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DROUGHT STRESS

Legume Production and Irrigation Strategies in the Aral Sea Basin: Yield, Yield Components, Water Relations and Crop Development of Common Bean (*Phaseolus vulgaris* L.) and Mungbean (*Vigna radiata* (L.) Wilczek)

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Abstract

With world population expected to reach 9.2 billion people by 2050, improved irrigation methods will be needed to increase the productivity of agricultural land and improve food supply worldwide. The objective of this work was to examine the effect of regulated deficit irrigation (RDI) and alternate furrow irrigation (AFI) on the yield and yield components of two legume species (common bean and mungbean) produced as a second crop following winter wheat in Uzbekistan, Central Asia. Water relations and crop development were also examined. The research was conducted during two successive growing seasons in the Fergana valley. Production of mungbean using the severe stress RDI treatment in combination with AFI resulted in the highest yields with the lowest quantity of applied water in 2004. In addition, yields of common bean in the moderate stress treatment were not different from the recommended schedule, although irrigation events were decreased from 4 to 2. AFI did not reduce yields, and it did not interact with RDI to reduce yields further. In general, mungbean yields were higher than those of common bean. The combination of AFI and RDI can allow legume production with reduced water inputs.

Introduction

Irrigated agricultural systems represent approximately 17 % of the cultivated area and contribute 40 % of total crop production worldwide (Kijne et al. 2003). Increased use of supplemental irrigation water in rainfed agriculture and improved irrigation methods will be needed to increase the productivity of agricultural land and improve food supply worldwide (Wallace 2000). Land and water resources in the Aral Sea basin have been degraded due to the expansion of irrigation networks, on-farm mismanagement of irrigation water and degraded infrastructure. This has caused serious economic and health problems along the lower reaches of the two large rivers flowing into the Aral Sea (Micklin 2000, Dukhovny 2003). Thus, sustainable irrigated agriculture is necessary to maintain food production *per capita*, but this will require technological improvements in water-use efficiency (WUE).

Regulated deficit irrigation (RDI) consists of finding the optimum balance between water use and crop yield. Under RDI, crop producers allow the crop to experience some water stress, but the water saved should allow an increase in the area irrigated, or it could be put to more productive use such as in industrial activities or for civil uses (English and Raja 1996). ICARDA has shown that a 50 % reduction in irrigation water applied decreased yields by 10–15 %, but overall farm productivity increased by 38 % when the water saved was used on other land (Pereira et al. 2002). However, it is important that farmers have control over the timing of irrigation events and amount of water applied and access to the tools for proper irrigation scheduling. One of these tools is precise information on factors such as the response and sensitivity of crops to water stress, stages of plant development when deficit irrigation should or should not be performed and how much water can be conserved (Kijne et al. 2003).

Previous studies on RDI were usually performed by either reducing the amount of water that is applied to crops to a fraction of the full evapotranspiration (ET), but otherwise keeping the same frequency of irrigations (Pandey et al. 1984, Oktem et al. 2003, de Souza et al. 2003, Oweis et al. 2004, Chaves et al. 2007), or withholding irrigation at specific growth stages (Nielsen and Nelson 1998, Calvache and Reichardt 1999, Pandey et al. 2000, Boutraa and Sanders 2001, Karam et al. 2007). We chose to impose RDI using increased time intervals between irrigation events, based on the water balance method for irrigation scheduling and greater depletion fractions as proposed by Allen et al. (1998).

Alternate furrow irrigation (AFI) consists of surface irrigation systems supplying water to every second furrow. Several field studies have demonstrated considerably improved WUE with this method (Grimes et al. 1968, Crabtree et al. 1985, Graterol et al. 1993, Kang et al. 2000, Tang et al. 2010). In a controlled environment with a divided root system, Kang et al. (1998) showed that water consumption by maize plants subjected to partial root drying was decreased by 34–37 % while yields only decreased 6–11 %. They also showed that transpiration rate decreased compared to well-watered controls but that the photosynthetic rate and leaf water content remained the same, thus leading to significant increases in WUE, shoot biomass production, and root development and distribution compared to controls. Using a similar method, Kirda et al. (2004) showed no significant decrease in the yield of tomato subjected to half of the irrigation water, when each side received water alternatively. Both groups suggested that by having half of its root system in dry soil, the plant continues to synthesize abscisic acid (ABA) in the roots, which reduces its transpiration rate. However, because water is available, growth is less affected. Dodd et al. (2010) demonstrated that sunflower transpiration was most correlated with the soil matrix potential in the dry side of the pot, closely followed by the ABA concentration in the leaf xylem.

In Uzbekistan, agricultural policies emphasize the culture of cotton, an important component of the Uzbek economy, and to a lesser degree, winter wheat. Both are subject to state regulation through a system of quotas, and little agricultural land is left for other food crops. The value of crop diversification for the economy and the benefit of legumes in cropping systems have long been recognized. Both common bean and mungbean are widely consumed in Central Asia. Common bean (*Phaseolus vulgaris* L.) is the most important pulse crop in the world, being consumed more than any other legume crop. Recent studies suggest that only 7 % of the growing area of common bean worldwide receives adequate rainfall (Broughton et al. 2003), and 60 % of the production occurs under severe drought stress (Graham and Ranalli 1997). Mungbean, also known as green gram, is a small-seeded legume crop less known in the Americas, but widely cultivated in Asia. It is also cultivated to some degree in the United States and in Australia and is often consumed as sprouts (Lawn and Ahn 1985, Poehlman 1991). The crop is known to perform well under conditions of low soil moisture availability. It remains, however, one of the least researched and most underexploited legume crops (De Costa et al. 1999).

