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SHOOT: ROOT DIFFERS IN WARM SEASON C_4-CEREALS WHEN GROWN ALONE IN PURE AND MIXED STANDS UNDER LOW AND HIGH WATER LEVELS

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Abstract

Shoot: root (S:R) 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 italica*, cv. German Strain R) grown in pure and mixed stands was investigated at one month interval in pot experiment at West Texas A&M University, Texas, USA during spring 2010. The results indicated that the three warm season grasses responded differently in terms of 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 was therefore ranked second in terms of competitiveness (corn > grain sorghum > millets). Better understanding of root architecture of different crop species in pure and mixed stands could maximize water and nutrients uptake. Early emergence of the three crop plants had positive effects on shoot and root biomass accumulation and was considered the best criteria in crops competitiveness. We also found that 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. We suggests that more studies are required to assess more accurately the root biomass contribution of different crops species in pure and mixed stands to improve carbon sequestration into the soils under different environmental conditions.

Introduction

Shoot to root ratio (S:R): shoot (leaf + stem) dry weight per plant divided by root dry weight per plant, of standing crop are commonly used to estimate the annual crop residue carbon inputs to the soil from the root biomass left in the soil at harvest, but the root biomass has often been neglected and the estimates of S:R for many commonly grown forage species are not available (Bolinder *et al*., 2002). Straw retention improves organic carbon in the soil, and the magnitude depends on soil types, climatic conditions and management strategies (Malhi *et al*., 2009, 2011). The annual carbon inputs to soils from crop residues can be divided into two major sources: aboveground i.e., straw, stubble and surface debris and below-ground i.e., root biomass left in the soil at harvest, root turnover, exudates and secretions. One of several management practices proposed to sequester atmospheric CO_2 as soil organic weight is to expand the area of crops such as perennial forages that increase the annual crop residue carbon inputs to soils (Bolinder *et al*., 2002).

Shoot to root dry weights can be influenced by competition among the standing crop plants, because the individual plants interact with its neighbors in the mixed stands (Sadras & Calderini, 2009); and that the competition may be both above- and below-ground (Rubio *et al*., 2001). Crop shoot and root 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 is stronger and can involve more neighbors than above-ground competition for light (Casper & Jackson, 1997). The degree of competition among crop plants varies due to differences in genetic makeup (Dubbs, 1971; Hannay *et al*., 1977), root architecture (Rubio *et al*., (2001), and crop nutrition (Ma *et al*., 2007; Eghball & Maranville, 1993; Dunbabin *et al*., 2001; Champiny & Talouizte, 1981; Dahmane & Graham, 1981; & Davidson, 1969). It is generally believed that crop plants do not compete for space (Aldrich, 1984), but Wilson (2007) found that competition for space can occur, but the effect is so small that can be ignored in plants communities. Whenever two plants grow near to 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). Shoot-root relationship by weights gives an estimate of root mass that remains in soil if shoot weight is known, and that dry weight partitioning in roots is high during the seedling stages and steadily declines throughout development (Evans & Wardlaw, 1976). Shoot-root ratios in various crops increase with advancement in age (Fageria *et al*., 1992), and the environmental stresses increase relative weights of roots compared to shoots (Eghball & Maranville, 1993).

Competition among warm season C_4-grasses (cereals) in pure and mixed stand maintained at low and high water levels have not yet been investigated by the researchers, and so there is lack of research on shoot to root ratio of crops in the mixed stands. The objective of this study was to investigate the differences in S:R among warm season C_4-cereals (corn, sorghum and millets) in pure and mixed stands in various combinations under low and high water levels at various growth stages.

Materials and Methods

Experimental site: Shoot to root ratio [shoot (leaf + stem) dry weight per plant divided by root dry weight per plant] response of three warm season grasses (cereals) viz., 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 high water level (the pots were maintained at field capacity in the whole growing season) and low water level (50 % less water was applied that needed at field capacity) in the pot experiment at the green house of Dryland Agriculture Institute, West Texas A&M University, Canyon, Texas, USA during spring 2010. Organic soil (Miracle Grow) was used as soil medium in the pots.

Experimental design: The experiment was performed in completely randomized design (CRD) 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).

