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Competition among warm season C_4-cereals influence water use efficiency and competition ratios

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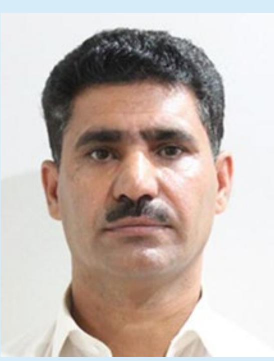
Abstract: Water use efficiency (WUE) and competition ratio (CR) response of three warm season C_4-cereals (grasses) viz. corn (*Zea mays* L., cv. Hybrid-5393 VT3), grain sorghum (*Sorghum bicolor* L. Moench, cv. Hybrid-84G62 PAT), and foxtail millets (*Setaria italic*, cv. German Strain R) in pure and mixed stands under low and high water levels was investigated. The experiment was conducted in pot experiment at Dryland Agriculture Institute, West Texas A&M University, Canyon, Texas, USA, during spring 2010. The objective of this study was to know whether the differences in the competitive ability of different crop species influence WUE or not? The planned mean comparison indicated that the corn WUE was 20, 11, and 6% higher in the mixed stand than in pure stand at 30, 60, and 90 days after emergence (DAE), respectively. The corn plants in pure stand had 91, 72, and 81% higher WUE than the average WUE of sorghum and millets in pure stand at 30, 60, and 90 DAE, respectively. Grain sorghum in pure stand had 70, 32, and 36% higher WUE than that of millets in pure stand at 30, 60, and 90 DAE, respectively. The WUE of three crops in mixed stand was 10 and 8% higher than the two crops mixed stand at the two early stages; but the WUE was 24% less in the three crops mixed stand than the two crops mixed stand at 90 DAE. Corn-mixed stand in two crops (average of corn + sorghum and corn + millets) had 78, 74, and 74% higher WUE than the mixed stand of sorghum and millets at 30, 60, and 90 DAE, respectively. Corn and millets mixed stand had 14, 10, and 26% higher WUE than the corn and sorghum mixed stand at 30, 60, and 90 DAE,



Amanullah

ABOUT THE AUTHOR

Amanullah is working as an associate professor in Agronomy, The University of Agriculture, Peshawar, Pakistan. He did his PhD in agronomy from the University of Agriculture, Peshawar in 2004, and postdoctorate from the Dryland Agriculture Institute, West Texas A&M University, Texas, USA in 2010. His field of interests includes Crop Nutrition, Crop Physiology, Crop Competition, Dryland Agriculture, and Crop Management under Stressful Environments. He has added more than 120 publications to his name, including 60 papers in the international impact factor journals. He has won the two consecutive research productivity awards from the Pakistan Council of Science and Technology, Islamabad in 2011–2012 and 2012–2013. So far, he has produced two PhDs students and more than 15 MSc (Hons) students.

PUBLIC INTEREST STATEMENT

Water use efficiency (WUE) and competition ratio (CR) response of three warm season C_4-cereals (corn, grain sorghum, and millets) in pure (sole crop) and mixed crops under low and high water levels was investigated. The three warm season cereals responded differently in terms of WUE and CR when grown in pure and mixed stands. Among the three crops under study, corn plants had the higher WUE and CR due to the highest total dry matter accumulation (shoots + roots) and was considered the best competitor, followed by sorghum, while millets stands in the bottom due to its less WUE and CR in mixed stands. This indicates that corn plants captured most of resources above and below the ground over time because of its well-developed shoots and roots. The results further confirmed that plant species with higher completion ratio in mixed stand have higher water use efficiency.

respectively. The increase in water level decreased WUE at the two late growth stages in all three crop plants. At the early growth stage (30 DAE), WUE increased in all crops at the higher water level. On the basis of CR, corn was found the best competitor, while millets was declared the least competitor in the mixed stands (corn > sorghum > millets). It was concluded that the higher the compatibility of a species in a mixed stands, the greater will be total biomass accumulation (corn > sorghum > millets) and hence WUE (corn > sorghum > millets).

Subjects: Environment & Agriculture; Bioscience; Food Science & Technology

Keywords: C_4 cereals; mixed stands; water levels; water use efficiency; land equivalent ratio; competition ratio

1. Introduction

Water use efficiency (WUE) can be affected by crop competition (Passioura, 2006) because each individual plant interacts (Sadras & Calderini, 2009) and competes with its neighbors both above and below ground (Rubio et al., 2001). Crop growth requires a number of resources, which are light, nutrients, and water. Several studies have shown that below-ground competition for water and nutrients can be stronger than above-ground competition for light (Casper & Jackson, 1997). The degree of competition among crop plants varies from species to species. Dubbs (1971) reported that Russian wild rye (*Elymus junceus* Fisch.) was the most competitive species and sainfoin (*Onobrychis viciaefolia* Scop.) the least competitive species, and that grasses yielded more when competing with legumes than when competing with each other. Alfalfa (*Medicago sativa* L.) plants received more competition from alfalfa plants than from plants of other species. In another study, Hanna, Kozub, and Smoliak (1977) found that total yield of the legume component in mixed stand was consistently higher for the alfalfa–grass than for the sainfoin–grass associations. Plants with contrasting root architecture may reduce the extent of competition among neighboring root systems, and the competition among roots of the same plant was three to five times greater than competition among roots of components species (Rubio et al., 2001). The yield of medic, in both pure and mixed stand, increased with increase in P rate up to 160 ppm P, and then decreased with further increase in P levels, and the Ryegrass plants benefited individually from growing in mixed stand with legume, producing as much shoot dry matter from three plants in mixture as from six in monoculture (Dahmane & Graham, 1981). It is generally believed that crop plants do not compete for space (Aldrich, 1984), but Wilson, Steel, and Steel (2007) found that competition for space can occur, but the effect is so small that that can be ignored in plant communities. Whenever two plants grow near one another, they will interact by altering the environment in which they grow, which will influence their acquisition of resources (light, water, and nutrients) and their growth (Sadras & Calderini, 2009). Plants can sense the presence of neighbors through changes in the ratio of red: far light even before the onset of competition for water and nutrients. There is some evidence that roots can respond to the presence of neighboring roots and can distinguish roots from the same plant and of neighboring plants (Sadras & Calderini, 2009).

