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Water use efficiency of common bean and green gram grown using alternate furrow and deficit irrigation

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ABSTRACT

The pressure on water resources in the Fergana Valley of Central Asia is expected to increase, as population and industrial activity grow. Increasing water use efficiency (WUE) associated with crop production is a way for arid and semi-arid areas to increase their agricultural production where there is little or no prospect for expansion of water resources. The WUE of two water saving irrigation technologies were evaluated for two legumes, grown as a second crop, in the Fergana Valley of Uzbekistan. Conventional and alternate furrow irrigation and three irrigation schedules were used to irrigate food legumes in a field experiment conducted over two growing seasons (2003 and 2004) after winter wheat harvest. The treatments consisted of factorial combinations of three factors, organized following a split-plot randomized complete block design with four blocks: three irrigation schedules (recommended, moderate and severe depletions) as the main plot factor and combinations of the two irrigation strategies (conventional and alternate furrow irrigation) and two crops (green gram and common bean) as the two sub-plot treatment. The WUE was quantified for commercial yield, above ground biomass and root biomass per unit of water consumed by the crop. The results of this study indicate the WUE for both commercial yield and biomass were approximately twice as high for green gram as bean. Conversely, the water use efficiency for root biomass in bean (0.15 kg m^{-3}) was slightly higher than in green gram (0.13 kg m^{-3}). WUE increased in green gram when deficit irrigation or alternate furrow irrigation were practiced, whereas it remained constant in bean for all treatment combinations. These results suggest that common bean is not as well suited to water scarce conditions as green gram. Alternate furrow irrigation and deficit irrigation are appropriate methods to increase WUE, allowing application of less irrigation water, particularly, for green gram production.

1. Introduction

Extensive environmental degradation of the Aral Sea basin has been the price of Uzbekistan's irrigated agriculture (cotton and wheat) dependent economy. The pressure on water resources is expected to increase as the requirements for increased food production and industrial needs increase in parallel with the country's rapidly growing population (Micklin, 2000). The

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improvement of on-farm irrigation systems and the introduction of low cost water saving irrigation technologies have been identified as key components of reducing agricultural water demand (Horst et al., 2005). Increasing water use efficiency (WUE), defined in this paper as the amount of plant material produced per unit of water transpired, is a way for arid and semi-arid areas to increase their agricultural production where there is little or no prospect for expansion of water resources. Wallace (2000) indicates that there are two approaches to increasing crop WUE. The first is by adopting technologies that increase the proportion of water that is transpired by the crop, as opposed to that lost to drainage, runoff or seepage. The second approach is to increase the crop's capacity to produce biomass (assimilate CO_2) and yield per unit of water transpired. Passioura (2004) adds that, from a farmer's perspective, increasing the harvest index (ratio of seed yield to total biomass) is a practical third approach to increasing WUE.

Regulated deficit irrigation (RDI) and alternate furrow irrigation (AFI) are two water saving technologies that are relatively inexpensive and easy to implement. Both strategies involve manipulating the soil water to induce the crop's inherent response to drought conditions (Davies et al., 2002). In water scarce environments, the goal is generally to increase the WUE. The same strategies may be used in the production of other crops, but with different objectives. For instance, in vineyards the objective is typically to retard vegetative growth and influence fruit quality (Loveys et al., 2004). In RDI, the irrigation water requirement is not completely fulfilled, allowing the soil water to be depleted beyond a threshold, such that the crop experiences water stress. The crop response, which may or may not include a reduction in the rate of water use and/or yield reductions, depends on the degree of soil drying, the crop characteristics and the timing of the water deficit. It is generally thought that withholding water during the vegetative period, as opposed to the flowering or fruit forming stages, has less impact on final yields (Loveys et al., 2004). The water savings associated with RDI are attributed to reductions in stomatal conductance which occurs as a result of the plant roots encountering drying soil, and precedes any change in leaf water potential. Stomatal regulation is thought to be mediated by chemical signals originating in the roots and traveling to the guard cells via the xylem. Further, these signals are now thought to involve both abscisic acid (ABA) and the alkalization of the xylem flow, associated with soil drying (Loveys et al., 2004; Wilkinson, 2004). While the stomata control both the rates of transpiration and CO_2 entry into the cell, some evidence suggests that initially the reduction in stomatal conductance is greater than the concurrent reduction in carbon assimilation. This results in increased instantaneous WUE values (Chaves and Oliveira, 2004). While some studies show that RDI improves WUE on a seasonal basis (Oweis et al., 2000; Zhang et al., 2000), other investigators have not found consistent evidence that WUE increases with deficit irrigation (Garside et al., 1992; Kang et al., 2000c; Lawn, 1982).