Data recording and handling: A total of 6 plants were uprooted at 30, 60 and 90 days after emergence (DAE) from each treatment (pot). In case of T_1, T_2 and T_3, 6 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, 2 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^{o}C for 24 hours. The samples were weighing by electronic balance (*Sartorius Basic, BA2105*) and the average data on dry weights 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 (Amanullah *et al*., 2010; Amanullah & Shah, 2011). The sum of the shoot and root dry weight was calculated as the total dry weight per plant. Shoot to root ratio (S:R) at each growth stage was calculated using the following formula:

$$\text{Shoot to Root Ratio (S:R)} = \frac{\text{Shoot dry weight plant}^{-1}}{\text{Root dry weight plant}^{-1}}$$

Statistical analysis: Data at each growth stage were subjected to analysis of variance (ANOVA) according to the methods described by Steel & Torrie (1980) and treatment means were compared using the least significant difference (LSD) at $P \leq 0.05$.

Results

Corn had relatively higher shoot to root ratio (S:R) of 0.90 under high than low water level (0.67) at 30 DAE but the differences were statistically not significant (Table 1). The S:R reduced to minimum (0.31) when corn was grown alone in pure stand, and reduced to 0.51 in corn and sorghum mixed stand. The inclusion of millets in the mixed stand increased S:R in corn. The highest S:R (1.18) was obtained when corn was grown mixed with both sorghum and millets, followed by corn + millets mixed stand (1.12), and the higher increase was noted at high than low water level. At second cut (60 DAE), corn had relatively higher S:R (2.95) under low than high water level (2.78). The S:R increased when corn was grown in mixed stand with millets (3.36) or grown alone in pure stand (3.11), and the higher increase was noted at low than high water level. The inclusion of sorghum in the mixed stand on the other hand reduced the S:R (2.79) in corn at 60 DAE, and the reduction in S:R was more (2.57) under high water level. At third cut (90 DAE), corn had the higher S:R (5.79) under high than low water level (5.42). Corn had maximum S:R (6.33) when grown in mixed stand with both sorghum + millets, and the higher increase was noticed at low (6.99) than high water level (5.68). The S:R reduced to minimum (4.54) when corn was grown in mixed stand with millets and the higher decrease was noted under low (4.28) than high water level (4.80).

Sorghum had the higher S:R under high (2.4) than low water level (1.8) at 30 DAE (Table 4). The S:R reduced to minimum (1.1) when sorghum was grown alone in pure stand, followed by 2.0 in mixed stand with corn. The S:R ranked second (2.5) when sorghum was grown in mixed stand with both corn and millets, and the higher increase was noted at low than high water level. At second cut (60 DAE), sorghum had higher S:R (3.65) under low water level than high water level (2.47). The S:R increased to the highest level when sorghum was grown alone in pure stand (4.34), however, no significant differences were noted between the two water levels. The S:R of sorghum ranked second (3.14) when grown in mixed stand with millets, and the higher increase was noted at low (4.70) than high (1.57) water level. The S:R reduced significantly to 1.99 when sorghum was grown in mixed stand with both corn + millets, and the higher decrease was noticed at low (1.73) than high (2.26) water level. At third cut (90 DAE), sorghum had the higher S:R (3.58) under high than low water level (3.05), but the differences were not significant ($p \leq 0.05$). Sorghum had maximum S:R (4.01) when grown in mixed stand with millets, and the higher increase was noticed at low (4.13) than high water level (3.89). The S:R reached to minimum (2.46) when sorghum was grown in mixed stand with corn, and the higher decrease (1.81) was calculated under high than low water level (3.12).

Millets had the higher S:R (3.48) under low than high water level (2.23) at 30 DAE (Table 7). The S:R reduced to minimum (2.44) when millets was grown in mixed stand with sorghum, and the higher decrease was observed at high (1.36) than low (3.52) water level. There was no significant difference in the S:R of millets grown either alone in pure stand or in mixed stand with corn. However, the increase in S:R was more under high water level (3.31) when grown alone in pure stand, but the increase was higher at low water level (4.17) when grown in mixed stand with corn. At second cut (60 DAE), millets had higher S:R (4.93) under high than low water level

(4.42). The S:R increased to maximum (7.35) when millets was grown alone in pure stand, and the higher increase was noted at high water level (8.09) than low water level (6.62). The S:R reduced significantly to 2.46 when millets was grown in mixed stand with both corn + sorghum, and the higher decrease (1.73) was observed under low water level. At third cut (90 DAE), millets had higher S:R under low (9.62) than high (7.92) water level. Millets had maximum S:R (13.32) when grown mixed with corn, and the higher increase was noticed at high (13.99) as compared to the low water level (12.66). The S:R reduced to minimum (3.90) when millets was grown together both corn + sorghum and the higher decrease (3.29) was calculated under high water level.