The main objective of this study was to evaluate the production of food legumes under RDI and AFI. This study is the first to evaluate the effect of RDI using the water balance method and increased time intervals between irrigation events in conjunction with AFI on the yield of common bean and mungbean. Another objective was to compare the performance of common bean and mungbean under Uzbekistan conditions and to determine possible constitutive and adaptive traits. A third objective was to confirm that being short-season crops, legumes could be grown after the harvest of winter wheat (early July) and thus be introduced in the current Uzbek cropping system to improve food security and diversity.

Materials and methods

Environment

The experiment was conducted in the Fergana valley (Fig. 1), in Uzbekistan, Central Asia (40°23′N, 71°45′E), from the beginning of July until the onset of cold temperatures in mid-October, in the growing seasons of 2003 and 2004. During this period, the climate is hot and dry, with

Fig. 1 Map of the Aral Sea basin and location of experimental area (Fergana Valley). The experimental field was situated in the Fergana Valley, Uzbekistan (40°23′N, 71°45′E).

typical daily high temperatures being 35–40 °C, and typical daily lows being 20–25 °C. Rain is infrequent, except in early October. From 15 July to 30 September 2003 and 2004, we recorded a total of 8.8 and 7.6 mm of rainfall, respectively, at our field sites. Climatic data (Fig. 2) were collected using an on-site Vantage Pro Meteorological station (Davis Instruments Corp., Hayward, CA, USA), located approximately 200 m from the field site. Based on textural analyses, soil at the experimental sites was a silt loam in 2003 and ranged from a sandy loam to a silt loam in 2004. The soils had an available water content of 96 mm in 2003 and 75 mm in 2004, in the top 60 cm. The organic matter content was determined in each plot, in the 0- to 30-cm and 30- to 70-cm layers. In both years, the soils had low organic matter contents (less than 2 %) and a well-developed plough pan at 30–40 cm.

Experimental design

The treatments were organized on the field site following a randomized complete block split-plot design. The treatments were comprised of factorial combinations of three factors: RDI level (recommended level, moderate deficit and severe deficit – see section on Irrigation scheduling for more details), irrigation water distribution pattern (alternate and every furrow irrigation) and crop (common bean and mungbean). RDI treatment was the main plot factor, and the combinations of furrow irrigation strategy and crop constituted the subplot factor. There were four blocks. Each subplot measured 15 × 12 m with an additional 1.5 m of buffer zone on each side of the irrigation ditch.

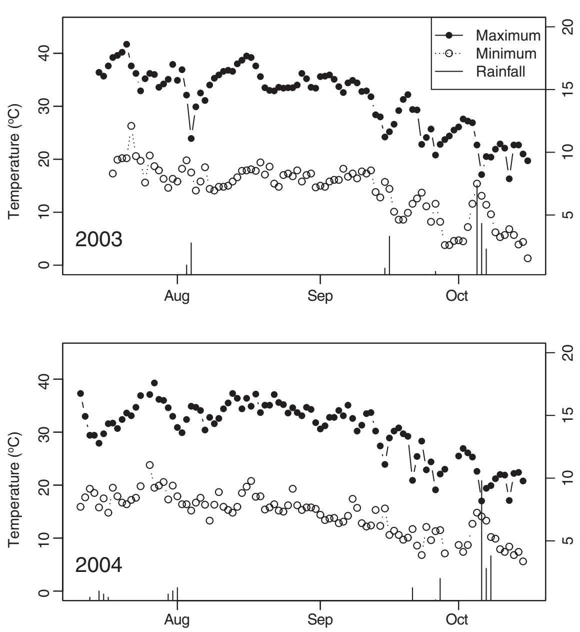

Fig. 2 Climatic data for the growing seasons of 2003 and 2004 in the Fergana Valley, Uzbekistan (40°23′N, 71°45′E), from the beginning of July until the end of October.

Irrigation scheduling

Levels of RDI were determined according to the concept of soil water depletion fractions, as defined by Allen et al. (1998). Depletion fractions are measures of soil water depletion as a percentage of the total available soil water. This results in longer time intervals between irrigation events in treatments with higher depletion fractions. For common bean, the depletion fractions used were 0.45 as the recommended level (Allen et al. 1998) and 0.6 and 0.7 as the moderate and severe stress levels, respectively. For mungbean, the recommended depletion fraction was also 0.45 (Allen et al. 1998), but the moderate and severe stress levels were 0.65 and 0.8, respectively. Local growers informed us that only one irrigation event is often necessary to successfully produce mungbean, suggesting greater tolerance to water stress than most crops. We expected these depletion fractions to be good approximations of a moderate and a severe level of stress for each of the crops. Prior to our work, yield effects of RDI depletion factors for common bean or mungbean were unknown. Soil moisture profiles for all twelve combinations of RDI, AFI and crops are illustrated in Fig. 3. A root depth of 60 cm was assumed based on experience of Dr. M. Horst and later confirmed with root excavations.