Partial root drying (PRD) is a variation of RDI that generally improves the WUE of crops, for example pot grown tomatoes (Davies et al., 2000) and pot grown common bean (Wakrim et al., 2005). In many cases, the strategy circumvents the yield losses frequently associated with RDI, as in grape (Loveys et al., 2000), soybean (Graterol et al., 1993) and pot and field grown maize (Kang et al., 1998, 2000a, b). PRD involves exposing part of the root system to drying soil while maintaining other sections in well watered soil, and is most effective when the two sections of roots are alternately exposed to wet and dry soil (Kang et al., 1998). The method is thought to work via a reduction in stomatal conductance mediated by a chemical signal generated in the roots when they are exposed to drying soil, as in RDI. This physiological response of the plant, due to exposure of some of its roots to drying soil while the plant is kept well hydrated by other roots in moist soil, is hypothesized to cause the benefits associated with PRD.

For furrow irrigation systems, PRD is practiced as alternate furrow irrigation. Wakrim et al. (2005) found the WUE of common bean increased, though with significant yield decreases for both RDI and PRD, in a pot experiment, and that there were no differences in yield or WUE between the two strategies.

The objectives of this study were (i) to quantify the effects of alternate furrow irrigation and RDI on the WUE (for each of commercial seed yield, above ground biomass, and root biomass, WUE_{seed}, $WUE_{biomass}$ and WUE_{root}, respectively) of common bean and green gram and (ii) to determine the optimal irrigation schedule and irrigation water requirement for each crop, in order to maximize their WUE.

2. Materials and methods

2.1. *Site description, experimental design and crop varieties*

Two seasons of field data were collected during 2003 and 2004 on two different adjacent fields on the private farm, "Azizbek-1", in the Fergana Valley of Uzbekistan (40°23′N, 71°45′E). Despite the close proximity of the fields, the soil characteristics and groundwater depths differed between site-years. For the 2003 site, the soil in the top 60 cm was classified as a silt loam with a coarser texture at depths greater than 1 m that prevented a groundwater contribution from the water table, which was at an average depth of 2.2 m. The available water content in 2003 was 96 mm in the top 60 cm of the soil. There was more variability in the field used in 2004, with the soil type ranging from a sandy loam to a silt loam over the field and an available water content of 75 mm in the top 60 cm. The ground water table was also considerably higher and varied along the length of the field, with an average depth of 1.45 m. At the start of August, the groundwater table rose to within 40 cm of the soil surface in some locations and contributed significantly to the soil water in the root zone for a period of less than one week, due to excessively heavy irrigations in an adjacent field.

The experimental layout was a randomized complete block (four blocks), split-plot design. The treatments were comprised of factorial combinations of three factors: irrigation schedule (main-plot factor—recommended rate, moderate and severe soil water depletion), irrigation strategy (conventional furrow or alternate furrow irrigation) and crop (common bean or green gram). The combinations of furrow-irrigation strategy and crop made up the split-plot treatments. Each plot measured 15 by 15 m and contained 23 furrows 12 m in length. All sampling was conducted within a central 5 by 5 m quadrat. The average field slopes were 0.0024 and 0.0023 m/m in 2003 and 2004, respectively. Due to variations in slope across and along the field, and the relatively short length of the experimental furrows, there was variability in slopes between and within individual plots.

Local varieties of common bean (*Phaseolus vulgaris*) and green gram (*Vigna radiata*) were planted half way between the top of the bed and the furrow bottom. Beds were 60 cm apart. In 2003, planting was carried out on 13 July and local practices were followed for planting density, resulting in a fairly sparse plant stand of 70,000 and 105,000 plants/ha for green gram and common bean, respectively. In 2004, the seeding date was 11 July and the plant density for both crops was increased to 333,000 plants/ha, to be comparable with densities found in similar studies at locations elsewhere in the world (Haqqani and Pandey, 1994). In both years the cropping history consisted of cotton the previous year followed by winter wheat which was harvested in early July. Pest and weed control were conducted as required.

2.2. Irrigation scheduling and management

In both years, a pre-irrigation of approximately 800 m^3 ha^{-1} was applied to every furrow in each plot, at 2 days before seeding. The purpose of this irrigation was to bring the soil in the 60 cm root zone to field capacity and to create a good seed bed. At the time of emergence, a second irrigation of 600 m^3 ha^{-1} was applied, also to every furrow, to encourage a full and even plant stand.

Subsequent irrigation scheduling was determined using daily water balances, which were determined for each of the twelve treatments. Each water balance calculated excess or deficit water in the crop root zone relative to field capacity. Inputs to the system considered were irrigation water requirement, precipitation and groundwater contribution. The only water output considered was crop evapotranspiration (ET), as deep percolation and run-off were assumed to be negligible.

Crop ET was determined from the water balance as the sum of precipitation, ground water contribution, irrigation water and the soil water use over the growing season. Additionally, Crop ET was predicted, to use in irrigation scheduling, with the FAO Penman–Monteith equation using weather data collected at the experimental site and crop coefficients for standard and stress conditions, as appropriate (Allen et al., 1998). The method assumes water stress occurs when the root zone water deficit is greater than recommended depletion of the available soil water, which is 45% of the readily available soil water for both green gram and common bean. In response to water stress, the crop reduces ET from a maximum value, ET_{max}, under non-stressed conditions to a value ET_{actual}, given by

$$ET_{actual} = k_s ET_{max} \quad (1)$$

where k_s is the water stress coefficient. The water stress coefficient varies linearly between 1 (no water stress) and 0 (permanent wilting point, or 100% depletion).