Discussions

At the early growth stage (30 DAE), the increase in the S:R of corn at high water level (Table 1) was attributed to production of higher root (Table 2) and shoot biomass (Table 3). The reduction in the S:R of corn in the pure or sorghum mixed stands was attributed to the reduction in the shoot biomass. In the pure corn stand, probably due to the more intra-specific plants competition among corn plants, and more inter-specific plants competition in the sorghum mixed stand had the negative impact on corn shoot biomass and so the S:R was reduced. Dubbs (1971) reported that alfalfa plants received more competition from other alfalfa plants than from plants of other species. The increase in plant heights, leaf area per plant, crop growth rate, shoot and root biomass of corn plants in the millets mixed stand (corn + millets) or with both sorghum and millets mixed stand (corn + sorghum + millets) increased the S:R in corn. The significant increase in shoot and root biomass as well as S:R of corn plants in the mixed stand had negative impact on the root and shoot growth, and total dry matter accumulation of millets. According to Bazzaz (1998), plants parts in space and their mode of display (plant architecture) are very important in plant-plant interactions. The increase in the S:R of grain sorghum at 30 DAE under high water level (Table 4) was attributed to the higher shoot biomass of sorghum (Table 6). Sorghum produced taller plants; more leaf area and shoot biomass because of the early emergence under high water level (data not shown). Sadras & Calderini (2009) suggested the importance of early crop vigor and plant heights for competitive ability in crop-crop competition. The reduction in the S:R of sorghum in the pure or corn mixed stand was probably attributed to the increase in root biomass (Table 5). In the corn mixed stand, more decrease in S:R of sorghum was observed at low water level, because at low water level the sorghum root biomass was increased to the maximum level (20.2 mg plant^{-1}) and so the S:R was reduced. Sorghum in the millets mixed stand, had the highest shoot biomass (43.9 mg plant^{-1}) under high water level and so the S:R was increased to maximum level. The increase in S:R of millets under high water level (Table 7) at 30 DAE was attributed to the lower root biomass (Table 8) produced by millets under high water level. Similarly, the production of the highest root biomass of millets (5.6 mg plant^{-1}) in the sorghum mixed stand under high water level decreased the S:R in millets. In the pure stand, millets produced the higher shoot biomass (Table 9) under high water level that increased the S:R in millets. But in the corn mixed stand, millets produced the higher root biomass (3.2 mg plant^{-1}) but lower shoot biomass (6.5 mg plant^{-1}) under high water level and so the S:R was reduced. Amanullah *et al*., (2011) found that under water stress condition, total plant biomass of barley (average of two cultivars) was more than wheat (average of six cultivars) because of higher tillers m^{-2} in barley (285) than wheat (224). Sorrenson *et al*., (1993) suggested that measurement of canopy architecture is very important in crop-crop competition.

Table 1. Shoot to root ratio response of corn when grown alone in pure and mixed stands with sorghum and millets under low and high water levels at various growth stages.

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	0.32	0.30	0.31	3.05	3.17	3.11	5.45	5.30	5.38
Corn in Sorghum (S)	0.36	0.66	0.51	2.57	3.01	2.79	7.23	5.12	6.17
Corn in Millets (M)	1.44	0.80	1.12	3.14	3.57	3.36	4.80	4.28	4.54
Corn in S + M	1.47	0.90	1.18	2.36	2.04	2.20	5.68	6.99	6.33
Mean	0.90	0.67	0.78	2.78	2.95	2.87	5.79	5.42	5.61
$LSD_{0.05}$									
Water Levels	ns			0.22			ns		
Crops Combination	0.11			0.61			1.15		
Interaction	0.16			0.86			1.62		

Where: 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 2. Root dry weight response of corn when grown alone and in combination with sorghum and millets under low and high water levels at various growth stages.