Daily ET values were computed from climatic data from our meteorological station (according to the FAO Penman –Monteith equation) and an ET gauge placed in a mungbean plot adjacent to our field (Allen et al. 1998). These were used in six water balances corresponding to six combinations of RDI and crop treatments with soil moisture readings to confirm the actual soil depletion. Once the soil was depleted to the appropriate fraction of soil available water, the irrigation amount was determined from the water balance, and the treatment was irrigated.

For AFI plots, the head of every second furrow was blocked with mud and straw so that water would not go in this furrow. Blocked furrows were alternated between irrigation events, when there was more than one event. Alternate furrow-irrigated plots were irrigated the same day as the corresponding every furrow-irrigated plot in each crop and RDI level, but only received 75 % of the water applied on a whole-plot basis. More details on the irrigation can be found in Webber et al. (2006).

Cultural practices

Each field site produced winter wheat immediately prior to our experimentation. The wheat was harvested, the straw

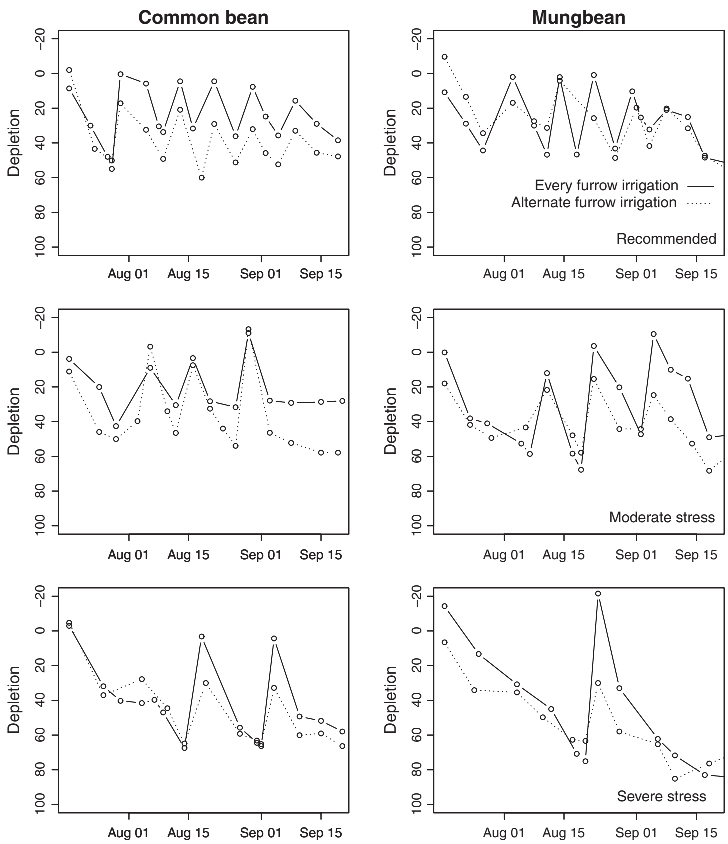

Fig. 3 Soil moisture profile of the different combinations of regulated deficit irrigation, irrigation strategies and crops under field conditions in the Fergana Valley, Uzbekistan.

and stubble burned and the field ploughed and tractor-drawn levelled, all following standard practices in the region. Sixty-centimetre-wide furrows were formed on the field site with a tractor-drawn lister; a pre-sowing irrigation of approximately 800 m^3 ha^{-1} was applied to every furrow to consolidate the resulting furrows and raised beds, and to bring the soil back to field capacity.

Seeds of common bean and mungbean were purchased at a local market, and some of the seeds harvested in the first year were kept for planting in the second year. We have retained a sample of these seeds, and they are available, upon request. We have also submitted them to the Australian Tropical Crops and Forages collection and are awaiting accession numbers. Certified cultivars were not available and these landraces were representative of what was available to farmers. The local common bean used in this study had a bushy and determinate growth habit. The local mungbean was also bushy, slightly prone to lodging and semi-determinate. Under the conditions of the field study, both crops were ready to harvest within 90 days. A second flush of flowering did not occur, although the flowering period lasted more than 2 weeks and a few flowers were still observed at the end of the season on mungbean. In addition, as these landraces from Uzbekistan were selected by farmers under hot and dry environments, we expect this germplasm to exhibit greater drought tolerance than most cultivars of their respective species.

Seeds were sown by hand, at a 5 cm depth, on both sides of the raised beds, at 10-cm intervals, to achieve a plant density of 300 000 plants ha^{-1}. Planting was carried out on 14 and 15 July 2003 and 9–12 July 2004. In 2004, based on experience acquired in 2003, an irrigation event of approximately 600 m^3 ha^{-1} applied to every furrow was included 5 days after seeding (DAS), to assist in seedling establishment.

Based on the availability of agrochemicals, fertilization in 2003 consisted of superphosphate applied immediately prior to the land levelling, plus a manual application of ammonium phosphate and potassium fertilizer a week after planting at the rate of approximately 28 kg ha^{-1} of N, 51 kg ha^{-1} of P and 8 kg ha^{-1} of K. In 2004, a mix of phosphate and potassium was applied in the furrow immediately prior to the pre-irrigation at a rate of approximately 40 kg ha^{-1} for both P and K. Nitrogen fertilizers were not available in 2004. Commercial inoculants for common bean and mungbean were unavailable. Thus, nodule development reported in the results section refers to symbioses formed with indigenous rhizobial strains. Based on the number of nodules and nitrogen analyses of leaves at various stages of growth, it appears that the nitrogen fixation was negligible in these crops. Weed control was conducted manually.

