegetative organ (stem and leaf) stopped increase at the beginning of the mature stage; however, the dry matter of reproductive organ kept increasing (Fig. 5b). Although the cotton plants in CFI had higher dry matter of shoot than that in AFI and FFI, the ratio of reproductive organ in shoot showed no difference among treatments (Fig. 5c).

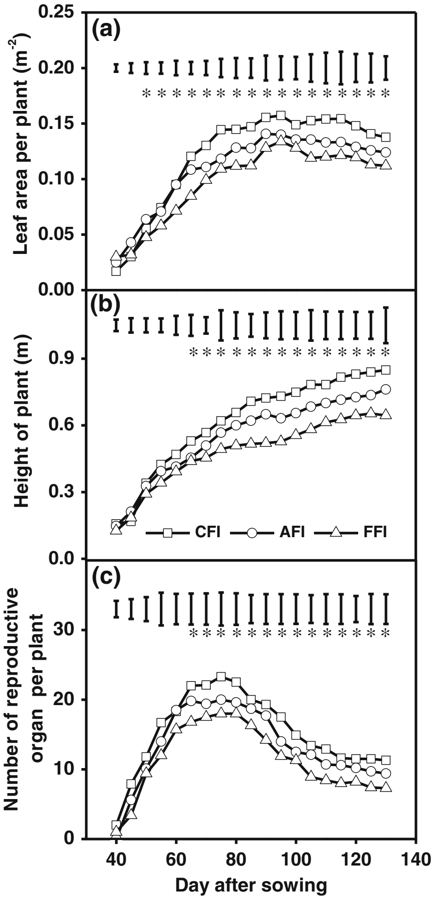

Fig. 4 The dynamics of cotton plant growth in term of leaf area per plant (**a**), height of plant (**b**) and number of reproductive organ per plant (**c**). *Vertical bars* are the minimum significant difference (MSD) by Tukey's Studentised range test and the asterisks show significant differences at $P_{0.05}$ level

Table 1 summarizes the biomass allocation between root and shoot, and the portion of reproductive biomass in total shoot of cotton plants grown under different treatments at harvesting time. PRI had resulted in higher root-shoot ratio in AFI and FFI than that in CFI (Table 1). This is to say plants under PRI developed more roots to reach soil water. However, PRI has not been found with higher proportion of reproductive biomass in shoot, which indicates that the overall water stress is moderate. This moderate stress had reduced shoot biomass, but the vegetative and reproductive part of the shoot was reduced in the same proportion (Fig. 5, Table 1).

The average total boll number, opening boll number, opening ratio and seed cotton yield per boll of each plant is shown in Table 2. Boll number per plant is significantly higher in CFI than in AFI and FFI (Table 2). However, there is no significant difference in opening boll number among treatments. Namely, CFI has the lowest boll/opening-boll ratio (Table 2). These results indicate that water stress from PRI may affect overall boll load per plant but has not affected the number of opening boll which formed the final yield. That is to say, PRI have significantly improved the reproductive and yield forming efficiency of cotton (Table 2). The average seed cotton yield per boll (boll size) is significantly lower in FFI than that of CFI and AFI, meanwhile AFI is slightly lower than CFI (but not significant, Table 2).

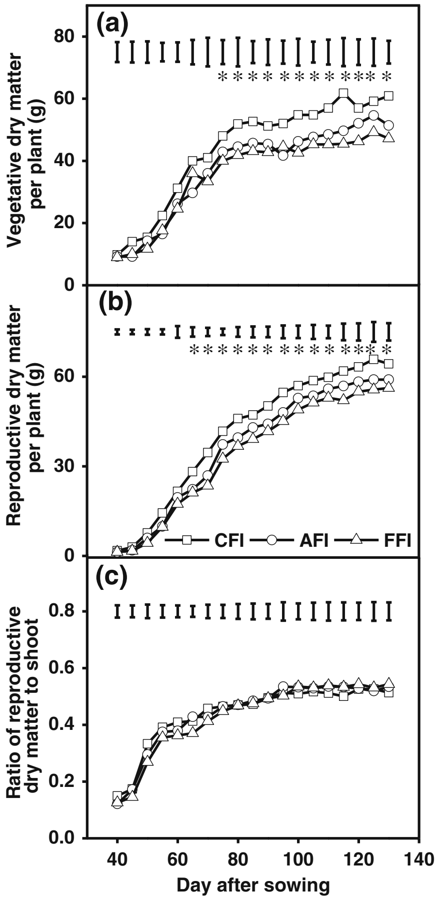

Fig. 5 The dynamics biomass allocation to vegetative part (**a**), reproductive part (**b**) of shoot and the ratio of the reproductive part to total shoot (**c**). *Vertical bars* are the minimum significant difference (MSD) by Tukey's Studentised range test and the asterisks show significant differences at $P_{0.05}$ level