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	157.3	151.9	154.6	381.7	652.3	517.0	3.10	4.41	3.76
Corn in Sorghum (S)	154.1	111.7	132.9	763.8	873.2	818.5	2.05	4.58	3.32
Corn in Millets (M)	125.9	130.8	128.3	735.3	905.0	820.2	7.05	5.40	6.23
Corn in S + M	117.7	135.4	126.5	1298.	1388.8	1343.	2.31	3.61	2.96
Mean	138.7	132.4	135.6	794.8	954.8	874.8	3.63	4.50	4.06
$LSD_{0.05}$									
Water Levels	1.9			ns			ns		
Crops Combination	5.2			332.4			1.62		
Interaction	7.3			470.0			2.29		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg $plant^{-1}$ but it is in g $plant^{-1}$ at the last growth stage

Table 3. Shoot dry weight response of corn when grown alone and in combination with sorghum and millets under low and high water levels at various growth stages.

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	50.60	45.85	48.23	1227.2	2213.7	1720.	15.22	22.00	18.61
Corn in Sorghum (S)	54.85	73.30	64.08	1947.0	2688.3	2317.	14.80	22.60	18.70
Corn in Millets (M)	181.20	104.9	143.08	2404.3	3178.8	2791.	30.30	23.10	26.70
Corn in S + M	172.40	122.0	147.23	3058.3	2744.3	2901.	13.13	25.22	19.17
Mean	114.76	86.54	100.65	2159.2	2706.3	2432.	18.36	23.23	20.79
$LSD_{0.05}$									
Water Levels	4.36			ns			2.02		
Crops Combination	11.94			ns			5.54		
Interaction	16.89			ns			7.83		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg $plant^{-1}$ but it is in g $plant^{-1}$ at the last growth stage.

Table 4. Shoot to root ratio response of grain sorghum when grown alone in pure and mixed stands with corn and millets under low and high water levels at various growth stages.

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	1.30	0.90	1.10	4.36	4.31	4.34	3.93	3.02	3.47
Sorghum in Corn (C)	2.69	1.38	2.04	1.68	3.87	2.77	1.81	3.12	2.46
Sorghum in Millets (S)	3.40	2.15	2.77	1.57	4.70	3.14	3.89	4.13	4.01
Sorghum in C + M	2.28	2.69	2.48	2.26	1.73	1.99	4.68	1.94	3.31
Mean	2.42	1.78	2.10	2.47	3.65	3.06	3.58	3.05	3.31
$LSD_{0.05}$									
Water Levels	0.14			0.42			ns		
Crops Combination	0.39			1.16			ns		
Interaction	0.56			1.64			ns		

Where: HWL stands for high water level and LWL stands for low water level

Table 5. Root dry weight response of grain sorghum when grown alone and in combination with corn and millets under low and high water levels at various growth stages.

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	13.4	13.0	13.2	149.5	155.7	152.6	1.02	1.34	1.18
Sorghum in Corn (C)	11.6	20.2	15.9	48.7	53.2	50.9	0.17	0.33	0.25
Sorghum in Millets (S)	13.0	12.1	12.6	106.3	165.0	135.7	0.98	1.34	1.16
Sorghum in C + M	10.9	12.8	11.9	73.8	54.8	64.3	0.05	0.15	0.10
Mean	12.2	14.5	13.4	94.6	107.1	100.9	0.56	0.79	0.67
$LSD_{0.05}$									
Water Levels	0.40			ns			ns		
Crops Combination	1.11			51.5			0.36		
Interaction	1.57			72.9			0.51		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg $plant^{-1}$ but it is in g $plant^{-1}$ at the last growth stage

Table 6. Shoot dry weight response of grain sorghum when grown alone and in combination with corn and millets under low and high water levels at various growth stages.

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	17.3	11.6	14.4	663.3	615.2	639.3	4.16	4.06	4.11
Sorghum in Corn (C)	31.2	28.0	29.6	81.5	186.7	134.1	0.30	1.03	0.67
Sorghum in Millets (S)	43.9	25.6	34.8	170.7	831.7	501.2	3.98	5.53	4.76
Sorghum in C + M	24.8	34.4	29.6	160.8	96.5	128.6	0.20	0.29	0.25
Mean	29.3	24.9	27.1	269.1	432.5	350.8	2.16	2.73	2.45
$LSD_{0.05}$									
Water Levels	1.53			ns			ns		
Crops Combination	4.18			262.8			1.67		
Interaction	5.91			371.7			2.37		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg $plant^{-1}$ but it is in g $plant^{-1}$ at the last growth stage

Table 7. Shoot to root ratio response of millets when grown alone in pure and mixed stands with corn and sorghum under low and high water levels at various growth stages.