Multiple harvests were necessary as mungbean pods tend to shatter when dry. In 2003, there were two harvests for common bean (3 and 4 October) and six for mungbean (21, 24, 27 and 30 September, and 7 and 13 October). In 2004, there were also two harvests for common bean (20 September and 3 October) and four for mungbean (21 and 26 September, and 1 and 9 October).

Measurements

An area of 5 × 5 m in the centre of each plot was used for sampling. Mature pods were harvested at regular intervals within the sampling area and threshed by hand. Grain yield was determined for each harvest, then combined across harvests, corrected for moisture content and converted into kg ha^{-1} from plant population estimates before statistical analysis.

Stem water potential (SWP) was measured on six plants per plot within the sampling area, 1 day before and 2 days after each irrigation event with a portable pump-up pressure bomb (PMS Instruments, Albany, NY, USA). Stomatal conductance was measured on ten plants, at the same time as SWP, with a diffusion porometer LI-1600M (LICOR Biosciences, Lincoln, NE, USA).

For crop height and number of flowers and pods, six plants were marked at the beginning of the season, and measurements were made on these same plants as the season progressed. In 2003, measurements were taken once a week after crop establishment, while in 2004, measurements were taken twice a week until the first pod harvest. Plants were also harvested at four growth stages during the season for the determination of leaf area, and above-ground biomass dry weight, and root dry weight (the latter in 2004 only). Fifty centimetre of row was harvested, plants were cut off at ground level, and roots were carefully dug out. Leaves were then separated and placed on a white sheet. A digital picture was taken of every individual plant, along with a standard of known area, and these images were later processed with the computer program SigmaScan Pro 5 (Systat Software, San Jose, CA, USA) to determine leaf area. Above-ground biomass was determined from the stem, leaves and reproductive structures when appropriate, of plants harvested in the destructive samplings described earlier. Plants were dried at 70 °C for at least 24 h, to a constant weight. Harvest index was calculated as the ratio of yield over total above-ground biomass at final harvest, all on a dry-weight basis.

Statistical analyses

Statistical analyses were performed by analyses of variance (ANOVA) and repeated measures analysis by multivariate analyses of variance (MANOVA) using the general linear model (proc GLM) in SAS/STAT software (SAS, Cary, NC, USA). Following a split-plot design, RDI main effects were tested against the RDI-by-block interaction as the error term. AFI treatment and crops were tested as the subplot effects on the residual error term. Interactions were also tested and presented when significant. We also tested the effect of the 'year' and found significant interactions with the RDI treatments. Therefore, results are presented separately for each year. In general, treatment effects or interactions were considered significant only when they occurred at the 0.05 level of probability. However, in some cases, we considered relevant differences when the probability level was between 0.05 and 0.1; in these cases, the P value is given in the text and in tables when appropriate. If fixed main effects or a fixed interaction was found to be significant in the ANOVA, then mean separations were carried out using *t*-tests on least squares means. In 2003, when significant, the plant population density was used as a covariate. Because there were few nodules, the statistical analysis for nodule number was performed with a nonparametric approach using the RANK procedure prior to proc GLM.

Results

Yield

The mungbean landrace responded differently than the common bean landrace to the various levels of RDI imposed during this experiment (Fig. 4), resulting in a crop-by-RDI interaction with P values of 0.0913 and 0.0005 for 2003 and 2004, respectively. While common bean yields decreased with increasing stress, mungbean yields were highest at the moderate water stress level (2003) and severe stress level (2004). Common bean yields at the moderate stress level were not significantly lower than bean yields at the recommended irrigation schedule. In addition, AFI did not reduce yields (Table 1), and the interaction with RDI or crop was not significant.

The yield difference between the two experimental years can be explained, at least in part, by the differences in the plant population density. In 2003, variation was relatively high, due to uneven emergence. In particular, plots in the severe stress treatment only reached 50–75 % ground cover, particularly in the mungbean plots. This probably led to yield limitations due to lower radiation interception, but might also have led to greater evaporation from the soil surface, and a lack of transpirational boundary layer. This would have resulted in more stressful environmental conditions for these plants, contributing to lower yields.

Harvest index

Harvest index (HI) was affected by RDI but differently for the two crops. In the severe stress treatment, HI decreased

