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Crop growth rate differs in warm season C_4-grasses grown in pure and mixed stands

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Crop growth rate (CGR) response of three warm season C_4-grasses (cereals) namely: corn (*Zea mays* L., cv. Hybrid-5393 VT3), grain sorghum (*Sorghum bicolor* L. Moench, cv. Hybrid-84G62 PAT), and foxtail millets (*Setaria italica*, cv. German Strain R) grown in pure and mixed stands under low and high water levels was investigated at one month interval namely: 30, 60 and 90 days after emergence (DAE), in pot experiment at Dryland Agriculture Institute, West Texas A&M University, Canyon, Texas, USA during spring 2010. The corn CGR in the mixed stands was 22, 11 and 9% higher than in pure stand at 30, 60 and 90 days after emergence (DAE), respectively. The corn plants in pure stand had 91, 66 and 84% higher CGR than the average CGR of both sorghum and millets at 30, 60 and 90 DAE, respectively. Grain sorghum in pure stand had 72, 30 and 40% higher CGR than that of millets in pure stand at 30, 60 and 90 DAE, respectively. The CGR of the three crops in mixed stand was 10 and 12% higher than the average of two crops mixed stand at the two early stages; but the CGR was reduced by 42% in the three crops mixed stand than the average of two crops mixed stand at 90 DAE. Corn mixed stand in two crops (average of corn + sorghum and corn + millets) had 78, 75 and 74% higher CGR than the mixed stand of sorghum and millets at 30, 60 and 90 DAE, respectively. Corn and millets mixed stand had 16, 9 and 38% higher CGR than the corn and sorghum mixed stand at 30, 60 and 90 DAE, respectively. Corn had higher CGR under high water at 30 DAE. There was no difference in the CGR of sorghum under low and high water levels at different growth stages. Millets had higher CGR under high water level at 30 DAE, but had lower CGR under high water level at 90 DAE. Among the three crops, corn plants had the higher CGR due to the 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, while foxtail millets ranked in the bottom in terms of competitiveness in the mixed stands.

Key words: *Zea mays*, *Sorghum bicolor*, *Setaria italica*, competition, water levels, crop growth rate.

INTRODUCTION

Crop growth rate [the total dry matter accumulation (shoot plus root dry weights) per unit ground area per unit time]

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is used to measure the primary productivity of crop plants (Youshida, 1981). Crop growth rate can be affected by competition among crop plants, because the crops are the members of community and each individual interact with its neighbors (Sadras and Calderini, 2009); and that the competition may have an impact on both above- and below-ground total biomass (Rubio et al., 2001). Crop growth requires a limited number of resources, which are light, nutrients and water. Several studies have shown that below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground competition for light (Casper and Jackson, 1997). The degree of competition below and above the ground may vary among different species. Dubbs (1971) reported that Russian wild rye (*Elymus junceus* Fisch.) was the most competitive species in terms of total dry matter accumulation and sainfoin (*Onobrychis viciaefolia* Scop.) the least. Wild rye yielded more when competing with legumes than with each other's (intra-specific competition). Competition between alfalfa plants was more intense than between other species. In another study, Hannay et al. (1977) found that total yield of the legume component in mixed stand was consistently higher for the alfalfa-grass association than for the sainfoin-grass. Competition for nutrients among neighbouring roots occurs when their individual nutrient depleted volumes overlap, causing a reduction in nutrient uptake.

Plants with contrasting root architecture (root length and numbers) may reduce the extent of competition among neighbouring root systems. Competition among roots of the same plant was three- to five-times greater than competition among roots of neighbouring plants (Rubio et al., 2001). The yield of medic (*Medicago trunculata*) in both pure and mixed stand increased with the increase of P rate up to 160 ppm P and then decreased with further increase in P levels; but 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 and Graham, 1981). It is generally believed that crop plants do not compete for space (Aldrich, 1984). This issue was recently investigated by Wilson (2007) and suggested that competition for space may occur, but the effect is so small it can be ignored within plants communities. Whenever two plants grow near each other, 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 rate (Sadras and 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 neighbouring roots and can distinguish roots from the same plant of neighbouring plants (Sadras and Calderini, 2009). There is lack of research on competition among warm season grasses in pure and mixed stand under different water regimes. The objective of this experiment was to investigate the differences in crop growth rate of warm season grasses (maize, sorghum and millets) in pure and mixed stands in various combinations under low and high water levels.

