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THE IMPACT OF SEED PRIMING AND ROW SPACING ON THE PRODUCTIVITY OF DIFFERENT CULTIVARS OF IRRIGATED WHEAT UNDER EARLY SEASON DROUGHT*

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SUMMARY

This study was conducted to improve wheat production under vegetative (early season) drought stress. Hydroprimed and osmoprimed (with $CaCl_2$) seeds of wheat cultivars Lasani-2008 (LS-2008) and Triple Dwarf-1 (TD-1), were sown in 20 (narrow), 25 (medium), and 30 cm (wider) spaced rows. Crop was grown under well-watered conditions till physiological maturity or was subjected to drought stress (50% field capacity) during vegetative phase and then grown under well-watered conditions. Drought stress caused substantial reduction in grain and biological yields, related traits, harvest index (HI) and water use efficiency (WUE). Nonetheless, planting osmoprimed seeds in narrowly spaced rows significantly improved the grain yield, HI and WUE. However, wheat planted in wider rows had bold grains. Furthermore, wheat cultivar LS-2008 produced better yield, even under drought stress, than cultivar TD-1. Economic analysis indicated that planting osmoprimed seeds of wheat cultivar LS-2008 in narrowly spaced rows under early season drought yielded maximum economic benefits. In conclusion, planting osmoprimed seeds of cultivar LS-2008 in narrowly spaced rows is a good agronomic option to improve the wheat performance under early season drought stress.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a primary food source of nutrition for masses across the globe (Braun *et al.*, 2010). More than 2.5 billion people consume wheat grain as their staple food (FAOSTAT, 2010). Human population is increasing at enormous rate, and is expected to be doubled in next 50 years (Chaves and Davies, 2010). During 2011–12, total area under wheat crop was 215 million hectares that yielded 671 million tons of wheat (FAO, 2012). In order to match the pace of ever-rising population of the globe; it is estimated that global wheat demand will increase by 60% until 2050. On the other hand, during this period, a decrease of 29% in wheat grain yield is expected due to different biotic and abiotic stresses (Manickavelu *et al.*, 2012).

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Drought stress is the most critical among abiotic stresses which are curtailing wheat productivity all around the world (Farooq *et al.*, 2014). Moreover, water scarcity will be among the worst problems in the coming decades due to climate change and increasing population pressure (Hendrix and Glaser, 2007; Lobell *et al.*, 2008). With declining rainfall, drought stress is projected to decrease per capita food production, thus becoming the principal determinant of global food security (Brown and Funk, 2008; Gleditsch *et al.*, 2006). Different metabolic events like nutrient uptake, carbon-fixation, growth, development and final productivity of crops are affected under drought stress (Farooq *et al.*, 2014).

About 60% of world agricultural production is rainfed with frequent drought episodes. These drought episodes cause substantial yield losses particularly in cereals (SIWI, 2001). During 2000, 70% of the total global area under wheat cultivation was rainfed (Portmann *et al.*, 2010), which faced periodic events of drought stress at different growth stages. Numerous studies have highlighted the severe effects of drought on wheat at vegetative and reproductive stage (Farooq *et al.*, 2014; Milad *et al.*, 2011; Rizza *et al.*, 2004; Schneekloth *et al.*, 2012; Sivamani *et al.*, 2000; Tuberosa and Salvi, 2006). Early season drought (vegetative drought) may cause 22–80% yield reductions in wheat. In Pakistan, wheat crop is irrigated through canal irrigation system and ground water using tubewells. However, the recent shortfall of energy in the country has caused severe drought periods in early stages of wheat crop. On the other hand, in canal irrigated areas, the cyclic canal closure results in insufficient supply of water, which leads to drought events in wheat crop (Sadaqat *et al.*, 2003). Both of these factors have been resulting in decreased crop yields due to the onset of early season drought stress in wheat crop.

Among several management practices, selection of drought tolerant wheat cultivars, seed priming and planting geometry have been found very effective in improving the wheat productivity under less than optimum conditions (Farooq, *et al.*, 2015; Farooq *et al.*, 2008; Jafar *et al.*, 2012). However, little work is reported regarding the management strategies for improving the wheat performance under vegetative drought stress.