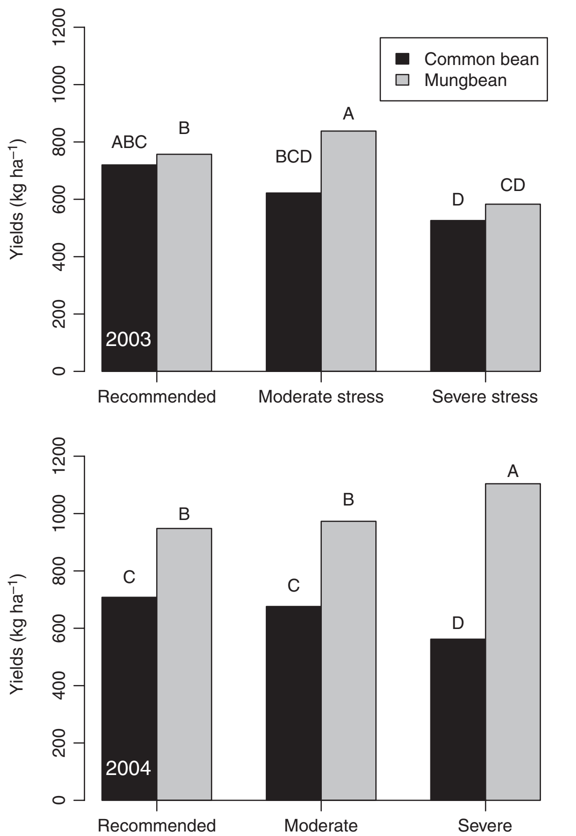

Fig. 4 Seed yields of common bean and mungbean in 2003 and 2004 subjected to regulated deficit irrigation under field conditions in the Fergana Valley, Uzbekistan. Histogram bars with the same letter are not different ($P < 0.05$) within the same year by *t*-tests on least squares means. Each bar represents an average of eight plots from four blocks and two AFI levels. The crop-by-RDI interaction was significant at $P = 0.0913$ in 2003 and $P = 0.0005$ in 2004.

in common bean, but increased in mungbean (Fig. 5). In addition, there were no differences between the recommended and moderate stress irrigation schedules within crops. Thus, it seems that mungbean has a greater capacity than common bean to allocate resources to seeds under conditions of severe stress. Again, there were no AFI effects, AFI-by-crop and AFI-by-RDI interactions.

Stem water potential

In both years, before irrigation events, mungbean maintained a higher (i.e. less negative) SWP than common bean across RDI and AFI treatments. In addition, SWP was not different between furrow irrigation strategies in either year (Table 1). The response to RDI was different for each year (Table 2). In 2003, there was a strong crop-by-RDI interaction in which mungbean decreased its SWP with increasing stress, while common bean showed the lowest SWP at the moderate stress level. This interaction, however, was not significant in 2004 ($P = 0.1238$), and numerically, the lowest SWP in common bean occurred in the severe stress level, whereas for mungbean, all depletion levels showed the same SWP.

After irrigation events, the SWP was lower under AFI for both crops and across RDI levels in both years (Table 1), but there was no RDI-by-AFI interaction. Again, the crops responded differently to RDI in each year (Table 2). In 2003, mungbean had a lower SWP after irrigation events in the severe water stress. On the other hand, for common bean, SWP was not different among RDI levels and thus had returned to a relatively high SWP following irrigation. In 2004, mungbean showed the highest SWP after irrigation events and no difference among RDI levels, while common bean had a lower SWP in the severe water-stress treatment. In any case, it seems that both crops are generally able to return to a high SWP after irrigation, no matter how dry the soil was when irrigated.

Stomatal conductance

In both years, common bean maintained a higher stomatal conductance than mungbean across RDI and AFI levels before irrigation events. Stomatal conductance of both crops decreased as water stress increased, but decreased proportionally more in common bean than in mungbean, as shown in the crop-by-RDI interaction detected in both years (Table 2).

The stomatal conductance after irrigation events was also higher in common bean than in mungbean across RDI and AFI levels (Table 2). Stomatal conductance was then unaffected by RDI, and values for stomatal conductance were higher than before irrigation events, indicating that gas exchange in all plants was able to recover from the stress, although in 2003, plants in the AFI plots showed a lower stomatal conductance than those in the conventional every furrow irrigation plot (Table 1). This effect, however, was not significant in 2004 ($P = 0.1410$).

Crop development

While common bean showed high vigour at the beginning of the season, mungbean grew slowly early in the season, followed by a rapid increase in growth a few weeks after planting, and reached maximum height and biomass near the end of the season. This was clear in the data for aboveground biomass, leaf area and crop height (Fig. 6). Common bean also flowered earlier than mungbean (data partly shown in pod development in Fig. 6d), and as such, the statistical analysis was performed separately for the two crops.

Table 1 Alternate furrow irrigation as compared to every furrow irrigation on yield, yield components and water relations of common bean and mungbean

	2003			2004		
Traits	Alternate furrow	Every furrow	P value	Alternate furrow	Every Furrow	P value
Yield (kg ha^{-1})	665	686	0.6001	832	826	0.8839
Number of seeds per pod	6.9	7.1	0.1490	6.6	6.8	0.1674
100 seed weight (g)	24.2	24.3	0.9023	19.1	20.0	0.1744
Pods per plant	25.2	26.8	0.1546	9.7	10.2	0.4014
Harvest index (%)	0.302	0.346	0.1339	0.306	0.284	0.2486
Stem water potential (MPa)						
Before irrigation events	−1.02	−1.00	0.5025	−0.81	−0.80	0.0554
After irrigation events	−0.89	−0.82	0.0027	−0.77	−0.75	0.0346
Stomatal conductance (mmol m^{-2} s^{-1})						
Before irrigation events	221.0	233.5	0.1409	357.5	330.3	0.0947
After irrigation events	316.9	364.4	<0.0001	449.0	461.7	0.1410
Nitrogen content (%)						
Harvest sampling	2.14	2.21	0.6006	1.77	1.81	0.7824
Grains	3.90	4.03	0.1532	3.93	4.12	0.1412

Values are least-square estimates of means from four blocks, two crops and three levels of RDI treatments, that is, 24 plots when there were no missing observations. There was no AFI level-by-crop or AFI level-by-RDI level interaction in any of the parameters presented.