According to Massinga, Currie, and Trooien (2003) and Van Wychen, Maxwell, Bussan, Miller, and Luschei (2004), total water use by weedy crops is similar to or greater than the water use of weed-free crops; but since the total dray matter accumulation is reduced, the WUE of a weedy crop will be lower than a weed-free crop. But according to Szente, Tuba, Nagy, and Csintalan (1993), WUE of fat hen (*Chenopodium album*) was significantly greater than that of sunflower (*Helianthus annuus*), when the two species were grown in mixed stand.

The part of this research work published recently (Amanullah & Stewart, 2013a) indicated that the three warm season grasses responded differently in terms of shoot-to-root ratio (S:R) when grown in pure and mixed stands under low and high water levels at different growth stages. In the mixed stands, the roots and shoot biomass accumulation in millets decreased while its S:R increased and was considered the least competitor in the mixed stands than sorghum and corn. Corn plants, on the other hand, with higher root and shoot biomass accumulation but lower S:R was ranked first (strong) in terms of competitiveness in the mixed stands. In contrast, grain sorghum in the mixed stands produced more root and shoot biomass while grown mixed with millets, but produced less root and shoot biomass in the corn mixed stands, and so was ranked second in terms of competitiveness (corn > grain sorghum > millets). Decreasing water level increased root biomass which declined the S:R in all three crop plants. With advancement in crop age, increase in shoot biomass was more than root biomass, and therefore, reduction in S:R was observed. There is lack of research on competition among warm season grasses in pure and mixed stand under low and high water levels. The objective of this experiment was to investigate the differences in WUE among warm season grasses (maize, sorghum, and millets) in pure and mixed stands in various combinations applied with low (water was applied to the pots up to field capacity when 100% of available water had been used)) and high (water was applied to the pots up to field capacity when 50% of available water had been used) water levels.

2. Materials and methods

2.1. Experimental site

WUE [the total dry matter accumulation (shoot plus root dry weights) per liter water used] response of three warm season C_4-grasses (the first stable product of photosynthesis is 4-carbon compound) viz. corn (*Zea mays* L., cv. Hybrid-5393 VT3), grain sorghum (*Sorghum bicolor* L. Moench, cv. Hybrid-84G62 PAT), and foxtail millets (*Setaria italic*, cv. German Strain R) was investigated in pure and mixed stands under low [(water was applied to the pots up to field capacity (the amount of water which a freely drained soil can hold) when 100% of available water had been used]) and high (water was applied to the pots up to field capacity when 50% of available water had been used) water levels in pot experiment at the green house of Dryland Agriculture Institute, West Texas A&M University, Canyon, Texas, USA during spring 2010.

2.2. Experimental design

The experiment was performed in completely randomized design with three repeats. There were seven grasses combinations [T_1 = corn in pure stand; 18 corn plants per pot, T_2 = grain sorghum in pure stand; 18 grain sorghum plants per pot, T_3 = foxtail millets in pure stand; 18 millets plants per pot, T_4 = corn and sorghum mixed stand; 9 plants each of corn and sorghum per pot, T_5 = corn and millets mixed stand; 9 plants each of corn and millets per pot, T_6 = sorghum and millets mixed stand; 9 plants each of sorghum and millets per pot, and T_7 = corn, sorghum, and millets mixed stand; 6 plants each of corn, sorghum, and millet per pot] and two water levels (high and low). A total of 100 ppm nitrogen (urea) was buried in each pot in two equal splits, i.e. 50% each at 7 and 60 DAE.

Potting mix called miracle grow was used as a soil medium in each pot. The volume of each pot was 6,283 cm^3, containing 2,000 g of potting mix (organic soil) pot^{-1}. Miracle grow is a formulated soil medium from 50–60% sphagnum peat moss, coconut husk fibers (coir pith), composted bark fines, wetting agent, and fertilizer. The nitrogen, phosphorus, and potassium sources have been coated to provide 0.10% slow release nitrogen (N), 0.10% slow release phosphate (P_2O_5), and 0.10% potash (K_2O). The bulk density (0.32 g cm^{-3}) and porosity (88%) for miracle grow was calculated in the green house.

Six plants were uprooted at 30, 60, and 90 DAE in each treatment. In case of T_1, $T_{2,}$ and T_3, six plants of the same crop were uprooted. In case of T_4, $T_{5,}$ and T_6, three plants of each crop were uprooted. But in case of T_7, two plants of each crop were uprooted. The roots of each crop were washed with tap water, and the plants were then divided into three parts i.e. roots, leaves, and stems. The materials was put in paper bags and then put in an oven at 80°C for about 20–24 h. The samples were weighed by electronic balance (*Sartorius Basic, BA2105*) and the average data on dry weight of root, leaf, and stem per plant was worked out. Shoot dry weight per plant was obtained by adding leaf dry weight with stem dry weight per plant. The sum of the shoot and root dry weight was calculated as the total dry weight per plant, and then WUE at each growth stage was calculated on the basis of total dry weight (shoot + root) using the procedures of Amanullah and Stewart (2013b).

2.3. Statistical analysis

Data on WUE at each growth stage were subjected to analysis of variance (ANOVA) according to the methods described in Steel and Torrie (1980) and treatment means were compared using the least significant difference (LSD) at $P \leq 0.05$. The complete ANOVA is given in Table 1. The planned mean comparisons of various treatments at 30, 60, and 90 DAE are given in Tables 2–4, respectively.