Plant drought tolerance starts from early seedling vigour, and seed priming is an excellent technique being used to improve seedling vigour and yield improvement of wheat under drought stress (Farooq *et al.*, 2015; Ludwig and Asseng, 2010). Seed priming also helps in earlier completion of growth phases, improvements in crop allometry, grain output and HI in wheat (Farooq *et al.*, 2008; Farooq *et al.*, 2015; Khan *et al.*, 2011).

Row spacing is another important agronomic practice, which can be used to improve drought tolerance of wheat. As evaporation form the soil depends upon the cover of bare soil exposed to sun, so narrow row spacing improves drought tolerance by minimizing evaporation losses (Farooq *et al.*, 2015). However, wheat cultivars should be planted considering the plant stature and tillering capacity. For example, dwarf cultivars with low tillering capacity sown in narrowly spaced rows, and cultivars exhibiting lower tillering potential with medium row spacing produced better yield (Chen and Neill, 2006; Hussain *et al.*, 2012, 2013).

Although, a recent study reported that combination of good agronomic practices may help improve wheat performance under terminal drought (Farooq *et al.*, 2015).

However, to the best of our knowledge, no study has been conducted to evaluate the potential of seed priming, divergent row spacing for yield improvement of diverse wheat genotypes under vegetative drought stress. Therefore, this two-year field trial was conducted to study the potential role of seed priming for improved performance of different wheat cultivars of diverse morphology, sown under different row spacings under vegetative drought stress.

MATERIALS AND METHODS

Experimental site description

This two-year field experiment was conducted at Experimental Farm, Department of Agronomy, Bahauddin Zakariya University, Multan, Pakistan (71.43°E, 30.20°N and 122 m asl) during winter seasons of 2010–11 and 2011–12. The experimental site lies in semi-arid, sub-tropical region. Weather data of both growing seasons is given in Table S1 (supplementary material available online at: http://dx.doi.org/10.1017/S0014479716000053). The experimental soil was uniform (ECe 2.56 dS m^{-1} and pH 8.9), and belonged to Sindhlianwali soil series (USDA classification).

Experimental details

Seeds of wheat cultivars LS-2008 (medium to tall statured and late maturing) and TD-1 (dwarf and early maturing suitable for semi-arid areas) were obtained from Wheat Research Institute, Faisalabad, Pakistan and Ali Tareen Farm, Lodhran, Pakistan, respectively. Seed of both cultivars was soaked in aerated water (hydropriming) or solution of $CaCl_2$ (ψs -1.25 MPa; osmopriming) for 18 h following Farooq *et al.* (2008). Seeds were removed from the respective solution, rinsed thoroughly with distilled water and were re-dried under shade with forced air near to their original weight. Seeds were then sealed in plastic bags and stored at 5 ºC until sowing.

Primed seeds of both cultivars were sown in 20 (narrow), 25 (medium) and 30 cm (wider) spaced rows. Crop was grown under well-watered conditions (100% field capacity) through the entire growth period or under vegetative drought stress (50% field capacity) up to stages 2–10.1 and then grown under drought free conditions (100% field capacity) from stages 10.1–14 according to Feekes scale (Large, 1954). For maintaining the required field capacity, soil samples were taken at one week interval from 15 and 30 cm soil depth and treatments were watered with measured amount of water using a cut-throat flume.

Experiment layout

The experiment was laid out according to randomized complete block design (RCBD) using factorial arrangements having net plot size of 3 × 4 m. Drought stress treatments, wheat cultivars, seed priming and row spacing were arranged in main, sub, sub-sub and sub-sub-sub plots, respectively. Each treatment had three replications while replication over time was done by repeating the experiment in two consecutive years.