The groundwater table depth was measured every 3 days at three and five locations across the field, respectively in 2003 and 2004. As stated above, there was no ground water contribution to the root zone in 2003. In 2004, the groundwater contribution was estimated using an empirical model (Ayars et al., 2006) that takes into account the distance between the root zone and groundwater table, soil type, ET, and the soil moisture content. The model was validated for our field data using the water balances for the recommended irrigation schedules for bean and green gram, where the non-stressed ET was estimated using the FAO Penman–Moneith equation.

Irrigations were applied when the root zone water deficit equaled the maximum allowable depletion of the available soil water (Table 1). For the FAO recommended irrigation schedule, or no stress condition, the plots were irrigated when 45% of the available water was depleted. The depletion factors, $p_{nominal}$, for the moderate stress treatments were 60% for common bean and 65% for green gram. For the treatments receiving the

Table 1 – Amount of irrigation water applied, number of irrigation events and the groundwater contribution to the crop root zone as a fraction of crop evapotranspiration for each treatment during the two growing seasons

Year	Crop	Irrigation schedule (nominal depletion factor)	Total irrigation (m^3 ha^{-1}) (number of irrigations)		Groundwater contribution to crop ET (%)	
			Conventional furrow	Alternate furrow	Conventional furrow	Alternate furrow
2003	Common bean	Recommended (0.45)	3100 (5)	3100 (6)	0	0
		Moderate stress (0.60)	3100 (4)	3050 (5)	0	0
		Severe stress (0.70)	3150 (4)	2450 (4)	0	0
	Green gram	Recommended (0.45)	3600 (6)	3050 (6)	0	0
		Moderate stress (0.65)	2800 (4)	2350 (4)	0	0
		Severe stress (0.80)	2000 (3)	1900 (3)	0	0
2004	Common bean	Recommended (0.45)	3000 (7)	2500 (7)	8	10
		Moderate stress (0.60)	2650 (5)	2200 (5)	8	11
		Severe stress (0.70)	2300 (4)	1950 (4)	10	12
	Green gram	Recommended (0.45)	3550 (7)	2850 (7)	7	8
		Moderate stress (0.65)	3000 (5)	2500 (5)	8	10
		Severe stress (0.80)	1700 (3)	1500 (3)	12	15

largest water stress, the depletion factors were 70% for common bean and 80% for green gram. The depletion factors, p, are not constant and vary as a function of their nominal value, $p_{nominal}$, and ET_{actual}, as given in the following relationship (Allen et al., 1998):

$$p = p_{nominal} + 0.04\,\text{day mm}^{-1}(5\,\text{mm day}^{-1} - ET_{actual}) \qquad (2)$$

Soil moisture measurements, made two days before and after each irrigation and every five days between irrigations, were used to check the water balance, particularly the effect of the water stress coefficient and the predicted groundwater contributions. Soil moisture was measured gravimetrically at 0, 10 and 20 cm depth and with a neutron probe at 40 and 60 cm, in the centre of two furrows in the conventional furrow treatment plots and in the centre of four furrows in the alternate furrow treatments. The gravimetric soil moisture measurements were converted to volumetric values by multiplying by the soil bulk density.

Plots were irrigated using either conventional or alternate furrow irrigation. In conventional furrow irrigation, water is introduced into every furrow in the plot. In alternate furrow irrigation, water is introduced into only every second furrow. The furrow receiving water is alternated between successive irrigations.

The literature contains very little on irrigation scheduling for alternate furrow irrigation systems. As a result, there was a change in our scheduling methodology for alternate furrow irrigation to ensure the water savings possible with this strategy. In 2003, separate irrigation schedules were used for the conventional and alternate furrow treatments within the same crop and depletion factor. In the alternate furrow treatments, the average of a wet and dry furrow's soil moisture was used in the water balance. As a result, the alternate furrow treatments had lower soil water contents and two of the alternate furrow irrigation treatments received one irrigation event more than their corresponding conventional furrow irrigation treatments. In 2004, the methodology was modified slightly to ensure equal numbers of irrigations for the alternate and conventional furrow corresponding treatments and significant water savings for the alternate furrow irrigation treatments. Irrigations for the alternate furrow treatments were applied on the same day as the corresponding conventional furrow treatment, with the result that only 75% of the water was applied.

In both years, initial inflow rates were selected using the SIRMOD software package (ISED, 1989). Within each experimental plot, the lower ends of the furrows were blocked, so there was no outflow. Inflows to each plot were measured with small portable flumes and from there distributed by field staff as evenly as possible to each of the furrows. Due to the high variability of slopes between plots, inflow rates were often adjusted to ensure the advance time (the time for the water front to reach to the end of a furrow) was approximately equal to one half of the total irrigation time. Small inflow rates were used for high efficiency and uniformity, as required with short furrows. As a result, it was not possible to measure the inflow into individual furrows. The choice to use shorter furrows than commonly found in other irrigation studies was justified as the simultaneous collection of data on irrigation scheduling and crop response to drought required very high distribution uniformity.