2.4. Competition indices

At 90 DAE, the total dry matter yield advantage of mixed crops was determined by calculating land equivalent ratio (LER) and CR. The LER is defined as the amount of land required under sole crop to obtain the same dry matter yield as produced in the mixed crop. The LER > 1 is beneficial and 1 < is harmful. The LER was calculated as follows:

Table 1. Analysis of variance for water use of warm season C_4-grasses (average) grown alone in pure and mixed stands under low and high water levels at 30, 60 and 90 days after emergence

Source of variance	Degree of freedom	Level of significance (DAE)		
		30 DAE	60 DAE	90 DAE
Replications	[2]	ns	ns	ns
Treatments (crops × water levels)	[13]	***	***	***
Water levels	{1}	***	***	***
Crops combinations	{6}	***	***	***
Sole vs. corn in combination	(1)	***	ns	ns
Corn vs. sorghum + millets	(1)	***	***	***
Sorghum vs. millets	(1)	***	ns	ns
2 crops vs. 3 crops	(1)	***	ns	*
Corn in 2 crops vs. no corn in 2 crops	(1)	***	***	***
Corn + sorghum vs. corn + millets	(1)	***	ns	**
Water levels × Crops combination	{6}	***	ns	***
Error	[26]			
Total	[41]			

*Significant at 5% level of probability.
**Significant at 1% level of probability.
***Significant at 0.1% level of probability.
ns means non-significant.

Table 2. Pre-planned mean comparisons and significance of differences in WUE of warm season C_4-grasses (average) grown alone in pure and mixed stands at first cut (30 DAE)

Comparisons	Mean 1	Mean 2	Difference	Significance
Sole corn vs. corn in combination	0.287	0.360	0.073	***
Corn vs. sorghum + millets	0.730	0.065	−0.665	***
Sorghum vs. millets	0.099	0.030	−0.069	***
2 crops vs. 3 crops	0.350	0.388	0.038	***
Corn in 2 crops vs. no corn in 2 crops	0.472	0.106	−0.365	***
Corn + sorghum vs. corn + millets	0.436	0.507	0.071	***

***Significant at 0.1% level of probability.
ns means non-significant.

Table 3. Pre-planned mean comparisons and significance of differences in WUE of warm season C_4-grasses (average) grown alone in pure and mixed stands at second cut (60 DAE)

Comparisons	Mean 1	Mean 2	Difference	Significance
Sole corn vs. corn in combination	1.455	1.641	0.186	ns
Corn vs. sorghum + millets	2.801	0.782	−2.019	***
Sorghum vs. millets	0.932	0.633	−0.298	ns
2 crops vs. 3 crops	1.604	1.751	0.147	ns
Corn in 2 crops vs. no corn in 2 crops	2.132	0.548	−1.585	***
Corn + sorghum vs. corn + millets	2.023	2.241	0.218	ns

***Significant at 0.1% level of probability.
ns means non-significant.

Table 4. Pre-planned mean comparisons and significance of differences in WUE of warm season C_4-grasses (average) grown alone in pure and mixed stands at third cut (90 DAE)

Comparisons	Mean 1	Mean 2	Difference	Significance
Sole corn vs. corn in combination	7.978	7.524	−0.455	ns
Corn vs. sorghum + millets	17.424	3.256	−14.168	***
Sorghum vs. millets	3.971	2.541	−1.430	ns
2 crops vs. 3 crops	7.999	6.098	−1.900	*
Corn in 2 crops vs. no corn in 2 crops	10.620	2.756	−7.864	***
Corn + sorghum vs. corn + millets	9.062	12.178	3.117	**

*Significant at 5% level of probability.
**Significant at 1% level of probability.
***Significant at 0.1% level of probability.
ns means non-significant.

$$\text{LER} = \frac{\text{TDM yield of crop in mixed cropping}}{\text{TDM yield of sole crop}}$$

The CR gives an assessment whether the association of the two component crops is advantageous or not. In other words, the CR gives a clear idea about which crop is more competitive and which crop is less competitive in the association. The CR was calculated as follows:

CR for corn (a) grown mixed in sorghum (b): $\text{CRa} = (\text{LERa}/\text{LERb}) \times (\text{Zba}/\text{Zab})$

CR for corn (a) grown mixed in millets (c): $\text{CRa} = (\text{LERa}/\text{LERc}) \times (\text{Zca}/\text{Zac})$

CR for sorghum (b) grown mixed in corn (a): $\text{CRb} = (\text{LERb}/\text{LERa}) \times (\text{Zab}/\text{Zba})$

CR for sorghum (b) grown mixed in millets (c): $\text{CRb} = (\text{LERb}/\text{LERc}) \times (\text{Zcb}/\text{Zbc})$

CR for millets (c) grown mixed in corn (a): $\text{CRc} = (\text{LERc}/\text{LERa}) \times (\text{Zac}/\text{Zca})$

CR for millets (c) grown mixed in sorghum (b): $\text{CRc} = (\text{LERc}/\text{LERc}) \times (\text{Zbc}/\text{Zcb})$

where Zab = proportion of species "a" grown in association with species "b"; Zba = proportion of species "b" grown in association with species "a"; and so on. If CRa > 1, it indicates that species a (corn) is more competitive than species b (sorghum) and if CRa < 1, it indicates a (corn) is less competitive than b (sorghum) and so on. This gives a clear idea about which crop is more competitive in association.

3. Results

3.1. Corn

WUE of corn plants was greater at high water level (HWL) (0.91 g L^{-1}) than low water level (LWL) (0.79 g l^{-1}) at 30 DAE (Table 5). The WUE reached maximum (0.98 g L^{-1}) when corn plants were grown in mixed stand with sorghum + millets, and the higher increase was noticed at HWL (1.04 g L^{-1}) than at LWL (0.92 g L^{-1}). The WUE decreased to 0.71 g L^{-1} in corn and sorghum mixed stand, and 0.73 g L^{-1} in pure corn stand, and the higher decrease in both cases was noticed at LWL than at HWL. At second cut (60 DAE), corn plants had higher WUE at LWL (5.23 g L^{-1}) than at HWL (2.77 g L^{-1}). The WUE ranked first (4.99 g L^{-1}) when corn was grown with sorghum + millets mixed stand, and the higher increase was noticed at LWL (5.90 g L^{-1}) than at HWL (4.08 g L^{-1}). The WUE reduced significantly to 2.80 g L^{-1} when corn was grown alone in pure stand, and the higher reduction was observed at HWL

Table 5. WUE (g L^{-1}) response of corn when grown alone in pure and mixed stands with sorghum and millets under low and high water levels