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	3.31	2.92	3.11	8.09	6.62	7.35	6.24	11.96	9.10
Millets in Corn (C)	2.03	4.17	3.10	3.33	4.34	3.83	13.99	12.66	13.32
Millets in Sorghum (S)	1.36	3.52	2.44	5.09	5.01	5.05	8.15	9.36	8.75
Millets in C + S	2.20	3.33	2.77	3.20	1.73	2.46	3.29	4.50	3.90
Mean	2.23	3.48	2.85	4.93	4.42	4.68	7.92	9.62	8.77
$LSD_{0.05}$									
Water Levels	0.13			ns			ns		
Crops Combination	0.37			1.18			ns		
Interaction	0.52			1.67			ns		

Where: HWL stands for high water level and LWL stands for low water level.

Table 8. Root dry weight response of millets when grown alone and in combination with corn and sorghum under low and high water levels at various growth stages.

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	2.1	2.1	2.1	62.2	67.3	64.8	0.30	0.32	0.31
Millets in Corn (C)	3.2	2.1	2.7	12.7	17.0	14.8	0.02	0.11	0.07
Millets in Sorghum (S)	5.6	2.3	4.0	54.5	23.7	39.1	0.08	0.15	0.11
Millets in C + S	2.9	1.8	2.4	9.3	13.0	11.1	0.04	0.04	0.04
Mean	3.5	2.1	2.8	34.6	30.3	32.4	0.11	0.16	0.13
$LSD_{0.05}$									
Water Levels	0.12			ns			0.02		
Crops Combination	0.34			12.5			0.04		
Interaction	0.48			17.6			0.06		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg $plant^{-1}$ but it is in g $plant^{-1}$ at the last growth stage

Table 9. Shoot dry weight response of millets when grown alone and in combination with corn and sorghum under low and high water levels at various growth stages.

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	6.9	5.9	6.4	500.7	449.8	475.3	1.85	3.85	2.85
Millets in Corn (C)	6.5	8.8	7.6	42.2	78.0	60.1	0.29	0.81	0.55
Millets in Sorghum (S)	7.5	8.1	7.8	257.5	126.2	191.8	0.76	1.33	1.04
Millets in C + S	6.3	5.9	6.1	27.5	22.0	24.8	0.13	0.18	0.15
Mean	6.8	7.2	7.0	207.0	169.0	188.0	0.76	1.54	1.15
$LSD_{0.05}$									
Water Levels	Ns			ns			0.20		
Crops Combination	0.55			74.0			0.55		
Interaction	0.77			104.6			0.78		

Where: HWL stands for high water level and LWL stands for low water level. The data in the first two growth stages is in mg plant^{-1} but it is in g plant^{-1} at the last growth stage