Crop husbandry

Pre-soaking irrigation (10 cm) was applied to bring soil under workable conditions. After soil reached at feasible moisture contents (optimum for seedbed preparation), fine seedbed was prepared by ploughing the soil followed by planking with tractor-driven implements. Wheat seeds were drilled using a seed rate of 125 kg ha^{-1} on November 10, 2010 and December 01, 2011 during 1st and 2nd year of experiment. Crop was fertilized with 120 kg nitrogen (N) and 95 kg phosphorus (P) using urea and di-ammonium phosphate as source during both years. Total P and half of N were applied as basal dose; while remaining half N was applied 30 days after crop sowing. Stale seedbed practice was performed each year before experiment for controlling weeds in the experimental area. Mature crop was harvested manually on April 13 and 26 during 2011 and 2012, respectively.

Yield and related traits

Total number of productive (spike bearing) tillers from randomly selected area (1 m^2) from three locations in each plot were counted and then averaged. Likewise, twenty randomly selected spikes from each treatment unit were used to record grains per spike. For recording 1000-grain weight, 3 random 1000-grain samples from each treatment unit were weighed to record 1000-grain weight. Whole plots were manually harvested, dried under sun for one week, after that bundles were made and weighed for recording biological yield. Manual threshing was done to separate the grains; grain yield was computed by weighing separated grains. Straw yield was computed by weighing the straw left after separation of grains. HI was taken as ratio of grain yield to biological yield and expressed in percentage.

Water use efficiency (g m^{-2})

WUE was recorded as ratio of grain yield to water supplied (Viets, 1962).

Economic analysis

For assessing economic feasibility of different agronomic practices, economic analysis of the experiment was performed. The details of fixed and variable cost are represented in Table S5 (Supplementary material). Due to the small size of plots, the grain yield was reduced to 10% to make the results comparable at farmer level as suggested by Byerlee (1988). Total gross income was computed keeping in view the existing market prices of wheat grains and straw in local market. Total net field benefits were calculated as the difference between gross income and variable cost while the net income was calculated as difference between the gross income and total cost (including both fix and variable costs) (Byerlee, 1988).