Crops combination	30 days after emergence			60 days after emergence			90 days after emergence		
	HWL	LWL	Mean	HWL	LWL	Mean	HWL	LWL	Mean
Corn (C) alone	0.75	0.71	0.73	1.51	4.09	2.80	10.47	24.38	17.42
Corn in sorghum (S)	0.75	0.67	0.71	2.54	5.09	3.81	9.63	25.09	17.36
Corn in millets (M)	1.11	0.85	0.98	2.94	5.83	4.39	21.34	26.31	23.83
Corn in S + M	1.04	0.93	0.99	4.08	5.90	4.99	8.82	26.91	17.87
Mean	**0.91**	**0.79**	**0.85**	**2.77**	**5.23**	**4.00**	**12.57**	**25.67**	**19.12**
$LSD_{0.05}$									
Water levels	0.02			0.69			1.71		
Crops combination	0.04			ns			4.69		
Interaction	0.06			2.67			6.63		

Notes: Where HWL stands for high water level (water was applied to the pots up to field capacity when 50% of available water had been used)) and LWL stands for low water level (water was applied to the pots up to field capacity when 100% of available water had been used).

Table 6. Total dry matter plant^{-1}(TDMPP), land equivalent ratio (LER) and CR of corn, sorghum and millets at 90 DAE

Crop stands	TDMPP (g plant^{-1})	LER	CR
Response of corn			
Corn as sole crop	22.37	1.00	1.00
Corn grown mixed with sorghum	22.02	0.98	5.66
Corn grown mixed with millets	32.93	1.47	7.38
Corn grown mixed in sorghum + millets	22.13	0.99	0.88
Response of sorghum			
Sorghum as sole crop	5.29	1.00	1.00
Sorghum grown mixed with corn	0.92	0.17	0.18
Sorghum grown mixed with millets	5.92	1.12	3.05
Sorghum grown mixed in corn + millets	0.35	0.07	0.06
Response of millets			
Millets as sole crop	3.16	1.00	1.00
Millets grown mixed with corn	0.63	0.20	0.14
Millets grown mixed with sorghum	1.16	0.37	0.33
Millets grown mixed in corn + sorghum	0.20	0.06	0.06

Notes: TDMPP of each crop was calculated as sum of the root and shoot dry weights plant^{-1} (g) at 90 DAE.

(1.51 g L^{-1}) than at LWL (4.09 g L^{-1}). At third cut (90 DAE), corn had high WUE (25.67 g L^{-1}) at LWL than at HWL (12.57 g L^{-1}). The WUE reached maximum (23.83 g L^{-1}) when corn was grown mixed with millets, and the higher increase was noticed at LWL (26.31 g L^{-1}) than at HWL (21.34 g L^{-1}). The WUE reduced significantly to 17.36, 17.42, and 17.87 g L^{-1} in corn + sorghum mixed stand, pure corn stand, and corn + sorghum + millets mixed stand, respectively. Interestingly, the significant reduction in all these three cases was observed at HWL as compared with LWL. The LER values greater than one was calculated for corn when grown mixed with millets (1.47), while the CR values were greater than one for corn when grown either mixed with sorghum (5.66) or mixed with millets (7.38) as shown in Table 6. These results confirmed that corn was the best competitor than sorghum and millets when corn was grown either with sorghum or millets (corn > sorghum > millets).

3.2. Grain sorghum

WUE of sorghum plants was higher under HWL (0.15 g L^{-1}) than LWL (0.14 g L^{-1}) at 30 DAE (Table 7). The WUE reached maximum (0.17 g L^{-1}) when sorghum plants were grown in mixed stand with millets, and the higher increase was noticed at HWL (0.20 g L^{-1}) than at LWL (0.13 g L^{-1}). The WUE reduced significantly to 0.09 g L^{-1} when sorghum was grown alone in pure stand, and the higher decrease was noticed at LWL than at HWL. At second cut (60 DAE), sorghum had higher WUE at LWL (0.77 g L^{-1}) than at HWL (0.34 g L^{-1}). The WUE ranked first (0.93 g L^{-1}) when sorghum was grown alone in pure stand, and the higher increase was noticed at LWL (1.10 g L^{-1}) than at HWL (0.76 g L^{-1}). The WUE reduced significantly to 0.22 g L^{-1} when sorghum was grown in mixed stand with millets although there was no difference in WUE of the two water levels. At third cut (90 DAE), sorghum had high WUE (3.25 g L^{-1}) at LWL than at HWL (1.55 g L^{-1}). The WUE reached maximum (4.59 g L^{-1}) when sorghum was grown mixed with millets, and the higher increase was noticed at LWL (6.35 g L^{-1}) than at HWL (2.84 g L^{-1}). The WUE reduced significantly to 0.28 g L^{-1} when sorghum was grown mixed with millets, and the higher reduction in WUE was observed at HWL than at LWL. The LER value greater than one (1.12) and CR value greater than one (3.05) for sorghum were calculated when sorghum was grown mixed with millets (Table 6), indicating that sorghum was stronger competitor than millets in the sorghum + millets mixed stand (sorghum > millets) and less competitor than corn in sorghum + corn mixed stand (sorghum < corn).

3.3. Millets

Like corn and sorghum, WUE of millets was also higher under HWL (0.037 g L^{-1}) than at LWL (0.033 g L^{-1}) at 30 DAE (Table 8). The WUE reached maximum (0.042 g L^{-1}) when millets was grown together with sorghum, and the higher increase was noticed at HWL (0.047 g L^{-1}) than at LWL

Table 7. WUE (g L^{-1}) response of grain sorghum when grown alone in pure and mixed stands with corn and millets under low and high water levels

Crops combination	30 days after emergence			60 days after emergence			90 days after emergence		
	HWL	LWL	Mean	HWL	LWL	Mean	HWL	LWL	Mean
Sorghum (S) alone	0.11	0.09	0.10	0.76	1.10	0.93	2.96	4.98	3.97
Sorghum in corn (C)	0.15	0.17	0.16	0.12	0.34	0.23	0.27	1.26	0.76
Sorghum in millets (S)	0.20	0.14	0.17	0.26	1.42	0.84	2.84	6.35	4.59
Sorghum in C + M	0.13	0.17	0.15	0.22	0.22	0.22	0.14	0.41	0.28
Mean	0.15	0.14	0.15	**0.34**	**0.77**	**0.56**	**1.55**	**3.25**	**2.40**
$LSD_{0.05}$									
Water levels	ns			0.15			0.54		
Crops combination	0.01			0.40			1.49		
Interaction	0.02			0.57			2.11		

Notes: Where HWL stands for high water level (water was applied to the pots up to field capacity when 50% of available water had been used)) and LWL stands for low water level (water was applied to the pots up to field capacity when 100% of available water had been used).