MATERIALS AND METHODS

Experimental site

Crop growth rate [the total dry matter accumulation (shoot plus root dry weights) per unit ground area per unit time] response (g m^{-2} day^{-1}) of three warm season grasses (cereals) namely corn (*Zea mays* L., cv. Hybrid-5393 VT3), grain sorghum (*Sorghum bicolor* L. Moench, cv. Hybrid-84G62 PAT), and foxtail millets (*Setaria italica*, cv. German Strain R) was investigated in pure and mixed stands under low water level (50 % less water was applied that required for the high water level) and high water level (maintained at field capacity, water was applied whenever reached to field capacity) in pot experiment at Dryland Agriculture Institute, West Texas A&M University, Canyon, Texas, USA during spring 2010. The potting soil known as *Miracle Grow* was used in the pots. Miracle Grow is formulated from 50-60% sphagnum peat moss, coconut husk fibers (coir pith), composted bark fines, pertile, 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 ACGIH threshold Limit Values (TLV) for nuisance (inert) dust containing less than 1% crystalline silica and no abestas are: 10 mg/m^3 inhalable particulates and 3 mg m^{-3} respirable particulate.

Experimental design

The experiment was performed in completely randomized design with three replicates. 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 (the pots maintained at field capacity) and low (used 50% less water than applied for the high water level)]. Nitrogen (urea) at the rate of 100 ppm was applied to each pot in two equal applications that is 50 ppm each at 7 and 60 DAE.

Data recording and handling

A total of six plants were uprooted at 30, 60 and 90 DAE from each treatment (pot). In case of T_1, T_2 and T_3, six plants of the same crop were uprooted, while in the case of T_4, T_5 and T_6, three plants of each crop were uprooted. But in the case of T_7, two plants of each species were uprooted. The roots of each crop were washed with tap water, and the plants were then divided into three parts that is 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 scale (*Sartorius Basic, BA2105*) and the average data on dry weight of root, leaf, and stem per plant was

Table 1. Analysis of variance for crop growth rate of summer cereals 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		
		30 DAE	60 DAE	90 DAE
Replications	[2]	ns	ns	ns
Treatments	[13]	***	**	***
Water levels	{1}	***	ns	ns
Crops combinations	{6}	***	**	***
Corn versus sorghum +millets	(1)	***	***	***
Sorghum versus millets	(1)	***	ns	ns
2 crops versus 3 crops	(1)	***	ns	*
Corn in 2 crops versus number corn in 2 crops	(1)	***	**	***
Corn + sorghum versus corn + millets	(1)	***	ns	*
Water levels x crops combination	{6}	***	ns	ns
Error	[26]			
Total	[41]			

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

Table 2. Crop growth rate means and significance of differences for the pre-planned comparisons at first cut (30 DAE).

Comparison	Mean 1	Mean 2	Difference	Significance
Sole corn versus corn in combination	1.782	2.295	0.514	***
Corn versus Sorghum + millets	4.566	0.390	-4.176	***
Sorghum versus millets	0.610	0.169	-0.441	***
2 Crops versus 3 crops	2.230	2.492	0.262	***
Corn in 2 crops versus number corn in 2 crops	3.017	0.655	-2.362	***
Corn + sorghum versus corn + millets	2.749	3.286	0.537	***

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

calculated. Shoot dry weight per plant was obtained by adding up leaf dry weight to 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 crop growth rate (CGR) at each growth stage was calculated on the basis of total dry weight (shoot + root) using the following formula:

$$CGR = W_2 - W_1 / (GA) (t_2 - t_1)$$

Where, W_1 = dry weight per plant at the beginning of interval (gram), W_2 = dry weight per plant at the end of interval (gram), $t_2 - t_1$ = the time interval between the two consecutive samplings (days), GA = ground area occupied by plants at each sampling (m^2), and CGR is in g m^{-2} day^{-1}.

Statistical analysis

Data on CGR at each sampling period were subjected (maybe another word) 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 ≤ 0.05. The complete ANOVA is presented in Table 1. Mean comparisons of various treatments at 30, 60 and 90 DAE is given in Tables 2, 3 and 4, respectively.