There was no effect of RDI treatment on above-ground biomass of common bean at any of the growth stages measured in either year. The above-ground biomass of mungbean, however, was lower in the harvest stage for the severe stress treatment in both years. There was also a 45 % decrease in mungbean biomass in 2003 at the flowering stage in the severe stress treatment (data not shown) compared to the recommended schedule, again probably due in part to a plant density-by-RDI interaction in that year, as discussed earlier. Similarly, there were no differences in common bean leaf area due to RDI levels, in either year; however, mungbean leaf area was lower under the severe stress treatment at flowering and harvest in 2003, but in none of the samplings in 2004, although the P value at harvest in 2004 was close to the significance level at 0.0638 (Fig. 6b).

Similarly, there was no effect of RDI on crop height for common bean, but after flowering, mungbean plants in the severe stress treatment were shorter than the other two RDI treatments in both years (Fig. 6c). In general, RDI had no effect on the number of flowers, except for one date in each of the two crops in 2004 only (data not shown). For common bean, 42 DAS, the number of flowers was highest in the moderate stress treatment, but lowest in the severe stress treatment. This might be explained by the fact that the moderate stress treatment had been irrigated a few days before, potentially leading to a flush of flowers following the relief of stress. In mungbean, this difference in the number of flowers occurred 60 DAS, towards the end of flowering. The recommended and moderate stress treatments had more flowers than the severe stress treatment, indicating that water stress may have shortened the flowering period in mungbean. RDI treatments had no effects on the number of pods m^{-2} in either crop in 2004 (Fig. 6d). However, mungbean was affected in 2003, as the number of pods was reduced in the severe stress treatment.

Finally, AFI had no effect on any of the crop development parameters observed (data not shown), and there were no AFI-by-crop or AFI-by-RDI interactions.

Nodule development

Common bean failed to nodulate with the indigenous rhizobia in the experimental site soil. However, we found nodules in 87 % of mungbean plots in 2003 and 100 % of mungbean plots in 2004, when the plant density was higher. We found an average of 4.2 nodules per plant in 2003 and 6.4 nodules per plant in 2004. However, no differences were observed among RDI levels in either year for the number or dry weight (available only in 2004) of nodules (data not shown).

Discussion

Our results show that it is not only possible to grow legumes after the harvest of winter wheat, but also that it could be done with one (mungbean) or two (common bean) irrigation events and using AFI. While both crops tolerated some level of stress, mungbean produced the highest yields with the lowest quantity of applied water in 2004. This suggests mungbean is better adapted to the dry and hot conditions of Uzbekistan. Our yield results for

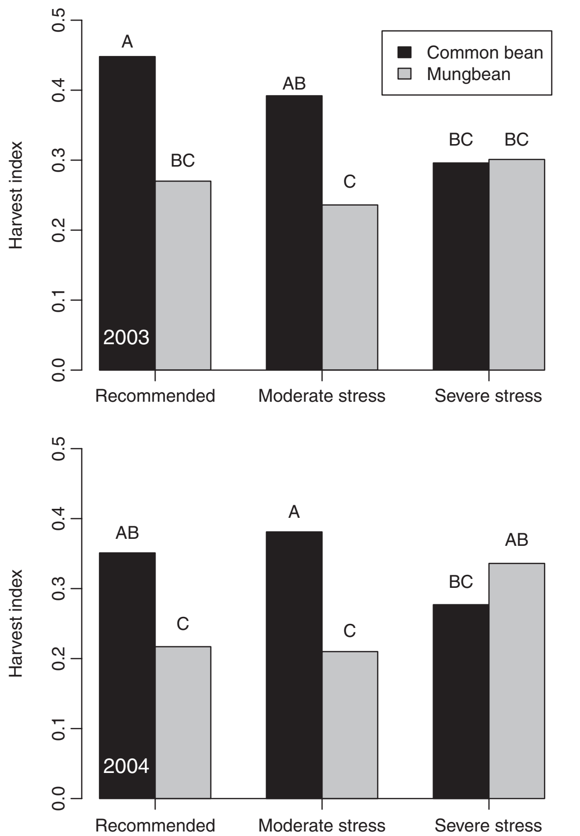

Fig. 5 Harvest index of common bean and mungbean in 2003 and 2004 subjected to regulated deficit irrigation under field conditions in the Fergana Valley, Uzbekistan. Histogram bars with the same letter are not different ($P < 0.05$) within the same year by *t*-tests on least squares means. Each bar represents an average of eight plots from four blocks and two AFI levels. The crop-by-RDI interaction was significant at $P = 0.0243$ in 2003 and $P < 0.0001$ in 2004.

mungbean contradict results from some of the previous experiments comparing the response to irrigation of mungbean with other crops (Pandey et al. 1984, Senthong and Pandey 1989, De Costa et al. 1999, Thomas et al. 2004), but are consistent with the experience of local growers. In a pot experiment, we also found that mungbean yields were reduced by water stress, but to a lesser extent compared to the reduction in yield of common bean (Bourgault et al. 2010). Irrigation schedules comprising four to six irrigation events following seedling establishment have been proposed (Poehlman 1991). In addition, mungbean was found to be quite sensitive to water stress, when compared to a number of other crops, showing the greatest decrease in yield between the well-watered control and most severe stress treatments (Pandey et al. 1984, Senthong and Pandey 1989). These researchers used sprinkler irrigation, and irrigation water was decreased according to the distance of the experimental plot from the sprinkler. The resulting small irrigation depth (water penetration in the soil) may be ineffective for mungbean, which seems to extend its roots deeper into the soil profile to extract water resources from greater depths (Haqqani and Pandey 1994). By filling the root zone during our single irrigation event, a few days before the onset of flowering, we appear to have provided mungbean with sufficient water at a critical time. Angus et al. (1983) found that mungbean was not responsive to irrigation, and Muchow (1985) found that mungbean had the highest yields under water-deficit conditions. In both cases, the dry treatment consisted in no irrigation at all after seedling establishment (and very limited rainfall if any).