2.3. Biomass and yield measurements

Seed and biomass yields were used to compute the respective WUE values. In 2003, common bean was harvested four times between 3 October and 1 November and green gram was harvested eight times starting 21 September with the final harvest on 2 November. In 2004, harvest dates were 20 September and 3 October for bean and green gram was

Table 2 – Seed above ground biomass and root biomass yields of common bean and green gram grown with three irrigation schedules (recommended, moderate and large depletions) and two irrigation strategies (conventional and alternate furrow irrigation) in 2003 and 2004 (from Bourgault et al., unpublished manuscript)

Year	Crop	Depletion factor for irrigation scheduling	Seed yield ($kg^3\,ha^{-1}$)		Above ground biomass at harvest ($kg^3\,ha^{-1}$)		Root biomass at harvest ($kg^3\,ha^{-1}$)	
			Conventional furrow	Alternate furrow	Conventional furrow	Alternate furrow	Conventional furrow	Alternate furrow
2003	Common bean	Recommended (0.45)	765 ABC	674 BCDE	2530 BC	3010 BC		
		Moderate (0.60)	620 BCDE	623 BCDE	2225 C	2297 C		
		Large (0.70)	552 DE	500 E	2162 C	2631 C		
	Green gram	Recommended (0.45)	793 AB	718 ABCD	2892 C	4267 B		
		Moderate (0.65)	870 A	806 AB	5571 A	4322 AB		
		Large (0.80)	554 CDE	612 CDE	2127 C	2962 C		
2004	Common bean	Recommended (0.45)	729 CD	687 DE	2264 EF	1978 EF	353 BC	293 DE
		Moderate (0.60)	782 CD	571 E	1957 EF	1604 F	327 BCD	322 BCD
		Large (0.70)	572 E	552 E	2421 E	1654 F	374 B	435 A
	Green gram	Recommended (0.45)	849 C	1047 AB	4916 AB	4241 BC	354 BC	319 BCD
		Moderate (0.65)	975 BC	970 BC	4817 AB	5068 A	305 CDE	334 BCD
		Large (0.80)	1045 AB	1163 A	3520 CD	3457 D	256 E	297 CDE

Within each year and measure, value associations with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

harvested four times between 21 September and 9 October. All plants within a central 5 m quadrat were harvested. One day before harvest, a 50 cm section of row was sampled to determine the above ground biomass and, in 2004 only, the root biomass.

2.4. Statistical analysis

Statistical significance for detection of differences between various means was determined using the general linear model (GLM) procedure of the Statistical Analysis System (SAS, from SAS Institute Inc.). Differences between specific least-square means were determined using *t*-test at $P \leq 0.05$. Data were analyzed separately in 2003 and 2004 as the fields used in the respective years differed in soil type, water holding capacity, groundwater depth, plant density and the irrigation scheduling for alternate furrow irrigation was slightly modified in 2004.

3. Results and discussion

3.1. Seed, above ground and root biomass yields

The seed, above ground and root biomass yields are given in Table 2 (Bourgault et al., unpublished manuscript). For common bean, RDI at the moderate depletion level produced the same seed yields as the recommended irrigation schedule while seed yields decreased with the large depletion factor. In green gram, RDI produced the highest yields, though the level at which the highest yields occurred changed between years. In 2003, RDI at the moderate depletion level produced the same seed yields as the recommended irrigation schedule, while seed yields decreased with the large depletion factor. In 2004, green gram yields increased with the use of the large depletion factor. For root biomass production, there was a strong interaction between crop and RDI. At the level of the large depletion factor, common bean increased root biomass yields while in green gram root biomass decreased.

The irrigation strategy did not have an effect on bean or green gram seed yields in 2003. In 2004, there was a strong interaction between the irrigation strategy and crop. Common bean yielded slightly less when alternate furrow irrigation was implemented compared to conventional furrow irrigation. Green gram yielded higher with alternate furrow irrigation. The irrigation strategy had no effect on the above ground biomass in 2003 and caused a decrease of 9% in 2004 when alternate furrow irrigation was used. It had no impact on root biomass yields.

3.2. Water use efficiency (WUE)

3.2.1. Crop effects

In both 2003 (Fig. 1) and 2004 (Fig. 2), the mean WUE_{seed} was approximately twice as large for green gram (0.45 and 0.54 kg m^{-3}) compared to common bean (0.26 and 0.34 kg m^{-3}). The differences between years were probably due to the different planting densities and, possibly, ground water contributions. $WUE_{biomass}$ was also over twice as large for green gram as bean in both 2003 (Fig. 3) and 2004 (Fig. 4). Averaged across all treatments, the ratio of WUE_{seed} to $WUE_{biomass}$, or the harvest index (HI), was smaller in green gram than bean in both 2003 (0.21–0.27) and 2004 (0.21–0.28), though this effect is considered minor relative to the larger magnitudes of the WUEs of green gram. WUE_{roots} (Fig. 5) was less, across all treatment combinations, for green gram, with an average value of 0.16 kg m^{-3} compared to 0.19 kg m^{-3} for common bean. Green gram invested proportionally more of its photosynthetic resources into yield and biomass production per unit of water transpired, whereas bean invested more heavily in root production.