RESULTS

Corn

Crop growth rate (CGR) of corn was higher with high (5.9 g m^{-2} day^{-1}) than with low water level (5.0 g m^{-2} day^{-1}) at 30 DAE (Table 5). The CGR reached to maximum (6.4 g m^{-2} day^{-1}) each when corn was grown together in mixed stand with millets or with both sorghum + millets, and the higher increase was noticed at high than at low water level. The CGR declined to 4.5 g m^{-2} day^{-1} when corn was grown mixed with sorghum, followed by 4.6 g m^{-2} day^{-1} when corn was grown alone in pure stand. At second cut (60 DAE), corn produced higher CGR at low (38.1 g m^{-2} day^{-1}) than at high water level (29.4 g m^{-2} day^{-1}). The CGR ranked first (43.8 g m^{-2} day^{-1}) when corn was grown mixed with both sorghum + millets, and the higher increase was noticed at high (44.8 g m^{-2} day^{-1}) than at low water level (42.8 g m^{-2} day^{-1}). The CGR reduced to minimum (22.1 g m^{-2} day^{-1}) when corn was grown alone in pure stand, and the higher reduction was observed at

Table 3. Crop growth rate means and significance of differences for the pre-planned comparisons at second cut (60 DAE).

Comparison	Mean 1	Mean 2	Difference	Significance
Sole Corn vs. Corn in combination	12.238	13.807	1.568	ns
Corn versus sorghum + millets	22.106	7.305	-14.801	***
Sorghum versus millets	8.580	6.029	-2.551	ns
2 crops versus 3 crops	13.342	15.201	1.859	ns
Corn in 2 crops versus number corn in 2 crops	17.785	4.455	-13.331	**
Corn + sorghum versus corn + millets	16.909	18.662	1.753	ns

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

Table 4. Crop growth rate means and significance of differences for the pre-planned comparisons at third cut (90 DAE).

Comparison	Mean 1	Mean 2	Difference	Significance
Sole Corn versus corn in combination	44.9	40.8	-4.1	ns
Corn versus sorghum + millets	101.9	16.5	-85.4	***
Sorghum versus millets	21.1	11.8	-9.2	ns
2 crops versus 3 crops	45.7	26.3	-19.3	*
Corn in 2 crops versus number corn in 2 crops	60.6	15.9	-44.7	***
Corn + sorghum versus corn + millets	46.4	74.8	28.4	*

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

Table 5. Crop growth rate (g m^{-2} day^{-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	4.7	4.5	4.6	14.8	29.4	22.1	86.0	117.8	101.9
Corn in sorghum (S)	4.7	4.2	4.5	27.4	37.6	32.5	65.1	114.2	89.6
Corn in millets (M)	7.3	5.4	6.4	30.6	42.7	36.6	177.0	115.8	146.4
Corn in S + M	6.8	6.0	6.4	44.8	42.8	43.8	38.2	117.0	77.6
Mean	5.9	5.0	5.4	29.4	38.1	33.8	91.6	116.2	103.9
$LSD_{0.05}$									
Water Levels	0.1			ns			ns		
Crops combination	0.3			ns			48.3		
Interaction	0.4			ns			68.3		

HWL stands for high water level (maintained at field capacity) and LWL stands for low water level (maintained at 50% less water than at HWL).

high (14.8 g m^{-2} day^{-1}) than at low water level (29.4 g m^{-2} day^{-1}). At third cut (90 DAE), corn had high CGR (116.2 g m^{-2} day^{-1}) at low than at high water level (91.6 g m^{-2} day^{-1}). The CGR reached maximum (146.4 g $plant^{-1}$ day^{-1}) when corn was grown mixed with millets, and the higher increase was noticed at high (177.0 g m^{-2} day^{-1}) than at low water level (115.8 g m^{-2} day^{-1}). The CGR was reduced significantly (77.6 g m^{-2} day^{-1}) when corn was grown in mixed stand with both sorghum + millets, and the higher reduction was observed at high (38.2 g m^{-2} day^{-1}) than at low water level (117.0 g m^{-2} day^{-1}).