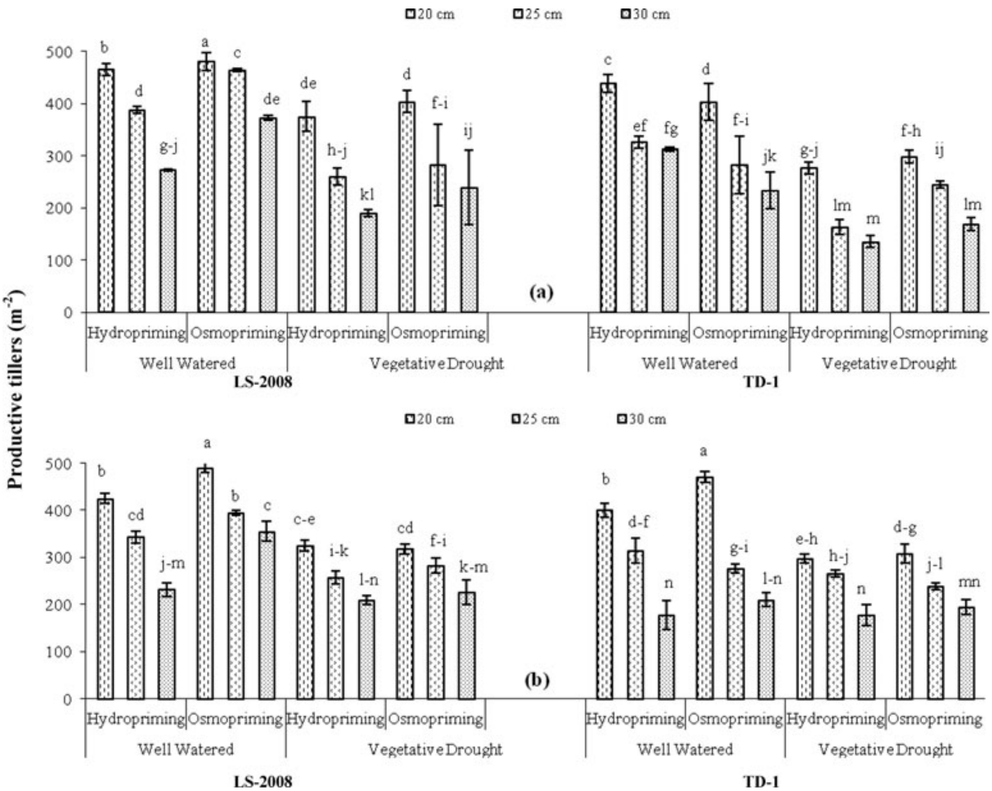

Figure 1. Effect of different seed priming techniques on number of productive tillers of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

Statistical analysis

The collected data were statistically analysed with MSTATC computer program using Fischer's analysis of variance technique (ANOVA). The ANOVA results indicated significant difference among the years data (see Table S2 Supplementary material), therefore the data from both years was analysed and represented separately (see ANOVA Table S3 and S4; Supplementary material). For comparing significance among treatment means, least significant difference test was used at 5% probability (Steel *et al.*, 1997). Significance among treatment means, and among their all possible interactions was tested. Treatments and interactions among them were found to be significant due to which the four way interactions (drought stress×cultivars×seed priming×row spacing) were represented in graphical form. Variability among the represented data was also tested and is represented in terms of standard errors. Computer program Microsoft Excel 2010 along was used for graphical presentation of data and computing standard errors.

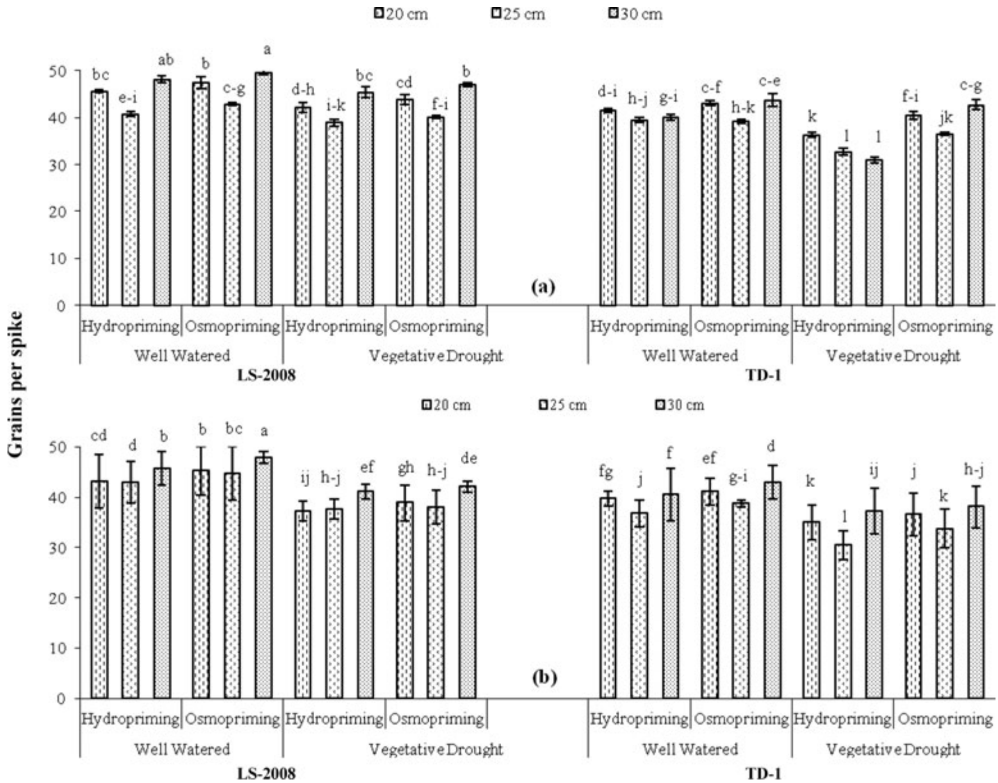

Figure 2. Effect of different seed priming techniques on number of grains per spike of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