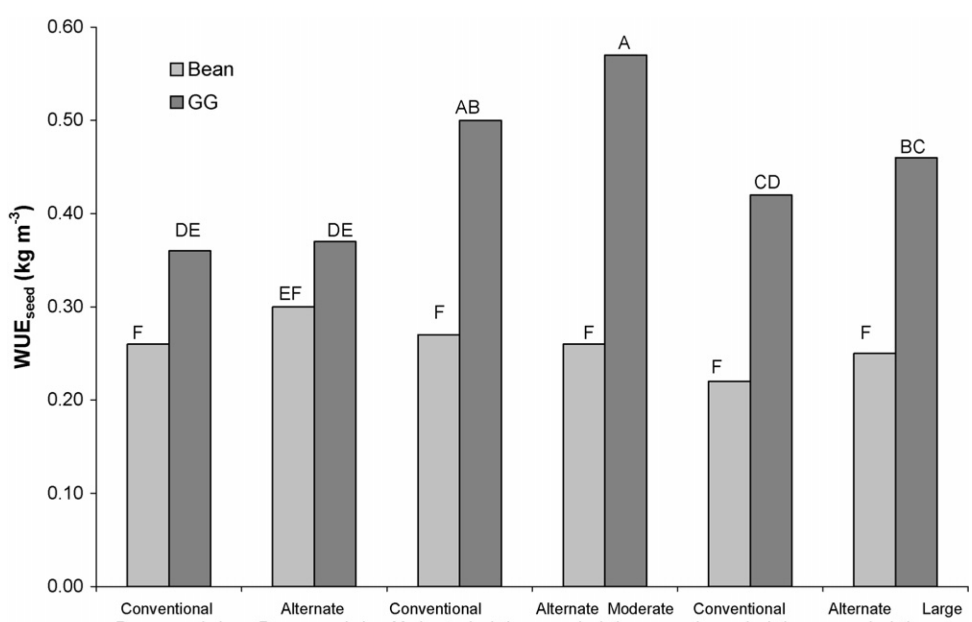

Fig. 1 – Commercial yield water use efficiency (WUE_{seed}) in 2003 for all treatments. Bars associated with the same letters are not different ($P \leq 0.05$) as determined using *t*-tests on least square means.

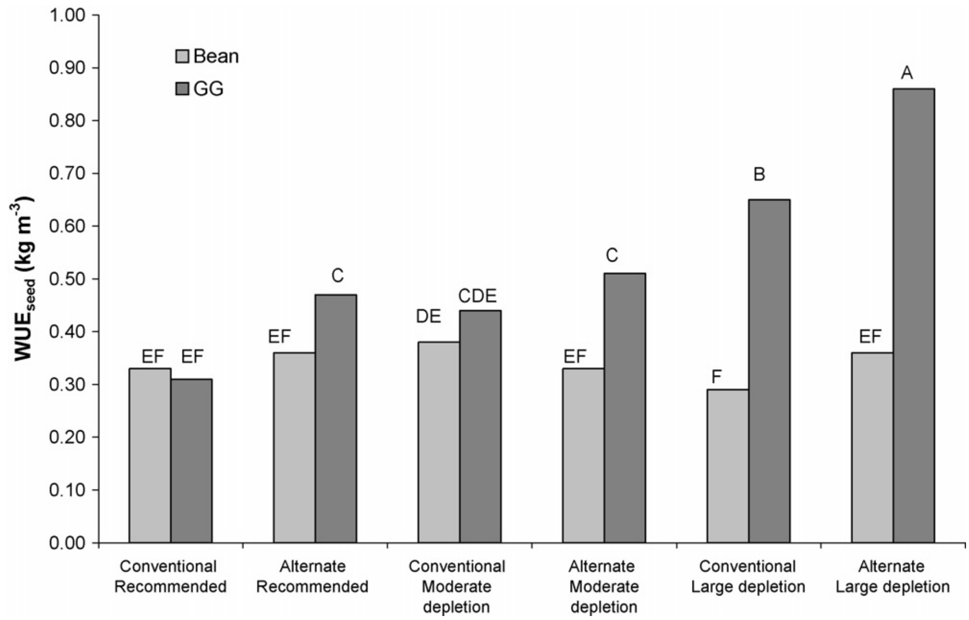

Fig. 2 – Commercial yield water use efficiency (WUE_{seed}) in 2004 for all treatments. Bars associated with the same letters are not different ($P \leq 0.05$) as determined using *t*-tests on least square means.