Discussion

The cotton yield is the major concern of the present experiment. Due to the reduction of water application, seed cotton yield in AFI and FFI were reduced to 96% and 82% of that in CFI (Tang et al. 2010). In spite of the reduced amount of irrigation, AFI maintained a reasonable yield. This agrees to most of earlier studies. Namely, with the implementation of PRI, it is possible to curtail irrigation amount without significant reduction in the final economic yield (Dry and Loveys 1998; Du et al. 2006; Kang et al. 2000; Loveys et al. 1998; Tang et al. 2005, 2010; Zegbe et al. 2004). Same as many studies, our data have shown PRI significantly increased WUE: in AFI and FFI the values are 24% and 10% higher than CFI (Tang et al. 2010).

The opening bolls forms the cotton yield, therefore the number of opening boll and the yield of per boll are

Table 1 Biomass allocation between root and shoot as well as reproductive biomass in shoot under different treatments at the time of harvesting

Years	Root to shoot			Reproductive biomass to total shoot		
	CFI	AFI	FFI	CFI	AFI	FFI
2005	0.11a	0.122a	0.163b	0.577	0.552	0.560
2006	0.093a	0.117b	0.132b	0.489	0.480	0.516
2007	0.111a	0.132b	0.130b	0.577	0.640	0.672
Means	0.108a	0.124b	0.142c	0.548	0.557	0.583

Data were analyzed by a complete randomized model using the GLM procedure of SAS software Version 8.0 (SAS Institute, Cary, NC, USA). Deferent letters denote significant difference between treatments at $P_{0.05}$. Data without accompanying letter denote that there is no significant difference among treatments.

Table 2 The number of total bolls per plant, opening bolls per plant, seed cotton yield per boll and the ratio of opening bolls in total bolls

Years	Total bolls			Opening bolls			Yield per boll (g)			Boll opening ratio		
	CFI	AFI	FFI	CFI	AFI	FFI	CFI	AFI	FFI	CFI	AFI	FFI
2005	11.39a	9.71ab	8.08b	6.34	5.96	5.61	6.16a	5.70a	5.27b	0.87a	0.95b	0.94b
2006	11.25a	7.90ab	6.21b	6.11	5.77	5.55	5.60a	5.94a	5.15b	0.86a	0.94b	0.99b
2007	11.31a	10.67a	7.60b	6.22	5.77	5.58	6.47a	6.01a	5.54b	0.90a	0.95b	0.98b
Means	11.31a	9.43a	7.30b	6.22	5.83	5.58	6.08a	5.88a	5.32b	0.88a	0.95b	0.97b

Data were analyzed by a complete randomized model using the GLM procedure of SAS software Version 8.0 (SAS Institute, Cary, NC, USA). Deferent letters denote significant difference between treatments at $P_{0.05}$. Data without accompanying letters denote that there is no significant difference among the treatments.

two building block of the cotton yield. Our data show that CFI has higher vegetative growth rate, higher reproductive growth rate, and even higher overall boll load than AFI and FFI (Figs. 4 and 5, & Table 2), but the opening boll numbers are not significantly different among treatments (Table 2). This implies water stress from PRI does affect the overall growth of plant and even the total boll number, but has not affected the numbers of opening boll. Statistically the same number of opening boll among treatments indicates that it was not the main factor resulting in the decrease of yield. However, the average yield per boll shows that FFI is significantly lower than CFI and AFI (Table 2). Furthermore, yield per boll in AFI also was slightly, but not significantly, lower than that in CFI (Table 2). These imply that the yield decrease is resulted from lowered yield per boll in FFI and AFI. The decease in boll size is obviously the result of water stress. Namely, with the same amount of irrigation, plants in AFI experienced significantly less water stress than FFI (Figs. 4 and 5, Tables 1 and 2). This means that although both AFI and FFI are deficit irrigation methods, AFI obviously is in great advantage than FFI in term of yield and water use efficiency (Fig. 6).

PRI is an irrigation method emphasizing the regulation of stomatal opening by non-hydraulic signal originally (Liang et al. 1996; Zhang and Davies 1989; Zhang and Davies 1990). Our data show that non-hydraulic signals influence the stomatal conductance (Fig. 2), but occur only when plants are under favorable water condition, i.e. in well hydrated state (Fig. 2). On the other hand, hydraulic signal (much reduced leaf water potential) is always a major factor affecting the stomatal conductance (Fig. 2). Namely, our data indicate that non-hydraulic signals only partially account for the stomatal inhibition under PRI. Stomatal opening is mainly inhibited by the much reduced leaf water potential in the very dry climate.