Table 8. WUE (g L^{-1}) response of millets when grown alone in pure and mixed stands with corn and sorghum under low and high water levels

Crops combination	30 days after emergence			60 days after emergence			90 days after emergence		
	HWL	LWL	Mean	HWL	LWL	Mean	HWL	LWL	Mean
Millets (M) alone	0.032	0.028	0.030	0.53	0.74	0.63	1.23	3.85	2.54
Millets in corn (C)	0.035	0.039	0.037	0.05	0.14	0.09	0.17	0.89	0.53
Millets in sorghum (S)	0.047	0.037	0.042	0.29	0.21	0.25	0.48	1.36	0.92
Millets in C + S	0.033	0.028	0.030	0.03	0.05	0.04	0.10	0.20	0.15
Mean	**0.037**	**0.033**	**0.035**	**0.23**	**0.28**	**0.26**	**0.50**	**1.58**	**1.04**
$LSD_{0.05}$									
Water levels	0.0007			0.04			0.16		
Crops combination	0.002			0.11			0.45		
Interaction	0.003			0.16			0.64		

Notes: Where HWL stands for high water level (water was applied to the pots up to field capacity when 50% of available water had been used)) and LWL stands for low water level (water was applied to the pots up to field capacity when 100% of available water had been used).

(0.037 g L^{-1}). The WUE reduced significantly to 0.030 g L^{-1} when millets was grown mixed with sorghum, being at par with millets in the pure stand (0.030 g L^{-1}), and the higher reduction in both cases was noticed at LWL than at HWL. At second cut (60 DAE), millets had higher WUE at LWL (0.28 g L^{-1}) than at HWL (0.23 g L^{-1}). The WUE ranked first (0.63 g L^{-1}) when millets was grown alone in pure stand, and the higher increase was noticed at LWL (0.74 g L^{-1}) than at HWL (0.53 g L^{-1}). The WUE reduced significantly to 0.04 g L^{-1} when millets was grown mixed with corn, and the higher reduction was noticed at HWL (0.03 g L^{-1}) than at LWL (0.05 g L^{-1}). At third cut (90 DAE), millets had higher WUE (1.58 g L^{-1}) at LWL than at HWL (0.50 g L^{-1}). The WUE reached maximum (2.54 g L^{-1}) when millets was grown alone in pure stand, and the higher increase was noticed at LWL (3.85 g L^{-1}) than at HWL (1.23 g L^{-1}). The WUE reduced significantly to 0.15 g L^{-1} when millets was grown mixed with both corn and sorghum, and the higher reduction in WUE was observed at HWL than LWL. All the LER and CR values were less than one for millets when grown in corn or grown in sorghum (Table 6), indicating that millets was least competitor than corn in the corn + millets mixed stand (millets < corn) and least competitor than sorghum in millets + sorghum mixed stand (millets < sorghum).

3.4. Crops average

The average WUE of the three summer grasses was higher (0.34 g L^{-1}) at HWL than LWL (0.30 g L^{-1}) at 30 DAE ($P \le 0.05$), as shown in Table 9. The WUE ranked first (0.730 g L^{-1}) when corn was grown alone in pure stand, followed by the average of corn + millets mixed stand (0.507 g L^{-1}). The WUE reduced to minimum (0.03 g L^{-1}), when millets was grown alone in pure stand. At second cut (60 DAE), WUE was higher (2.07 g L^{-1}) at LWL than HWL (1.05 g L^{-1}). The WUE reached to maximum (2.80 g L^{-1}) when corn was grown alone in pure stand, being at par with the average of corn + sorghum (2.02 g L^{-1}) and corn + millets (2.24 g L^{-1}) mixed stands; while WUE reduced to minimum (0.54 g L^{-1}) in the sorghum + millets mixed stand. At third cut (90 DAE), WUE at LWL was higher (10.43 g L^{-1}) than at HWL (5.00 g L^{-1}). The WUE reached to maximum (17.42 g L^{-1}) when corn was grown alone in pure stand, followed by corn + millets mixed stand (12.17 g L^{-1}); while WUE reduced to minimum (2.54 g L^{-1}) when millets was grown alone in pure stand, being at par with pure sorghum stand (3.971 g L^{-1}) and sorghum + millets mixed stand (2.756 g L^{-1}).

4. Discussion

The higher WUE of corn at HWL than LWL at the early stage (30 DAE) was obtained because of the delay in emergence of corn plants at low than at high water level. The early emergence at HWL resulted in more dry matter accumulation in corn that increased the WUE. According to Sadras and

Table 9. Average WUE (g L^{-1}) response of summer cereals when grown alone in pure and mixed stands under low and high water levels

Crops combinations	30 days after emergence			60 days after emergence			90 days after emergence		
	HWL	LWL	Mean	HWL	LWL	Mean	HWL	LWL	Mean
Corn (C) alone	0.74	0.71	0.73	1.50	4.09	2.80	10.46	24.37	17.42
Sorghum (S) alone	0.11	0.08	0.09	0.76	1.10	0.93	2.96	4.98	3.97
Millets (M) alone	0.03	0.02	0.03	0.52	0.73	0.63	1.22	3.85	2.54
Average of C + S	0.45	0.42	0.43	1.33	2.71	2.02	4.94	13.17	9.06
Average of C + M	0.57	0.44	0.50	1.49	2.98	2.24	10.79	13.59	12.17
Average of S + M	0.12	0.08	0.10	0.27	0.81	0.54	1.65	3.85	2.75
Average of C + S + M	0.40	0.37	0.38	1.44	2.05	1.75	3.02	9.17	6.09
Mean	**0.34**	**0.30**	**0.32**	**1.05**	**2.07**	**1.56**	**5.00**	**10.43**	**7.71**
$LSD_{0.05}$									
Water levels	0.01			0.53			1.19		
Crops combination	0.01			1.00			2.23		
Interaction	0.02			1.42			3.16		

Notes: Where HWL stands for high water level (water was applied to the pots up to field capacity when 50% of available water had been used)) and LWL stands for low water level (water was applied to the pots up to field capacity when 100% of available water had been used).