3.2.2. Irrigation schedule effect

When RDI was practiced the response of the two crops was very different. For common bean, WUE_{seed} remained constant across all treatment combinations at 0.26 kg m^{-3} (2003) and 0.34 kg m^{-3} (2004). Likewise, $WUE_{biomass}$ was constant across all stress levels. While WUE_{seed} and $WUE_{biomass}$ did not change when subjected to soil drying, the HI decreased at the severe stress level. WUE_{roots} increased to 0.23 kg m^{-3} with the large depletion factor, from 0.16 kg m^{-3} for the well-watered treatment. This indicates that bean sensed the water deficit in the soil and responded by investing more photosynthetic resources in root production per unit of water use in an attempt to extract more water. However, this strategy was not able to translate into increased values of WUE_{seed} or $WUE_{biomass}$. Green gram responded to RDI by increasing its WUE_{seed} by 48% (moderate depletion) in 2003 and 95% (large depletion) in 2004. With the use of RDI, $WUE_{biomass}$ also increased compared to the recommended depletion. Like common bean, green gram responded to the severe water stress by increasing its WUE_{roots}. However, while bean increased its root biomass under severe stress; green gram actually reduced its root biomass (Table 2). The increase in

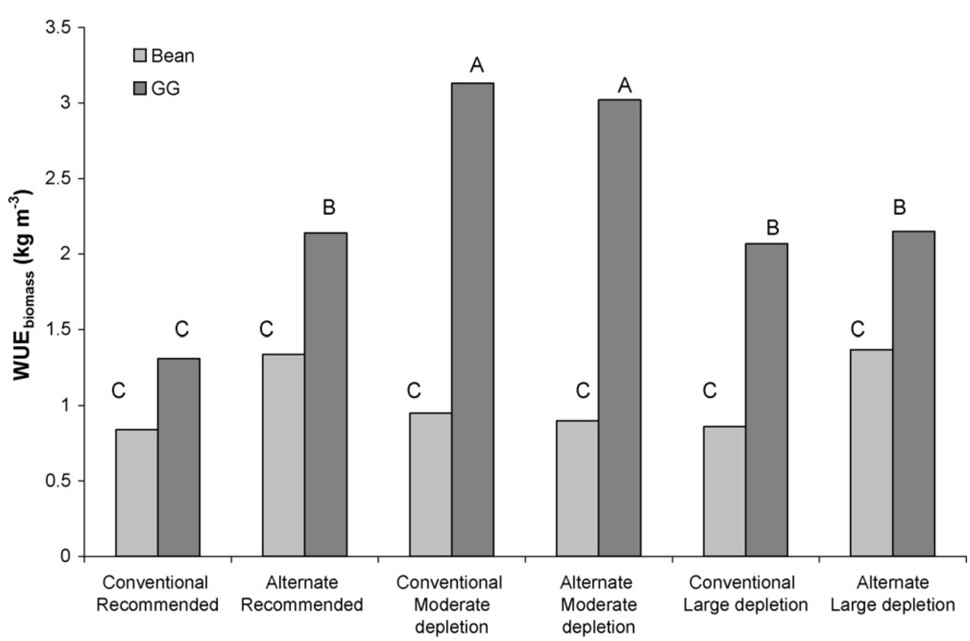

Fig. 3 – Total above ground biomass water use efficiency ($WUE_{biomass}$) in 2003 for all treatments. Bars associated with the same letters are not different ($P \leq 0.05$) as determined using *t*-tests on least square means.

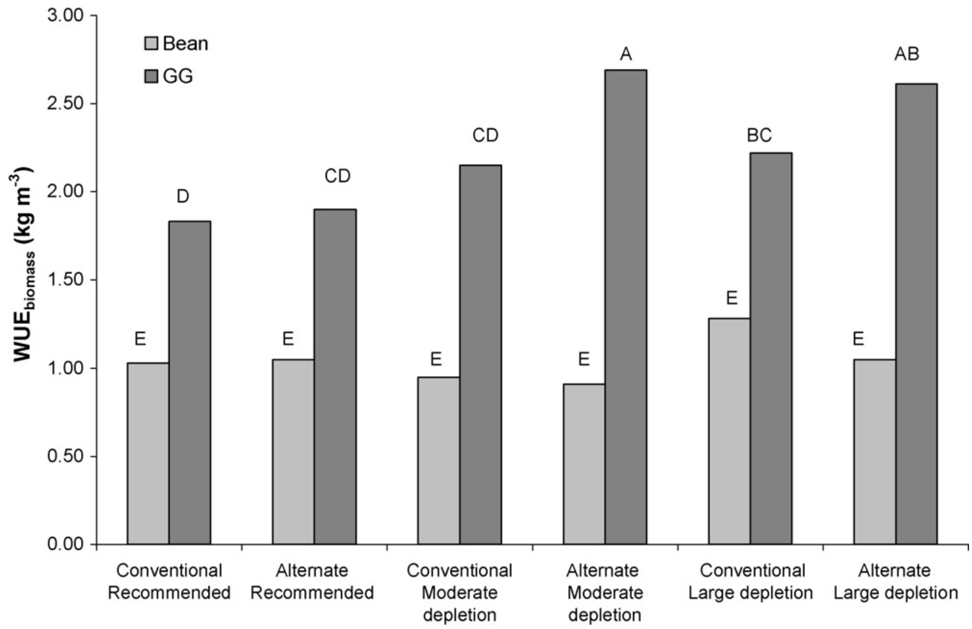

Fig. 4 – Total above ground biomass water use efficiency ($WUE_{biomass}$) in 2004 for all treatments. Bars associated with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

WUE_{roots} for green gram is therefore explained by the greatly reduced water use at the high stress level (Webber et al., unpublished manuscript). This suggests the two crops use very different mechanisms to respond to soil drying; bean produced more roots whereas green gram reduced its rate of water use.