At the second growth stage (60 DAE), the higher S:R of corn plants at low than high water level (Table 1) was probably attributed to the higher shoot biomass of corn at low (2.7 g plant^{-1}) than high (2.1 g plant^{-1}) water level (Table 3). The increase in S:R of corn in the pure stand was because of the significant reduction in the root biomass per plant, because of the more intra-specific plants competition in corn plants reduced the root biomass. The increase in S:R of corn in the millets mixed stand probably might be attributed to the significant increase in both shoot and root biomass (Table 2) of corn plants. The increase in corn growth rate, water use efficiency because of its taller plants and longer roots system, higher leaf area per plant, higher shoot and root biomass in the millets mixed stands (data not shown) increased the S:R in corn. Because of the very well established shoot and root systems of corn plants in the millets mixed stand had negative impact on the growth rate, shoot and root biomass of millets on one hand, but on the other hand, corn plants below and above the ground benefited more because of the less inter-specific plants competition from millets plants. But the more inter-specific plants competition from sorghum in the sorghum mixed stand shown negative impact on shoot and root biomass of corn plants as well as S:R in corn. The higher root and lower shoot biomass of corn in the three crop mixed stand (corn + sorghum + millets) particularly under low water level reduced the S:R in corn. Rubio *et al*., (2001) reported that plants with contrasting root architecture may reduce the extent of competition among neighboring root systems. The higher S:R in sorghum (60 DAE) at low water level (Table 4) was attributed to the higher shoot biomass (432.5 mg plant^{-1}) produced by sorghum under low water level (Table 6). When sorghum was grown alone in the pure stand, its root biomass increased to the maximum level (152.6 mg plant^{-1}) (Table 5) that probably may helped the plants to take more water and nutrients that in turn increased the shoot biomass to the maximum level (639.3 mg plant^{-1}). Dry matter accumulation in the shoot biomass was higher than the root biomass and so the S:R in sorghum was also increased. Due to the very well established shoot and root architecture of sorghum in the millets mixed stand under low water level, the sorghum plants produced more root biomass (165.0 mg plant^{-1}) as well as shoot biomass (831.7 mg plant^{-1}) that resulted in the higher S:R in sorghum when grown mixed with millets. But due the dominant corn plants in the three crops mixed stands probably may have took more nutrients and water that had adversely affected the shoot (128.6 mg plant^{-1}) and root biomass (64.3 mg plant^{-1}) in sorghum indicated the supremacy of corn plants in the mixed stands. According to Costa *et al*., (2002) & Davidson (1969), the mineral nutrients P and N exerted pronounced influences on photosynthates and dry weight partitioning between shoots and roots. The increase in S:R of millets (60 DAE) under high water level (Table 7) was attributed to the higher shoot biomass produced by millets (207.0 mg plant^{-1}) than produced under low (169.0 mg plant^{-1}) water level (Table 9). In the pure stand, millets produced the highest shoot (475.3 mg plant^{-1}) and root biomass (64.8 mg plant^{-1}) indicating less intra-specific plants competition and therefore the S:R was increased in the pure millets stand. In the three crops mixed stands, millets was proved to be the least competitor by producing the lowest shoot biomass (24.8 mg plant^{-1}) and the lowest root biomass (11.1 mg plant^{-1}) that resulted in the lowest S:R in millets. Sorrenson *et al*., (1993) suggested that the measurement of canopy architecture is very important in crop-crop competition.

At the third cut (90 DAE), the higher S:R of corn plants at low than high water level (Table 1) was attributed to the higher root biomass (Table 2) of corn plants at low than high water level. At low water level, although the shoot biomass in corn was also increased (Table 3), but this increase was more in the root biomass as compared to shoot biomass that resulted in the S:R was reduced. The higher shoot biomass of corn in the corn + sorghum + millets mixed stand under low water level was the major cause to increase the S:R at low than high level. The contribution to the total shoot biomass was from stem than the leaf biomass. The decrease in S:R of corn in the millets mixed stand was attributed to the significant increase in root biomass of corn plants. The increase in S:R of corn in the millets mixed stand at high water level was due to the higher shoot biomass of corn. The higher crop growth rate, taller plants and higher leaf area per plant increased the shoot biomass, but the main reason in the reduction in S:R was the higher root biomass of corn in the millets mixed stands. The very well established root architecture of corn plants under low water levels in the millets mixed stand had negative impacts on the growth, shoot and root biomass of millets and so corn plants benefited more and resulted in the lower S:R. Generally the corn because of higher shoot and root biomass production in the pure and mixed stand was considered the best competitor, followed by sorghum and the millets was considered the least competitor in the mixed stands. The S:R in corn increased at the late growth stage than the early two growth stages probably because of more dry matter portioning to shoot than roots at the late growth stage. Robinson *et al*., (1994), Marschner (1995), and Lucas *et al*., (2000) reported that in cereals due to the increasing N supply enhanced both shoot and root growth, but usually shoot growth increases more than root growth, leading to increased S:R on dry weight basis when N supply was increased. The higher S:R in sorghum (90 DAE) under low water level (Table 4) was attributed to the higher shoot biomass produced by sorghum (2.73 g plant^{-1}) under low water level as compared with high water level (2.16 g plant^{-1}) (Table 5). Because of the very well established shoot and root system of sorghum in the millets mixed stand particularly under low water level, increased the root biomass (1.34 g plant^{-1}) (Table 4) as well as shoot biomass (5.53 g plant^{-1}) under lower water level, and so the S:R in sorghum was increased in the millets mixed stand. However, the dominant competitor, the corn plants in the mixed stands had adversely affected both shoot and root biomass of sorghum which declined the S:R in sorghum. The changes in the S:R in sorghum under pure and mixed stands was due to the differences in the root biomass of sorghum produced because of inter plants competition. These differences in the root biomass probably might have influenced the water and nutrients uptake and so the shoot biomass of sorghum also varied in different treatments. Casper & Jackson (1997) reported that the below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground com-petition. The increase in S:R of millets (90 DAE) under low water level (Table 7) was attributed to the higher shoot biomass produced by millets under low (1.54 g plant^{-1}) than high (0.76 mg plant^{-1}) water level (Table 9). In the corn mixed stand, millets had the lowest root biomass (0.02 mg plant^{-1}) under high water level (Table 8) and so the S:R in millets reduced significantly under high than low water level. In the three crops mixed stands, millets was proved to be the least competitor by producing the lowest shoot (0.15 g plant^{-1}) and lowest root biomass (0.04 mg plant^{-1}) that resulted in the lowest S:R in millets. The increase in shoot biomass under low water level (0.18 g plant^{-1}) than high water level (0.13 g plant^{-1}) increased the S:R under low than high water level. In our study, millets was found to be the least competitor in the mixed stands, because the shoot and root biomass of millets were found minimum in the mixed stands. The reduction in the root biomass of millets in the mixed stands probably might have negatively influenced the water and nutrients uptake and so the shoot biomass in millets was also declined. Casper & Jackson (1997) reported that the below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground com-petition. But Sorrenson *et al*., (1993) suggested that the measurement of canopy architecture is very important in crop-crop competition.