Calderini (2009), there has been emerging evidence of the importance of early crop vigor for competitive ability of crop plants. The increase in corn WUE at 30 DAE was due to taller plants, higher leaf area per plant (unpublished data), higher crop growth rate (Amanullah, 2014b), shoot and root dry weights (Amanullah & Stewart, 2013a) in mixed stands with millets (corn + millets) or mixed with both sorghum and millets (corn + sorghum + millets). The increase in WUE with increase in CGR was earlier reported by Amanullah and Stewart (2013b). The very well-developed canopy and root architecture of corn plants had negative impacts on the growth and total dry matter accumulation of millets and sorghum plants that adversely reduced the WUE of both sorghum and millets in the corn mixed stands. Likewise, Bazzaz (1998) reported that plant parts in space and their mode of display (plant architecture) are very important in plant–plant interactions. The intra-plants competition among corn plants in pure (sole) stand reduced shoots and roots dry weights (Amanullah & Stewart, 2013a), and so the WUE of corn plants was declined in the pure stand. This indicates that corn plants in the pure stand were quite competitive among themselves. According to Dubbs (1971), sole alfalfa plants received more competition from other alfalfa plants than from plants of other species. The reduction in WUE of corn plants was noticed when corn was grown mixed with sorghum (corn + sorghum) than corn + millets mixed stand indicating that the sorghum plants competed very well with corn than sorghum. Millets plants don't have much negative impact on the corn WUE, on the other hand, sorghum with well-developed canopy, root distribution, and number (data not shown) had more adverse effects on corn plants. According to Sorrensen-Cothern, Ford, and Sprugel (1993), measurement of canopy architecture is very important in crop–crop competition. The lower WUE of corn plants at high than at low water level at 60 and 90 DAE was due to the inefficient use of water by corn plants. On the other hand, in case of shortage of water under low water level, the corn plants used the water more efficiently and thereby increased WUE. The increase in the WUE of corn plants when it was grown mixed stand with sorghum and millets mixed stand (corn + sorghum + millets) was due to the reduction in the crop growth rate (Amanullah, 2014b) and total dry weights of both millets and sorghum (Amanullah & Stewart, 2013a) in the mixed stand. The strong intra-plants competition among the corn plants in the pure stand reduced the CGR, and shoots and roots dry weights that resulted in the lower WUE. According to Rubio et al. (2001), competition among roots of the same plant was three to five times greater than competition among roots of neighboring plants. Rubio et al. (2001) reported that competition among plants occur both above and below ground. The above-ground competition involves one principal resource (light); below-ground competition encompasses a broader spectrum of resources, including water and all the essential mineral nutrients. Root architecture of corn plants in the mixed stand was very well established than that of sorghum and millets, and therefore corn plants probably may have taken more nutrients and water than the two crops. According to Casper and Jackson (1997), below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground com-petition. The increase in the WUE of corn plants when it was grown mixed with millets (corn + millets) was due to the reduction in the growth of millets and also the reduction in intra-plants competition among the corn plants. On the other hand, including sorghum in the mixed stands with corn (corn + sorghum or corn + sorghum + millets) had negative impacts on the root length and root dry weight of corn plants that resulted in the lower corn WUE. Rubio et al. (2001) reported that plants with contrasting root architecture may reduce the extent of competition among neighboring root systems.

When sorghum was grown mixed with other crops, its plant heights, and stem and leaf dry weights increased that resulted in the higher WUE of sorghum at 30 DAE. At the early growth stage, sorghum reduced its plant heights; leaf area and shoot dry weight (unpublished data) that declined its WUE in the pure stand because the emergence was delayed in the pure stand than in the mixed stand. Sadras and Calderini (2009) suggested the importance of early crop vigor for competitive ability in crop–crop competition. Similar to corn plants, the lower WUE of sorghum at high than at low water level was attributed to the negative effects of high water level on plant height, root length, leaf area, and shoot and root dry weights of sorghum (Amanullah & Stewart, 2013a) at 60 DAE. Sadras and Calderini (2009) reported that plant height tend to be the most common shoot trait implicated in competitive ability of different crops. The increase in the WUE of sorghum when it was grown alone in pure or mixed stand with millets (sorghum + millets) was due to the increase in shoot and root dry weights of sorghum over millets. But including corn in the mixtures with sorghum (corn + sorghum or corn + sorghum + millets) had negative impacts on both shoot and root growth of sorghum that declined the WUE. The higher leaf area per plant and root dry weights of corn plants had negative influence on the shoot and root dry weights and WUE of sorghum, indicating that corn was more competitive than sorghum in the mixed stand. Caldwell, Dean, Nowak, Dzurec, and Richards (1983) suggested that the species with higher root density may be more competitive than the species with lower root density. Moreover, different species demand different quantities of resources from their environment, and so different species will have different impacts on their neighborhoods (Bazzaz, 1998). The lower WUE of sorghum plants (90 DAE) at high than at low water level was attributed to the negative effects of high water level on plant height, root length, leaf area, and shoot and root dry weights of sorghum (data not shown). The increase in the WUE of sorghum when it was grown alone in pure or mixed stand with millets (sorghum + millets) was due to the increase in shoot and root dry weights of sorghum over millets. On the other hand, the higher leaf area per plant, and root and shoot dry weights of corn plants in the mixed stand with sorghum (corn + sorghum or corn + sorghum + millets) had negative influence on the shoot and root dry weights of sorghum that resulted in the lower WUE of sorghum in the mixed stand. Rubio et al. (2001) reported that competition among plants occur both above and below ground. According to Casper and Jackson (1997), the below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground competition.