RESULTS

Yield and related traits

Wheat cultivars, seed priming, row spacing and early season DS had significant effect on yield and related traits of wheat during both years (Figures 1–5). Population of productive tillers of both cultivars was decreased under DS; nevertheless osmopriming in narrowly spaced rows tended to modify the drought induced decrease in productive tillers to some extent during both years (Figure 1). Osmoprimed LS-2008 during 1st year, and both cultivars during 2nd year with narrow spacing had higher productive tillers; while hydroprimed TD-1 under wider row spacing had lower number of productive tillers under DS at vegetative stage during both years (Figure 1).

DS significantly decreased the number of grains per spike of both cultivars during both years of trial; however, osmopriming in wider rows improved the number of grains per spike of both cultivars under WW and DS conditions (Figure 2). Osmoprimed LS-2008 sown under wider spacing had more number of grains per spike under WW conditions during both years. Osmopriming also improved number of grains under

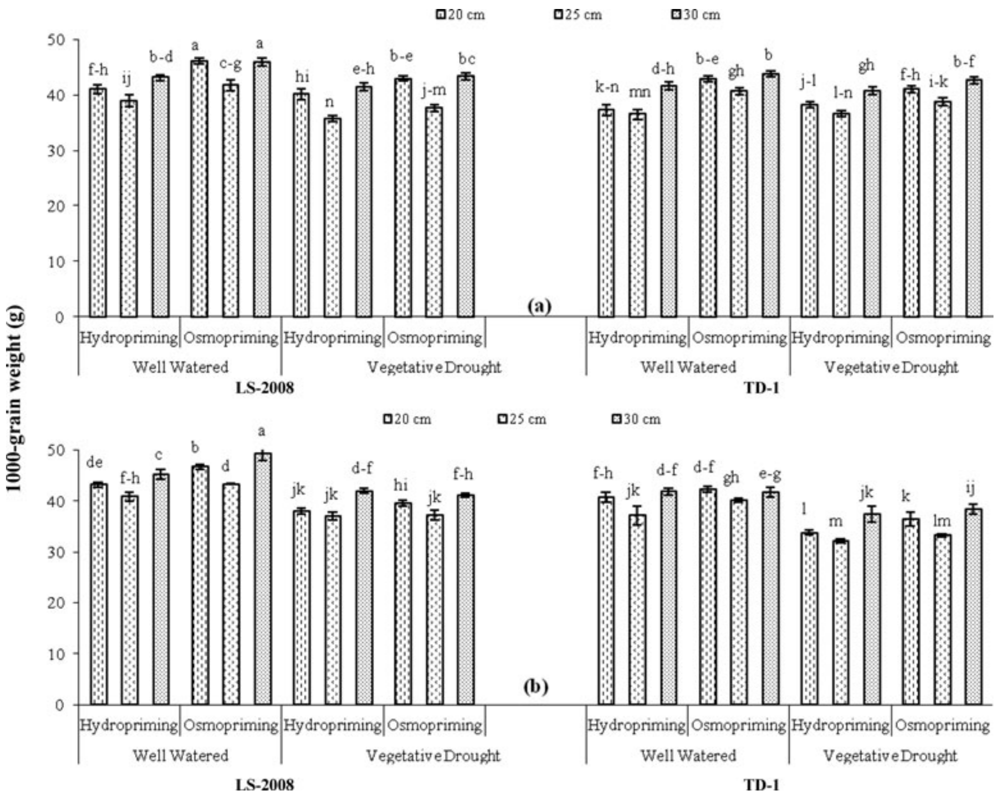

Figure 3. Effect of different seed priming techniques on number of 1000-grain weight of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

DS in both cultivars under narrow and wider row spacings (Figure 2). Both cultivars had substantial cut in grain weight under DS at vegetative stage; while osmopriming improved the grain weight of both cultivars under WW and DS during both years of experimentation (Figure 3). Osmoprimed LS-2008 wheat seeds sown in narrow and wider row spacing during 1st year and in wider row spacing during 2nd year under WW conditions had maximum grain weight; whereas hydroprimed seeds of cultivar TD-1 sown under medium row spacing had minimum grain weight in both years (Figure 3). Grain yield of both cultivars was largely decreased under DS at vegetative stage during both years; nonetheless, osmopriming and narrow row spacing significantly improved the grain yield of both cultivars LS-2008 and TD-1, regardless of year and water conditions (Figure 4). Moreover, osmoprimed seeds of cultivar LS-2008 planted in narrowly spaced rows produced more yield under WW conditions in both years (Figure 4).