Our results regarding the response of common bean to water stress are consistent with the findings of other

Table 2 Water relations of common bean and mungbean under three levels of regulated deficit irrigation

	Stem water potential (MPa)				Stomatal conductance (mmol m^{-2} s^{-1})			
	Average before irrigation events		Average after irrigation events		Average before irrigation events		Average after irrigation events	
Crop								
Depletion fraction	2003	2004	2003	2004	2003	2004	2003	2004
Bean								
Recommended	−1.00 bc	−0.91 b	−0.92 c	−0.86 b	317 a	449 a	394 a	569 a
Moderate	−1.17 d	−0.88 b	−0.88 c	−0.90 b	273 b	463 a	388 a	544 a
Severe stress	−1.06 bc	−0.86 b	−0.92 c	−0.87 b	214 c	317 b	389 a	520 a
Mungbean								
Recommended	−0.82 a	−0.70 a	−0.78 b	−0.65 a	209 c	310 bc	282 b	406 b
Moderate	−0.88 b	−0.67 a	−1.06 a	−0.65 a	187 cd	261 d	272 b	354 c
Severe stress	−1.12 cd	−0.70 a	−0.73 c	−0.65 a	164 d	264 cd	300 b	338 c
Interaction significance (P value)	<0.0001	0.1238	0.0283	0.0223	0.0281	0.0021	0.7492	0.4168

Values are least-square estimates of means from four blocks and two AFI levels. Values with the same letter in the same parameter (i.e. in the same column) are not statistically different at $P < 0.05$.

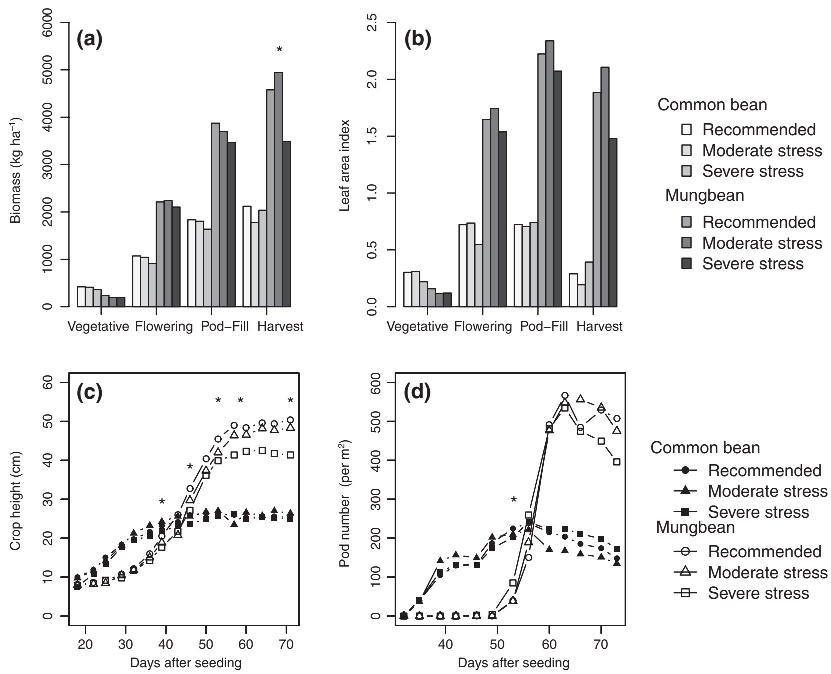

Fig. 6 Crop development (biomass (a), leaf area index (b), crop height (c) and number of pods (d)) of common bean and mungbean subjected to regulated deficit irrigation under field conditions in the Fergana Valley, Uzbekistan, in 2004. Values are averages of eight plots from four blocks and two AFI levels. Significant differences between RDI treatments for mungbean are identified by an asterisk (*). No significant differences were observed in common bean.

researchers, who also measured a decrease in yield (Nielsen and Nelson 1998, Dapaah et al. 2000, Boutraa and Sanders 2001, Wakrim et al. 2005). In a companion paper (Webber et al. 2006), we showed that the WUE of common bean remained constant over the various treatments. However, because producers rarely monitor the inflow of irrigation water and typically over-irrigate fields (EC-IFAS 1999), it seems likely that the reduction in the frequency of irrigation events (from four irrigation events to two using a moderate stress RDI schedule) would lead to considerable water savings in a producer's fields. Thus, the potential WUE benefits of RDI in common bean should not be dismissed.