Water stress is known to affect shoot growth, especially the leaf elongation (Sharp and Davies 1989; Chaves et al. 2002). Our result indicates that the growth of shoot is indeed reduced by the reduction of irrigation amount, demonstrated by the decrease in leaf area and plant height with significant difference among treatments (Fig. 4). Inhibition of leaf elongation or shoot growth by water stress is a well-studied topic (Kramer 1988; Frensch 1997; Hsiao and Jing 1987). Such inhibition is usually explained by root-shoot signaling that regulates the leaf or shoot growth (Termaat et al. 1985; Passioura 1988; Saab

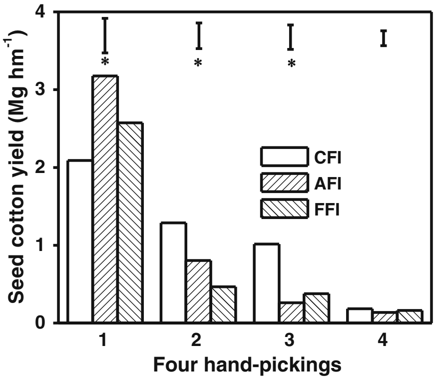

Fig. 6 Composition of seed cotton yield of CFI, AFI and FFI at each of the four hand-pickings. Data are average for the 3 years. *Vertical bars* are the minimum significant difference (MSD) by Tukey's Studentised range test and the asterisks indicate significant differences at $P_{0.05}$ level

and Sharp 1989; Gowing et al. 1990). Obviously, in AFI of the current study, shoot received less stress signals than FFI so that plant growth was less inhibited, although both treatments received same amount of irrigation. The shifts of the wet and dry part lessened the influences of water reduction.

When PRI was carried out, only half of rootzone got irrigation water. This means 70% irrigation is given to 50% rootzone in our case (Fig. 1). Thus, the wet side of PRI got more water than that of CFI, which has changed the root morphology of PRI (Fig. 3). PRI plants developed deeper root system, with higher value in total root length and root number (Fig. 3), as water stress is more likely to affect root than shoot (Brouwer 1983) and irrigation water is bound to go deeper when 70% of the water was given to 50% of the area. Hence higher root-shoot ratio of PRI is acquired as expected (Table 1). However, when PRI was carried out and the growth of shoot was limited by water stress, the reproductive growth and vegetative growth in shoot were reduced in same proportion (Figs. 4 and 5, Table 1). Namely, the ratio of reproductive organ to total shoot biomass, does not show significant differences among treatments (Figs. 4 and 5, Table 1). These make it difficult to understand the significantly increased WUE in AFI (Tang et al. 2010).

Yield formation in cotton plants is a much more complicated issue than plant growth, as development of the bud, flower and boll in cotton functions not only in their development but also shedding off and final opening (in term of boll, it may be left dry and never open at the end). Both processes are regulated by the internal plant N/C balance and the supply of which is strongly influenced by irrigation practice (Cein and Bilgel 2002). The differences among treatments indicate that PRI actually decreases the bolls load per plant, but does not affect the number of opening bolls which finally form the yield of cotton (Table 2). This means that either the shedding ratio was higher or more bolls was left dry and did not open finally in CFI. Either way would mean that in AFI, higher ratio of bolls formed final yield than in CFI. These indicate AFI does improve cotton yield by increasing reproductive efficiency. Namely, in AFI, it may have the same portion of biomass allocated to reproductive organs as in CFI. However, in AFI, higher portion of the reproductive organs formed the final yield (Table 2). In fact, Fig. 6 shows that AFI has also advanced the reproductive stage and as a result, improved the yield quality and increased market value of the yield.

Concluding remark

In conclusion, our results reveal that AFI saves substantial amount of irrigation water and largely maintain the seed cotton yield. By concentrating irrigation water to part of the soil, AFI seems to be much more beneficial than just saving water. It is a kind of deficit irrigation, but it may have extra benefit comparing to conventional deficit irrigation. The moderate water stress developed in the shoots and alternate root-zone drying under PRI led to increased root biomass distribution. Although the vegetative and reproductive parts of the shoot were reduced in the same proportion under the PRI, the number of opening boll that formed the final yield was much less reduced in PRI. In addition, PRI promoted the development of the reproductive organs and led to earlier flowering. The early matured bolls produced seed-cotton yield with a higher market value. AFI consistently performed better than FFI in the 3 years of study. We conclude that AFI can be used as an irrigation method with positive regulative effects on stomatal opening and plant reproductive development.

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