Similarly, biological yield of both cultivars was substantially decreased under DS in both years; however, osmopriming and narrow row spacing significantly improved the biological yield of both cultivars under WW and DS (Figure 5). HI was also

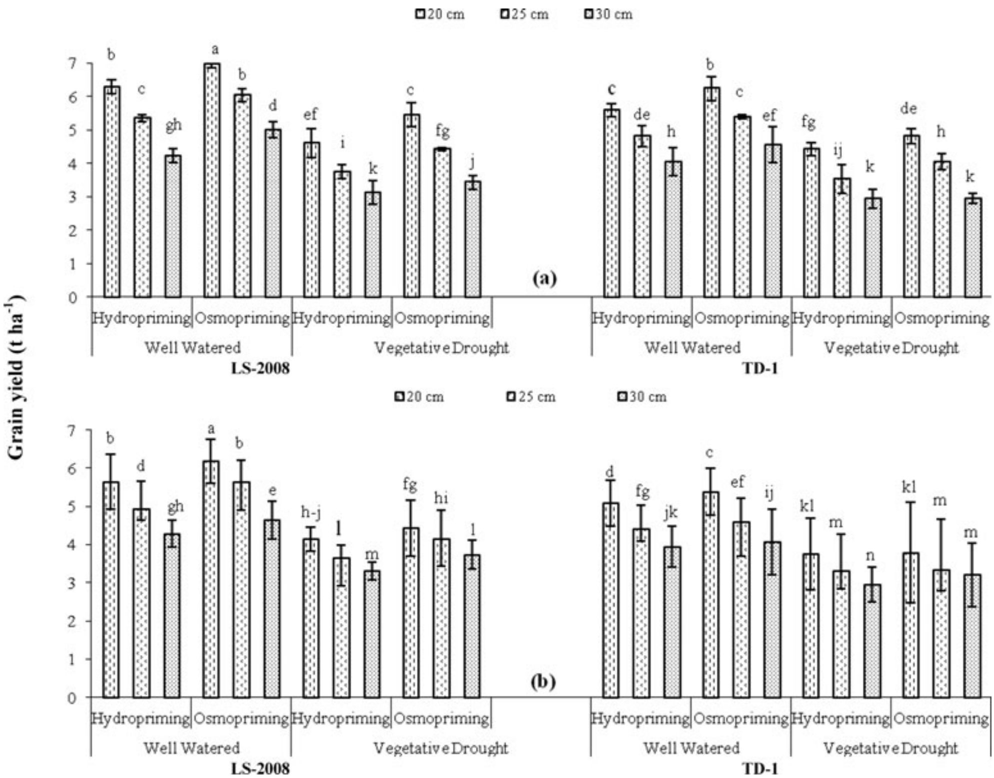

Figure 4. Effect of different seed priming techniques on grain yield of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

decreased under DS; however, wheat performed better in the case of osmoprimed seeds in narrowly spaced rows, regardless of year (Figure 6). Osmoprimed seeds of cultivar TD-1 during 1st year and cultivar LS-2008 during 2nd year sown in narrowly spaced rows had higher HI; nonetheless there was no difference in HI from cultivars LS-2008 and TD-1 under same conditions during 1st year (Figure 6). With respect to genotype, the higher yields and yield components values were recorded for LS-2008 than TD-1, in both experimental years (Figures 2–7).