In the corn and millets mixed stand (90 DAE), millets had the lowest root biomass (Table 8) and so the average S:R was increased (Table 7). Furthermore, the corn plants in the millets mixed stand had highest shoot biomass because of less intra-specific plant completion among corn plants than the high intra-specific competition in the pure corn stand, was another reason to increase the S:R in corn + millets mixed stand. As compared with millets, sorghum had negative impact on the shoot and root biomass of corn in the sorghum mixed stands. But including millets in the mixed stand had positive impact on the root and shoot biomass of corn. Casper & Jackson (1997) reported that the below-ground competition for water and nutrients can be stronger and can involve more neighbors than above-ground com-petition. In this study we noted that the shoot biomass increased at a higher rate than root biomass with passage of time and so the S:R increased with advancement in crop age. Evans & Wardlaw (1976) reported that in contrast to shoot, dry weight partitioning in roots is high during the seedling stages of crop growth and steadily declines throughout development. Amanullah *et al*., (2009) found that total biomass accumulation in maize increased with increase in plant height and leaf area per plant, and that total biomass accumulation was significantly higher at physiological maturity than at silking. Similarly, Fageria *et al*., (1992) reported increase in shoot-root ratios in different crop species as plants advanced in age. Better understanding of root biomass accumulation in pure and mixed stands could help to maximize water and nutrients uptake and sequester more carbon into the soils. According to Malhi *et al*., (2009), adoption of better management strategies can increase the amount of organic C and/or N stored in the soils.

Conclusions

The three warm season C_4-cereals (corn, grain sorghum and foxtail millets) responded differently in terms of shoot to root ratio when grown in pure and mixed stands. Among the three crops, millets plants had the higher S:R due to its lowest dry matter accumulation particularly in the roots. The roots and shoot dry matter accumulation in millets was drastically declined in the mixed stands, and therefore, it was considered the least competitor in the mixed stands as compared to sorghum and corn. Corn plants on the other hand with lower S:R probably may have captured the most resources above (light) and below (water and nutrients) over time because of its well developed shoot and root systems and was ranked first in terms of competitiveness in the mixed stands. Grain sorghum was ranked second in terms of competitiveness in the mixed stands (corn > grain sorghum > millets). Measurement of both shoot and root biomass was considered very important in crop-crop competition. Better understanding of root growth of different crop species in pure and mixed stands was suggested to maximize water and nutrients uptake, and adaptation to diverse agro climatic conditions. Early emergence improved both shoots and root growth and was also considered the best criteria in crops competitiveness. The decrease in water level improved root growth than the shoot growth and so the S:R decreased under low water level. The shoot biomass increased at higher rate than root biomass with passage of time and so the S:R increased with advancement in crop age. It was suggested that more studies are required to assess more accurately the root biomass contribution of different crops species in pure and mixed stands to improve carbon sequestration into the soils under different environmental conditions.

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