The higher WUE of millets at high than at low water level at 30 DAE was because of the delay in emergence at low than at high water level. Sadras and Calderini (2009) suggested the importance of early crop vigor for competitive ability of crop plants. At the early growth stage, millets reduced its plant heights, leaf area, and shoot dry weight when it was grown in mixed stand with other crops that decreased the WUE, indicating that millets was less competitive than corn and sorghum. The higher leaf, stem, and root dry weight of millets when it was grown mixed with sorghum (sorghum + millets) under high water level resulted in the higher WUE of millets at 60 DAE. The increase in the WUE when millets was grown alone in pure stand was due to the increase in shoot and root dry weights of millets, indicating less intra-plants competition among the millets than in the inter-plants competition in the mixed stands. The higher leaf area and taller plants (canopy architecture); deeper roots, more number of roots, and higher root dry weight of corn plants

(Amanullah & Stewart, 2013a) had negative influence on the shoot and root dry weights of millets plants, and so the WUE of millets was reduced. Competition among crop plants occur both above and below ground (Rubio et al., 2001), and therefore, measurement of canopy architecture is important in crop–crop competition (Sorrensen-Cothern et al., 1993). As compared to corn, that declined the WUE of millets to minimum, sorghum plants had little influence on the shoot and root dry weights as well as the WUE of millets.

The lower WUE of millets (90 DAE) at high than at low water level was attributed to the negative effects of high water level on plant height, root length, leaf area, and shoot and root dry weight of millets (data not shown). When corn was included in the mixtures with millets (corn + millets or corn + sorghum + millets), negative impacts on the shoot and root development of millets decreased the total plant dry weight of millets, and so the WUE was reduced. The higher leaf area, and root and shoot dry weight of corn in the mixture had negative influence on the root and shoot dry weights of millets that had negative influence on the total plant dry weight and WUE of millets. On the other hand, sorghum plants had little negative influence on the shoot and root dry weights as well as the WUE of millets. In the pure stand, WUE of millets was increased due to the increase in leaf area per plant, plant height, and shoot and root dry weights indicating less intra-plants competition in millets. Massinga et al. (2003) and Van Wychen et al. (2004) reported that the WUE of a weedy crop (mixed stand) will be lower than a weed-free crop (pure stand). According to Amanullah (2014b), among the three summer cereal crops, corn plants had the higher crop growth rate due to its highest total dry matter accumulation in both shoots and roots and was considered the best competitor in all the mixed stands. Grain sorghum ranked second in terms of crop growth rate, while foxtail millets ranked in the bottom in terms of competitiveness and crop growth rate in the mixed stands. The WUE of these crops had positive relationship with crop growth rate.

The higher average WUE of summer grasses at high than at low water level at 30 DAE was because of the delay in emergence at low than at high water level. Advantage of early crop vigor in crop–crop competition is earlier reported by Sadras and Calderini (2009). The WUE of corn in pure stand was the highest than all other treatments due the highest shoot and root dry weights of corn. The corn plants were considered the most competitive, sorghum ranked second, while the millets plants were least competitive in the mixed stand and stood in the bottom in the ranking. The corn plants had very faster CGR when it was grown mixed with millets; therefore, the combination of corn + millets mixed stand had the second highest WUE. According to Moony (1976), among the plants, which normally use the same set of resources, the individual that captures the most resources over time is assumed to be the most successful competitor and potentially the most fertile producer. The contribution of millets in the corn + millets mixture was very less because the corn plants suppressed adversely the shoot and root growth of millets. The highest WUE of corn in the pure stand was attributed to the highest shoot and root dry weights of corn. Similarly, corn had the highest shoot and root dry weights when it was grown mixed with millets (corn + millets) that resulted in the second highest WUE. The lowest shoot and root dry weights produced by sorghum and millets mixed stand or pure stands of sorghum and millets had the lowest WUE at 60 DAE. The WUE of corn in pure stand was the highest than all other treatments due the highest shoot and root dry weights of corn plants. The corn plants also had the highest shoot and root dry weights when it was grown mixed with millets; therefore, the combination of corn + millets mixed stand also had the second highest WUE at 90 DAE. Amanullah (2014a) reported the higher WUE of wheat and rye under organic soils than inorganic soils, which was due to the higher dry matter accumulation and partitioning into shoots and roots. There was positive relationship between total dry weight plant^{-1} and WUE (Amanullah, 2014a). Although, the contribution of millets plants in the corn + millets mixed stand was very less because the corn plants suppressed the shoot and root dry development of millets adversely. The corn plants were considered the most competitive, followed by sorghum, while the millets plants were least competitive in different mixed stands. Dubbs (1971) reported differences in competitiveness of different species, while Szente et al. (1993) found differences in the WUE of different species in the mixed stand.

The LER (land equivalent ratio) values were greater than one in corn + millets mixed stand (1.47) and sorghum + millets mixed stand (1.12) than all other combinations (Table 6). According to Willey (1979), intercropping systems that constantly give LERs greater than one are considered to be more efficient systems from a land use point of view than sole cropping. The CR values were greater than one for corn when grown either mixed with sorghum (5.66) or millets (7.38). The CR value for sorghum was also greater > 1.0 (3.05) when grown mixed with millets (Table 6). The greater CR values for corn grown mixed either in millets or sorghum were attributed to shading effect of corn that negatively affected the growth and biomass yield of both sorghum and millets. Similarly, the shading effect of sorghum also had negative impact on the growth and biomass of millets. According to Willey and Rao (1980), a better measure of competitive ability of the crops can be obtained from CR, which is also an advantageous index over relative crowding coefficient and aggressivity. When two crops are grown together, yield advantages occur because of differences in their use of resources (Willey, Natarajan, Reddy, & Rao, 1983).