The difference in the two crop's responses is further illustrated by looking at the HI. In 2004, at the recommended and moderate depletion levels, the HI was lower in green gram (0.21) than bean (0.37). At the severe stress level, the ratio was reversed; HI was greater for green gram (0.34) than bean (0.28), with the probability of significance taken as $P \leq 0.10$. Bean's decrease in HI with water stress was also evident in 2003 (18% decrease), though only statistically significant at the $P \leq 0.11$ level and the HI in green gram was the same at all levels of RDI. It seems clear that the two crops react oppositely under severe water stress; in bean, the HI decreases, whereas it remains the same or increases for green gram. It appears that under stress, bean partitions less of its resources to seed production and more to root production. The strategy to extract more water by developing more root biomass comes at the expense of seed production.

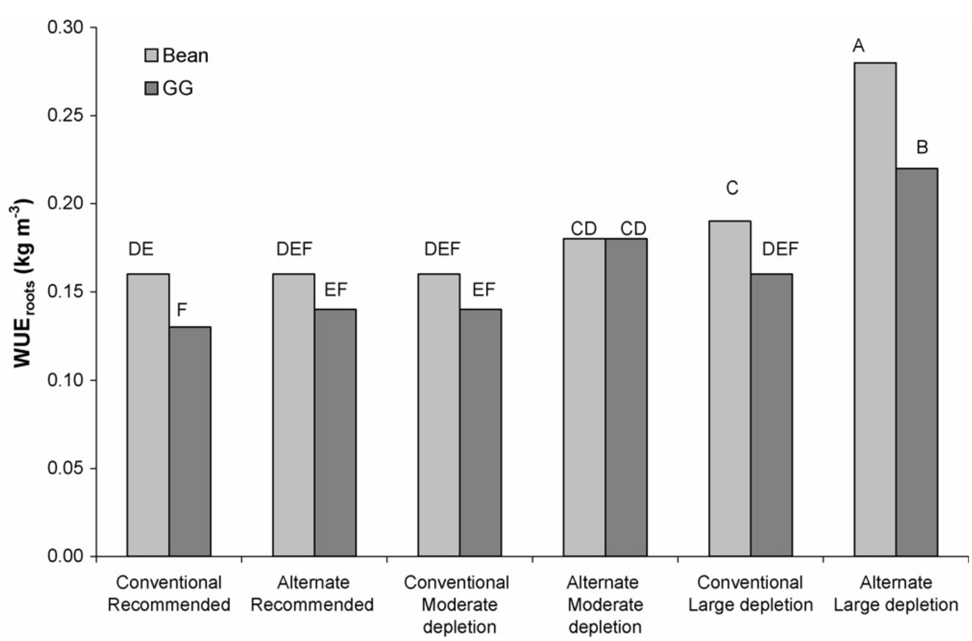

Fig. 5 – Root biomass water use efficiency (WUE_{roots}) in 2004 for all treatments. Bars associated with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

3.2.3. Irrigation strategy effects

The effect of alternate furrow irrigation on WUE_{seed} differed between the crops. Alternate furrow irrigation had no effect on the WUE_{seed} in common bean across all levels of water stress, contrary to the findings of Wakrim et al. (2005). In green gram, WUE_{seed} increased by 10% in 2003 ($P \leq 0.10$) and by 31% in 2004 compared to the conventional furrow irrigation treatments. The larger difference in 2004 is expected due to the modifications in irrigation scheduling as detailed in Section 2. There was no evidence of interaction between using alternate furrow irrigation and the level of water stress imposed on the WUE_{seed}. $WUE_{biomass}$ was unchanged in common bean by alternate furrow irrigation, and in green gram it was unchanged in 2003 and increased by 16% in 2004. WUE_{roots} increased in both crops when the strategy was used in combination with RDI.

3.3. Optimal irrigation schedule and irrigation water requirements

The volume of applied irrigation water given in Table 1 is the sum of the pre-irrigation, a small irrigation at the time of emergence and all subsequent irrigations. The climatic conditions were similar both years, with little variation in reference crop evapotranspiration (ET_0) between years (Fig. 6). Rainfall amounted to only 17 and 5 mm in 2003 and 2004, respectively.