Differences between crops in some of the physiological parameters observed point to what might be important adaptive traits for legumes growing in semi-arid environments. Mungbean was able to maintain or increase its HI under stress, while common bean HI decreased with increasing stress. Its partitioning to yield thus appears to be superior under stress. Mungbean also maintained a lower stomatal conductance across RDI and AFI levels, but a lower proportional decrease with (i.e. a lower response to) increasing stress, which suggests some intrinsic water-saving characteristic rather than an active response to stress. A similar mechanism seems to be at play in cowpea (Hamidou et al. 2007) and Bambara groundnut (Jorgensen et al. 2010), where drought-resistant cultivars showed lower stomatal conductance when well watered. It would be interesting in further studies to investigate whether there is genotypic variability in this trait as well as in epicuticular wax accumulation as found in maize (Meeks et al. 2012) or in the performance of the antioxidant defence system as found in wheat (Singh et al. 2012) as these mechanisms could be superior in mungbean compared to common bean.

No other physiological or developmental trait can account for the improved performance of mungbean under Uzbekistan conditions. Mungbean also maintained a higher SWP than common bean and showed no response to increasing stress in 2004. Osmotic adjustment (defined as a decrease in osmotic potential to maintain water uptake) in this case does not seem to contribute meaningfully to water-stress tolerance. Similarly, the general lack of differences between irrigation treatments in above-ground biomass weight, leaf area production and the number of flowers and pods further seems to indicate that water stress had very little effects on production *per se*, but rather affected translocation of resources to seeds late in the season.

AFI, which saves 25 % of the water applied by not watering every second furrow, did not reduce yields, or most of the yield components measured, and did not affect crops negatively when combined with RDI treatments. Although SWP was reduced in the AFI treatment after irrigation events, this was not translated into yield differences. Therefore, AFI appears to be a simple yet effective way to increase WUE while maintaining yields. More importantly, this study is the first to evaluate the combination of AFI and RDI, and we have found that AFI does not cause further negative effect on crops already subjected to RDI.

Comparisons of the effects of water-deficit stress on crop yields are difficult due to the various methods used to impose the water deficit. Previous studies on RDI were usually performed by either reducing the amount of water that is applied to crops to a fraction of the full ET, but otherwise keeping the same frequency of irrigations (Pandey et al. 1984, Oktem et al. 2003, de Souza et al. 2003, Oweis et al. 2004, Chaves et al. 2007), or withholding irrigation at specific growth stages (Nielsen and Nelson 1998, Calvache and Reichardt 1999, Pandey et al. 2000, Boutraa and Sanders 2001, Karam et al. 2007). While applying a fraction of the ET might be a practical way to impose RDI with sprinkler and drip irrigation, in surface irrigation systems very small irrigation depths are not technically feasible. Further, these small irrigation depths do not bring the soil profile back to field capacity, but rather wet the upper layers, and result in a soil depletion that increases over time. This could potentially lead to severe damage at the yield formation stage. On the other hand, withholding irrigation water at specific growth stages is too simplistic. Even if rainfall is negligible, air temperature, wind speed, irradiation, relative humidity, crop ground cover, soil's water-holding capacity and fertility conditions are all factors that affect ET and that might vary considerably from year to year. The water stress is thus difficult to reproduce.

The concept of depletion fractions integrates the effects of environmental conditions, crop conditions and management through daily ET and available soil moisture. The depletion fractions are also adjusted for the daily crop ET. RDI using increased time intervals between irrigation events, based on the water balance method for irrigation scheduling and greater depletion fractions (as proposed by (Allen et al. 1998) and used in Panda et al. (2003) and in this study), is probably a better approach because: (i) the method is available no matter what water application technology is being used; (ii) the depletion fractions represent an independent measure of stress over soil types and climatic conditions; (iii) filling the entire soil profile potentially encourages deeper root growth and greater drought tolerance; (iv) the lower frequency of irrigation events lowers the water losses from evaporation; and (v) it is not practical for crop producers to grow a control plot to calculate the ET and then apply a fraction of it to the rest of their fields, as would be required using a fraction of the full ET as used in many research studies.

Although our results show that the combination of RDI and AFI is viable, yields of both mungbean and common bean crops were still relatively low compared to yields achieved in other areas, and the establishment of a genetic improvement programme for these two crops and collaborations with other international centres would be beneficial to the region. It is also important to note that mungbean has not benefited from the same research and breeding efforts as many other legume and cereal crops. Breeding programmes in Thailand and Australia have selected against undesirable characteristics, such as the shattering of pods, and selected for a more determinate maturing of pods. Some of the developed genotypes might present interesting genetic material for a local breeding programme. Improved germplasm and improved rhizobial inoculants combined with improved distribution could improve agricultural production in Uzbekistan, even within the current cotton and wheat quota policies.

Conclusions

Overall, RDI in combination with AFI, as well as the cultivation of legumes following the harvest of winter wheat, is not only possible, but could have considerable positive effects on the economy, environment and national food security of Uzbekistan and nearby areas of Central Asia. We suggest that while both mungbean and common bean are possible crops, mungbean is better adapted to hot and dry conditions prevalent in semi-arid areas. Our results suggest that water deficit affects the translocation of resources to seeds and that mungbean is able to maintain its HI under severe stress while common bean did not. Mungbean tolerance to water deficit further seems to be related to lower stomatal conductance across water availabilities. A single, but deep, irrigation event around flowering might be all that is necessary for mungbean to yield well and to do so before the onset of rain and lower temperatures in the fall. RDI is also possible with common bean, where yields were not substantially decreased by the moderate stress treatment. A reduction in irrigation events would also be desirable, as crop producers tend to over-irrigate to ensure even water distribution.

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