Grain sorghum

There was no interaction in the CGR of sorghum under high and low water levels at 30 DAE (Table 6). The CGR reached to maximum (1.1 g m^{-2} day^{-1}) when sorghum was grown along with millets, followed by 1.0 g m^{-2} day^{-1} when sorghum was grown together with corn. The CGR of

Table 6. Crop growth rate (g m^{-2} day^{-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	0.7	0.5	0.6	8.77	8.39	8.58	20.2	21.9	21.1
Sorghum in Corn (C)	1.0	1.1	1.0	0.75	1.92	1.34	1.2	5.0	3.1
Sorghum in Millets (S)	1.3	0.8	1.1	2.19	10.75	6.47	25.1	27.8	26.5
Sorghum in C + M	0.8	1.1	0.9	2.07	1.18	1.63	0.1	1.3	0.7
Mean	0.9	0.9	0.9	3.45	5.56	4.50	11.7	14.0	12.8
$LSD_{0.05}$									
Water Levels	ns			ns			ns		
Crops Combination	0.09			3.45			11.6		
Interaction	0.13			4.88			16.4		

HWL stands for high water level (maintained at field capacity) and LWL stands for low water level (maintained at 50% less water than at HWL).

Table 7. Crop growth rate (g m^{-2} day^{-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	0.18	0.16	0.17	6.28	5.78	6.03	5.8	17.9	11.8
Millets in Corn (C)	0.19	0.23	0.21	0.46	0.90	0.68	1.9	4.4	3.1
Millets in Sorghum (S)	0.28	0.22	0.25	3.34	1.53	2.44	3.8	6.7	5.2
Millets in C + S	0.18	0.14	0.16	0.26	0.27	0.27	0.6	0.8	0.7
Mean	0.21	0.19	0.20	2.59	2.12	2.35	3.0	7.5	5.2
$LSD_{0.05}$									
Water Levels	0.01			ns			1.0		
Crops Combination	0.02			0.97			2.7		
Interaction	0.02			1.38			3.9		

HWL stands for high water level (maintained at field capacity) and LWL stands for low water level (maintained at 50% less water than at HWL).

sorghum declined to minimum (0.6 g m^{-2} day^{-1}) when sorghum was grown alone in pure stand. At second cut (60 DAE), sorghum produced higher CGR (5.56 g m^{-2} day^{-1}) at low than at high water level (3.45 g m^{-2} day^{-1}). The CGR ranked first (8.58 g m^{-2} day^{-1}) when sorghum was grown alone in pure stand, followed by sorghum + millets mixed stand (6.47 g m^{-2} day^{-1}). The CGR reduced significantly (1.34 g m^{-2} day^{-1}) when sorghum was grown mixed with corn, and the higher reduction was observed at high (0.75 g m^{-2} day^{-1}) than at low water level (1.92 g m^{-2} day^{-1}). At third cut (90 DAE), sorghum had high CGR (14.0 g m^{-2} day^{-1}) at low than high water level (11.7 g m^{-2} day^{-1}). The CGR reached maximum (26.5 g $plant^{-1}$ day^{-1}) when sorghum was grown mixed with millets, and the higher increase was noticed at low (27.8 g m^{-2} day^{-1}) than at high water level (25.1 g m^{-2} day^{-1}). The CGR reduced significantly to 0.7 g m^{-2} day^{-1} when sorghum was grown with both corn + millets mixed stand, and the higher reduction was observed at high (0.1 g m^{-2} day^{-1}) than at low water level (1.3 g m^{-2} day^{-1}).

Foxtail millets

Crop growth rate of millets was relatively higher (0.21 g m^{-2} day^{-1}) under high than low water level (0.19 g m^{-2} day^{-1}) at 30 DAE (Table 7). The CGR reached maximum to 0.25 g m^{-2} day^{-1} when millets was grown together with sorghum, followed by 0.21 g m^{-2} day^{-1} when millets was grown together with corn. The CGR declined to 0.16 g m-