Alternate furrow irrigation produced water savings of 25% for both crops at all irrigation levels in 2004. In our first attempt (in 2003) to find an optimal irrigation schedule using alternate furrow irrigation, average soil moisture values from both the wet and dry furrows were used for irrigation scheduling in the alternate furrow plots. As a consequence of this, the soil moisture values were always drier in the alternate furrow treatments. As a result, the alternate furrow plots were irrigated more frequently and, in 2003, no consistent pattern of water saving was realized compared to the corresponding conventional furrow irrigated plots. We decided that in extending the FAO 56 methodology for irrigation scheduling to alternate furrow irrigation systems, only the soil moisture in the wetted furrows should be considered to ensure water savings.

Based on the results of the two seasons of field work, it is possible to make irrigation recommendations to maximize the WUE_{seed} of green gram grown as a second crop in the Fergana Valley, and probably in a wider area of Central Asia. Implementing RDI and irrigating in alternate furrows produced the highest WUE_{seed}, yield and the greatest seasonal water savings. In 2003, there was no ground water contribution and the moderate depletion factor produced the highest WUE_{seed} with no yield losses. This involved a pre-seeding irrigation, a second small irrigation a few days after seedling emergence and two vegetative irrigations applied when the soil water depletion was 65%. In 2004, with a groundwater contribution (Table 1), the large depletion factor gave the highest WUE_{seed} and yields. This strategy included a pre-seeding irrigation, a second small irrigation at seedling emergence and one full irrigation when the soil water depletion reached 80%, coinciding with the time of flowering. Based on our findings for green gram's WUE and yield (Bourgault et al., unpublished manuscript), we conclude that the FAO irrigation recommendations for this crop (Allen et al., 1998) led to over irrigation and reduced yields.

Based on the results of this experiment, no irrigation recommendations can be suggested to maximize WUE for common bean. As WUE was constant for all levels of water stress and alternate furrow irrigation, any reduction in water use resulted in a corresponding reduction in yield. In deciding on an irrigation schedule, farmers would need to weigh the relative cost of yield losses with water savings in choosing an appropriate soil water depletion factor.

The differences in WUE between the two crops when subjected to soil water deficits clearly indicate that the crops employ different mechanisms in response to drought conditions and require different approaches for irrigation. When subjected to RDI at the large depletion level, the average irrigation requirement for green gram was reduced by 43% (2003) and 50% (2004) whereas the irrigation requirement for bean was reduced by only 15% (2003) and 22% (2004). Green gram's physiological response makes it an excellent crop to

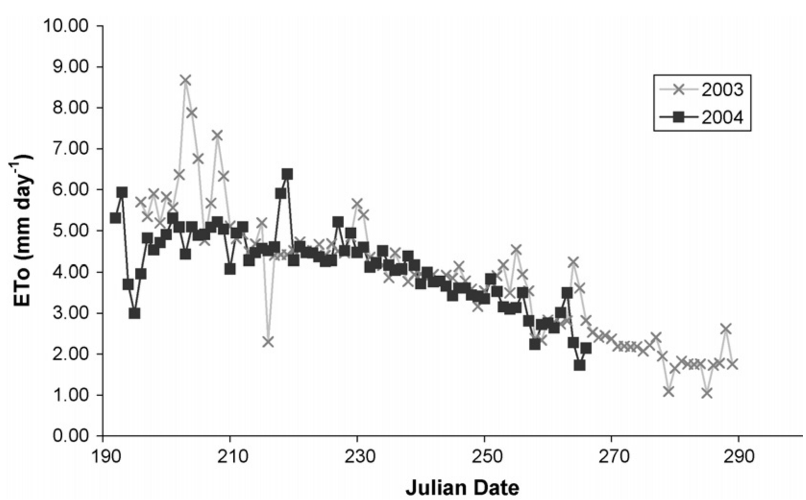

Fig. 6 – Comparison of the FAO Penman–Moneith reference crop evapotranspiration (ET_0) between years as determined at the experimental sites.

irrigate with alternate furrow and deficit irrigation techniques, both to save water and increase WUE. When subjected to soil drying, it has a mechanism that enables it to reduce its water consumption while maintaining yields. Common bean's physiological response to drought does not lend itself to either of the two water saving technologies. Unlike green gram, which appears to closely regulate its water use, common bean did not reduce its irrigation requirement, but invested in root development. Bean's strategy was not successful at improving its WUE_{seed} and any reduction in applied water resulted in yield reductions.

4. Conclusions

Both alternate furrow irrigation and deficit irrigation practices can reduce irrigation water requirements and increase water use efficiency, important considerations for arid and semi-arid climates. Consistent water savings, of close to 25%, are realised with alternate furrow irrigation over conventional furrow irrigation and when used in combination with deficit irrigation scheduling, water savings can be as large as 50% with no yield reductions, as compared to the recommended irrigation volumes. However, our study indicated that the success of these technologies depends largely on the ability of the crop to withstand and/or adapt to water stress. Green gram's WUE was twice that of common bean. When less water was applied to green gram, WUE doubled as compared to the recommended irrigation amounts. On the other hand, the commercial seed and above ground biomass WUEs of common bean were constant for all combinations of deficit irrigation and alternate furrow irrigation suggesting it is not as well adapted to water-scarce conditions.

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