5. Conclusion

The three warm season C_4-grasses (corn, grain sorghum, and foxtail millets) responded differently in terms of WUE when grown in pure and mixed stands. Among the three crops, corn plants had the higher WUE due to the highest dry matter accumulation in both shoots and roots and was considered the best competitor in all the mixed stands. This indicated that corn plants captured the most resources above (light) and below (water and nutrients) the ground over time because of its well-developed shoots and roots (Amanullah & Stewart, 2013a). Grain sorghum ranked second best competitor, while foxtail millets ranked in the bottom in terms of competitiveness in the mixed stands. Measurement of canopy and root architecture was considered very important in crop–crop competition. The intra-plant competition among the crop plants in pure stands was also observed that had negative impacts on growth and WUE. Better understanding of root architecture of different crop species in pure and mixed stands was suggested to maximize water and nutrients uptake, and adaptation to diverse agroclimatic conditions. Early emergence was also considered as the best criteria in crops competitiveness. The decrease in water level was suggested to increase WUE in crop. The increase in total dry matter accumulation in the crops could increase WUE, and the increase is higher with age advancement. On the basis of CR, corn was found the best competitor, while millets was declared the least competitor (corn > sorghum > millets).

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References

Aldrich, R. J. (1984). Nature of weed competition. In *Weed-crop ecology. Principles in weed management* (pp. 189–213). Belton, CA: Breton.

Amanullah. (2014a). Wheat and rye differ in dry matter partitioning, shoot-root ratio and water use efficiency under organic and inorganic soils. *Journal of Plant Nutrition, 37*, 1885–1897. http://dx.doi.org/10.1080/01904167.2014.911888

Amanullah. (2014b). Crop growth rate differs in warm season C_4-grasses grown in pure and mixed stands. *African Journal of Biotechnology, 13*, 3036–3051. http://dx.doi.org/10.5897/AJB

Amanullah, & Stewart, B. A. (2013a). Shoot: Root differs in warm season C_4-cereals when grown alone in pure and mixed stands under low and high water levels. *Pakistan Journal of Botany, 45*, 83–90.

Amanullah, & Stewart, B. A. (2013b). Dry matter partitioning, growth analysis and water use efficiency response of oats (*Avena sativa* L.) to excessive nitrogen and phosphorus application. *Journal of Agricultural Science and Technology, 15*, 479–489.

Bazzaz, F. A. (1998). *Plants in changing environments*. Cambridge: Cambridge University Press.

Caldwell, M. M., Dean, T. J., Nowak, R. S., Dzurec, R. S., & Richards, J. H. (1983). Bunchgrass architecture, light interception, and water use efficiency: Assessment by fiber optic point quadrats and gas exchange. *Oecologia, 59*, 178–184. http://dx.doi.org/10.1007/BF00378835

Casper, B. D., & Jackson, R. B. (1997). Plant competition underground. *Annual Review of Ecology and Systematics, 28*, 545–570. http://dx.doi.org/10.1146/ecolsys.1997.28.issue-1

Dahmane, A. B. K., & Graham, R. D. (1981). Effect of phosphate supply and competition from grasses on growth and nitrogen fixation of *Medicago truncalata*. *Australian Journal of Agricultural Research, 32*, 761–772. http://dx.doi.org/10.1071/AR9810761

Dubbs, A. L. (1971). Competition between grass and legume species on dryland1. *Agronomy Journal, 63*, 359–362. http://dx.doi.org/10.2134/agronj1971.00021962006300030003x

Hanna, M. R., Kozub, G. C., & Smoliak, S. (1977). Forage production of sainfoin and alfalfa on dryland in mixed- and alternate-row seedlings with three grasses. *Canadian Journal of Plant Science, 57*, 61–70. http://dx.doi.org/10.4141/cjps77-010

Massinga, R. A., Currie, R. s., & Trooien, T. P. (2003). Water use and light interception under Palmer amaranth (Amaranthus palmeri) and corn competition. *Weed Science, 51*, 523–531. http://dx.doi.org/10.1614/0043-1745(2003)051[0523:WUALIU]2.0.CO;2

Moony, H. A. (1976). Some contributions of physiological ecology to plant population biology. *Systematic Botany, 1*, 260–283.

Passioura, J. (2006). Increasing crop productivity when water is scarce—From breeding to field management. *Agricultural Water Management. Special Issue on Water Scarcity: Challenges and opportunities for crop science, 80*, 176–196.

Rubio, G., Walk, T., Ge, Z., Yank, X., Liaok, H., & Lynch, J. P. (2001). Root gravitropism and below-ground competition among neighbouring plants: A modelling approach. *Annals of Botany, 88*, 929–940. http://dx.doi.org/10.1006/anbo.2001.1530

Sadras, V. O., & Calderini, D. F. (2009). *Crop physiology: Applications for genetic improvement and agronomy*. New York, NY: Elsevier and Academic Press.

Sorrensen-Cothern, K. A., Ford, E. D., & Sprugel, D. G. (1993). A model of competition incorporating plasticity through modular foliage and crown development. *Ecological Monographs, 63*, 277–304. http://dx.doi.org/10.2307/2937102

Steel, R. G. D., & Torrie, J. H. (1980). *Principles and procedures of statistics*. New York, NY: McGraw-Hill.

Szente, K., Tuba, Z., Nagy, Z., & Csintalan, Z. (1993). Competition between *Chenopodium album* and *Helianthus annuus* as reflected in photosynthesis and respiration. *Photosynthetica, 28*, 465–472.

Van Wychen, L. R., Maxwell, B. D., Bussan, A. J., Miller, P. R., & Luschei, E. C. (2004). Wild oat (Avena fatua) habitat and water use in cereal grain cropping systems. *Weed Science, 52*, 352–358. http://dx.doi.org/10.1614/P2002-158

Willey, R. W. (1979). Intercropping its importance and research needs. Part I. Competition and yield advantage. *Field Crops Abstract, 32*, 1–10.

Willey, R. W., Natarajan, M., Reddy, M. S., & Rao, M. R. (1983). Intercropping studies with annual crops. In J. Nugent & M. Connor (Eds.), *Better Crop for Food* (pp. 83–100). London: Pitman.

Willey, R. W., & Rao, M. R. (1980). A competitive ratio for quantifying competition between intercrops. *Experimental Agriculture, 16*, 117–125. http://dx.doi.org/10.1017/S0014479700010802

Wilson, J. B., Steel, J. B., & Steel, S. L. K. (2007). Do plants ever compete for space? *Folia Geobotanica, 42*, 431–436. http://dx.doi.org/10.1007/BF02861704