Table 8. Average crop growth rate (g m^{-2} day^{-1}) response of summer cereals when grown alone in pure and mixed stands 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	4.65	4.47	4.56	14.83	29.38	22.10	86.0	117.8	101.9
Sorghum (S) alone	0.69	0.52	0.61	8.76	8.39	8.58	20.2	21.9	21.1
Millets (M) alone	0.18	0.15	0.16	6.28	5.77	6.02	5.8	17.9	11.8
Average of C + S	2.83	2.66	2.74	14.08	19.73	16.90	33.1	59.6	46.4
Average of C + M	3.73	2.83	3.28	15.54	21.77	18.66	89.5	60.1	74.8
Average of S + M	0.78	0.52	0.65	2.76	6.14	4.45	14.5	17.2	15.9
Average of C + S + M	2.59	2.38	2.49	15.72	14.67	15.20	13.0	39.7	26.3
Mean	2.21	1.93	2.07	11.14	15.125	13.13	37.4	47.7	42.6
$LSD_{0.05}$									
Water levels	0.07			ns			ns		
Crops combination	0.13			8.69			22.0		
Interaction	0.18			12.30			31.2		

HWL stands for high water level (maintained at field capacity) and LWL stands for low water level (maintained at 50% less water than at HWL).

^{2} day^{-1} when millets was grown mixed with both corn and sorghum mixed stand (corn + sorghum + millets). At second cut (60 DAE), millets had higher CGR at high (2.59 g m^{-2} day^{-1}) than at low water level (2.12 g m^{-2} day^{-1}). The CGR ranked first (6.03 g m^{-2} day^{-1}) when millets was grown alone in pure stand, and the higher increase was noticed at high (6.28 g m^{-2} day^{-1}) than at low water level (5.78 g m^{-2} day^{-1}). The CGR reduced significantly (0.27 g m^{-2} day^{-1}) when millets was grown mixed with corn + sorghum, and there was no difference in CGR at high (0.26 g m^{-2} day^{-1}) and low water level (0.27 g m^{-2} day^{-1}). At third cut (90 DAE), millets had high CGR (7.5 g m^{-2} day^{-1}) at low than high water level (3.0 g m^{-2} day^{-1}). The CGR reached maximum (11.8 g $plant^{-1}$ day^{-1}) when millets was grown alone in pure stand, and the higher increase was noticed at low (17.9 g m^{-2} day^{-1}) than at high water level (5.8 g m^{-2} day^{-1}). The CGR reduced significantly to 0.7 g m^{-2} day^{-1} when millets was grown mixed with corn, and the higher reduction was observed at high (0.6 g m^{-2} day^{-1}) than at low water level (0.8 g m^{-2} day^{-1}).

Crops average

The average CGR of the three summer grasses was higher (2.21 g m^{-2} day^{-1}) at high than low water level (1.93 g m^{-2} day^{-1}) at 30 DAE (Table 8). The CGR ranked first (4.56 g m^{-2} day^{-1}) when corn was grown alone in pure stand, followed by the average of corn + millets mixed stand (3.28 g m^{-2} day^{-1}). The CGR reduced to minimum (0.16 g m^{-2} day^{-1}), when millets was grown alone in pure stand. At second cut (60 DAE), there were no significant difference in the CGR at low and high water levels. However, the CGR was higher (15.12 g m^{-2} day^{-1}) at low than high water level (11.14 g m^{-2} day^{-1}). The CGR reached to maximum (22.10 g m^{-2} day^{-1}) when corn was grown alone in pure stand, followed by the average of corn + millets mixed stand (18.66 g m^{-2} day^{-1}); while CGR reduced to minimum (4.45 g m^{-2} day^{-1}) when sorghum + millets mixed stand was averaged, being at par with each sorghum and millets in the pure stands. At third cut (90 DAE); there were no significant difference in the CGR at low and high water levels. However, the average CGR was higher (47.7 g m^{-2} day^{-1}) at high than low water level (37.4 g m^{-2} day^{-1}). The CGR reached to maximum (101.9 g m^{-2} day^{-1}) when corn was grown alone in pure stand, followed by the average of corn + millets mixed stand (74.8 g m^{-2} day^{-1}). The CGR reduced to minimum (11.8 g m^{-2} day^{-1}), when millets was grown alone in pure stand.

DISCUSSION

Corn

The higher CGR of corn at high than at low water level at early stage was explained by the delay in emergence of corn at low than at high water level. The increase in corn CGR was due to its taller plants, higher leaf area and highest shoot and root dry weights in mixed stand with millets (corn + millets) or both sorghum and millets mixed stand (corn + sorghum + millets) because of the very well developed canopy and root architecture of corn at the early growth stage (Figures 1 and 2) had negative impacts on the growth and total dry matter accumulation

Figure 1. Corn (Left), grain sorghum (middle) and foxtail millets (right) shoot and root lengths 30 days after emergence.

of millets and sorghum adversely reduced the CGR of sorghum and millets in the mixed stand with corn. According to Bazzaz (1998), plants parts in space and their mode of display (plant architecture) are very important in plant-plant interactions. The intra plants completion among corn plants was observed when corn was grown alone in pure stand that reduced both shoots and roots dry weights and so the CGR of corn declined in pure stand. This indicates that corn plants in pure stand were quite competitive among themselves. Dubbs (1971) reported that alfalfa plants received more competition from other alfalfa plants than from plants of other species. The lower CGR of corn plants was noticed when corn was grown mixed with sorghum (corn + sorghum) indicating that the sorghum plants competed very well against corn that reduced the shoots and roots dry weights (Amanullah and Stewart, 2013) and CGR of corn plants (Figures 1 and 3). As compared to millets, that do not have negative impacts on the corn CGR, sorghum on the other hand with well developed canopy had more adverse effects on corn plants (Figures 1 and 4). According to Sorrenson et al. (1993), measurement of canopy architecture is very important in crop-crop competition. The lower CGR of corn plants at high than at low water level at 60 DAE was due to the negative effects of high water level on plant heights, root length, leaf area, shoots and roots dry weights of corn plants (Amanullah and Stewart, 2013). The increase in the CGR of corn

Figure 2. Corn root system (very strong) 30 days after emergence.

plants when it was grown in mixed stand with both sorghum and millets (corn + sorghum + millets) was probably due to the reduction in the growth and total dry weights of millets and sorghum and also there was no strong intra plants competition among the corn plants in the mixed stand.

The strong intra plants completion among the corn plants in the pure stand reduced the shoots and roots dry weights that resulted in the lower corn CGR. 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. Dubbs (1971) reported that alfalfa plants received more competition from other alfalfa plants than from plants of other species. The lower CGR of corn plants at high than at low water level at 90 DAE was due to the negative effects of high water level on plant heights, root length, leaf area, shoot, root and total plant dry weights of corn (data not shown). Rubio et al. (2001) reported that competition among plants occurs for 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

Figure 3. Grain sorghum root system (strong) 30 days after emergence.

plants in the mixed stand was better established than that of sorghum and millets, and therefore, corn plants probably may have took more nutrients and water than the two crops. 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 increase in the CGR of corn plants when grown mixed with millets (corn + millets) was due to the reduction in the growth of millets (Figure 8) and also the reduction in intra plants competition among the corn plants. On the other hand, mixing sorghum 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 CGR (Figure 7).

Rubio et al. (2001) reported that plants with contrasting root architecture may reduce the extent of competition among neighboring root systems.

Grain sorghum

When sorghum was grown mixed with other crops, its plant heights, stem and leaf dry weights increased that resulted in the higher CGR of sorghum at 30 DAE. At the early growth stage, sorghum reduced its plant heights; leaf area and shoot dry weight that declined its CGR in the pure stand because of delay in emergence as compared to the early emergence in mixed stand. According to Sadras and Calderini (2009), there has been emerging evidence of the importance of early crop

Figure 4. Foxtail millets root system (weak) 30 days after emergence.

vigor for competitive ability of crop plants. Likewise corn plants, the lower CGR 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, shoot and root dry weights of sorghum (Amanullah and Stewart, 2013) at 60 DAE. According to Sadras and Calderini (2009), plant height tend to be the most common shoot trait implicated in competitive ability of different crops. The increase in the CGR 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 (Figures 3 and 4). 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 sorghum CGR. The higher leaf area and root dry weights of corn plants had negative influence on the root and shoot and root dry weights and CGR of sorghum (Figures 5 and 6). According to Caldwell et al. (1983), 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 CGR 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, shoot and root dry weights of sorghum ((Amanullah and

Figure 5. Millets (Left), corn (Middle) and grain sorghum (Right) shoot and root growth 60 days after emergence under low water level.

Stewart, 2013)). The increase in the CGR of sorghum when it was grown alone in pure or mixed stand with millets (Figure 9) was due to the increase in shoot and root dry weights of sorghum. But the higher leaf area and root 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 (Figures 7 and 10) which resulted in the lower CGR of sorghum plans. 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.

Foxtail millets

The higher CGR of millets plants at high than at low water level at 30 DAE was because of the delay in

Figure 6. Millets (Left), corn (Middle) and grain sorghum (Right) shoot and root growth 60 days after emergence under high water level.

emergence at low than at high water level. According to Sadras and Calderini (2009), there has been emerging evidence of 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 both crops (Figure 1) that declined the CGR in millets plants. 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 CGR of millets at 60 DAE. The increase in the CGR of millets when it was grown alone in pure stand was due to the increase in shoot and root dry weights of millets indicating less intraspecific plants competition among the millets plants than in the inter plants competition in the mixed stands. Including corn in the mixtures with millets (Figures 8 and 10) (corn + millets or corn + sorghum + millets) had negative impacts on the shoot and root dry

Figure 7. Corn and grain sorghum grown together in mixed stand under low (Left) and high (Right) water level 90 days after emergence

Figure 8. Corn and foxtail millets grown together in mixed stand under low (left) and high (right) water level 90 days after emergence.

Figure 9. Grain sorghum and foxtail millets grown together in mixed stand under low (Left) and high (Right) water level 90 days after emergence.

Figure 10. Corn, grain sorghum and foxtail millets grown together in mixed stand under low (Left) and high (Right) water level 90 days after emergence.

weights of millets that resulted in the minimum CGR. The higher leaf area and taller plants (canopy architecture); deeper roots, more number of roots and higher root dry weight of corn plants (root architecture) had negative influence on the shoot and root dry weights of millets plants and so the CGR 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 very important in crop-crop competition (Sorrenson et al., 1993). As compared to corn, that declined the CGR of millets to minimum, sorghum plants had little influence on the shoot and root dry weights as well as the CGR of millets. The lower CGR 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, shoot and root dry weights of millets (Amanullah and Stewart, 2013).

The increase in the CGR of millets when grown alone in pure stand was due to the increase in shoot and root dry weights of millets. The leaf area, plant height, shoot and root dry weights of millets plants increased significantly when grown alone in pure stand indicating less intra plants competition among the millets. When corn was included in the mixtures with millets (corn + millets or corn + sorghum + millets) had negative impacts on the shoot and root development of millets that declined the total plant dry weights of millets and so the CGR was reduced. The higher leaf area, 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 CGR of millets (Figure 8). On the other hand, sorghum plants had little negative influence on the shoot and root dry weights as well as the CGR of millets. Competition among plants occur both above- and below-ground (Rubio et al., 2001), but the below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground competition Casper and Jackson (1997).

Crops average

The higher average CGR 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. The CGR 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, followed by sorghum, while the millets plants were least competitive in different mixed stand. The corn plants developed very faster when it was grown mixed with millets; therefore the combination of corn + millets had the second highest CGR. 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. Because of the less root and shoot dry weights of millets in the pure stand (30 DAE) resulted in the minimum CGR. The highest CGR 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 CGR. The lowest shoot and root dry weights produced by the mixed stand of sorghum and millets (sorghum + millets) or pure stands of sorghum and millets had the lowest CGR at 60 DAE.

The CGR 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 also had the highest shoot and root dry weights (Amanullah and Stewart, 2013) when it was grown mixed with millets; therefore the combination of corn + millets mixed stand also had the second highest CGR at 90 DAE. Although, the contribution of millets 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 that Russian wild rye (*Elymus junceus* Fisch.) was the most competitive species and sainfoin (*Onobrychis viciaefolia* Scop.) the least competitive. In general, all species were quite competitive to themselves in pure stands due to intra plant competition.

Conclusions

The three warm season grasses (corn, sorghum and millets) responded differently in terms of crop growth rate when grown in pure and mixed stands under low and high water levels at different growth stages. Among the three crops, corn plants had the higher CGR due to the highest dry matter accumulation in both shoots and roots (Amanullah and Stewart, 2013) 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) ground over time because of its well developed shoot and root canopy architectures. Measurement of canopy and root architecture is considered very important in crop-crop competition. The intra-plant competition among the crop plants in pure stands was also observed and had negative impacts on the CGR. 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 agro climatic conditions.

Conflict of Interest

The author(s) have not declared any conflict of interest.

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