Water use efficiency (WUE)

All the investigated factors significantly affected WUE, both in 2010/11 and 2011/12 growing seasons (Figure 7). WUE of both cultivars was hampered under DS in both years; however, planting osmoprimed seeds in narrow rows improved the WUE of both tested cultivars under drought during both years (Figure 7). Osmoprimed seeds of cultivar LS-2008 sown in narrow rows had higher WUE under WW and DS during 1st year and under WW environs during 2nd year (Figure 7).

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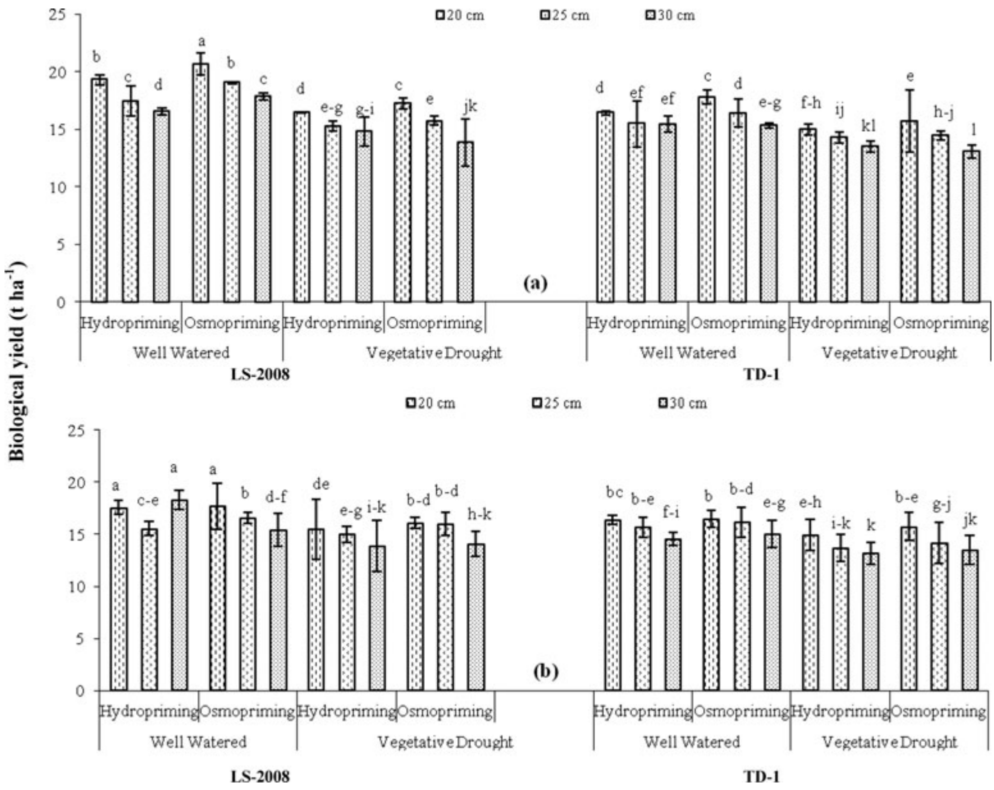

Figure 5. Effect of different seed priming techniques on biological yield of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

Economic analysis

Economics of this study indicated higher gross income, net field benefits and net economic returns under WW conditions than DS conditions during both years of experiment (Table 1). Sowing osmoprimed seeds of cultivar LS-2008 in narrow rows under WW conditions had highest net income during both years. Likewise, osmopriming of LS-2008 seeds and planting under narrow spacings also had higher net income under vegetative drought than other treatment set under drought during both years of trial (Table 1).

DISCUSSION

Water deficit, even during vegetative growth phase, substantially influenced the growth and yield of wheat cultivars. Although, wheat is more sensitive to terminal drought (Farooq *et al.*, 2014; Milad *et al.*, 2011; Sivamani *et al.*, 2000); early season (vegetative stage) drought may also cause up to 80% reduction in grain yield (Sivamani *et al.*, 2000; Tuberosa and Salvi, 2006). This yield reduction is caused by drought-induced decrease in yield components as has been observed in this study. For instance, early

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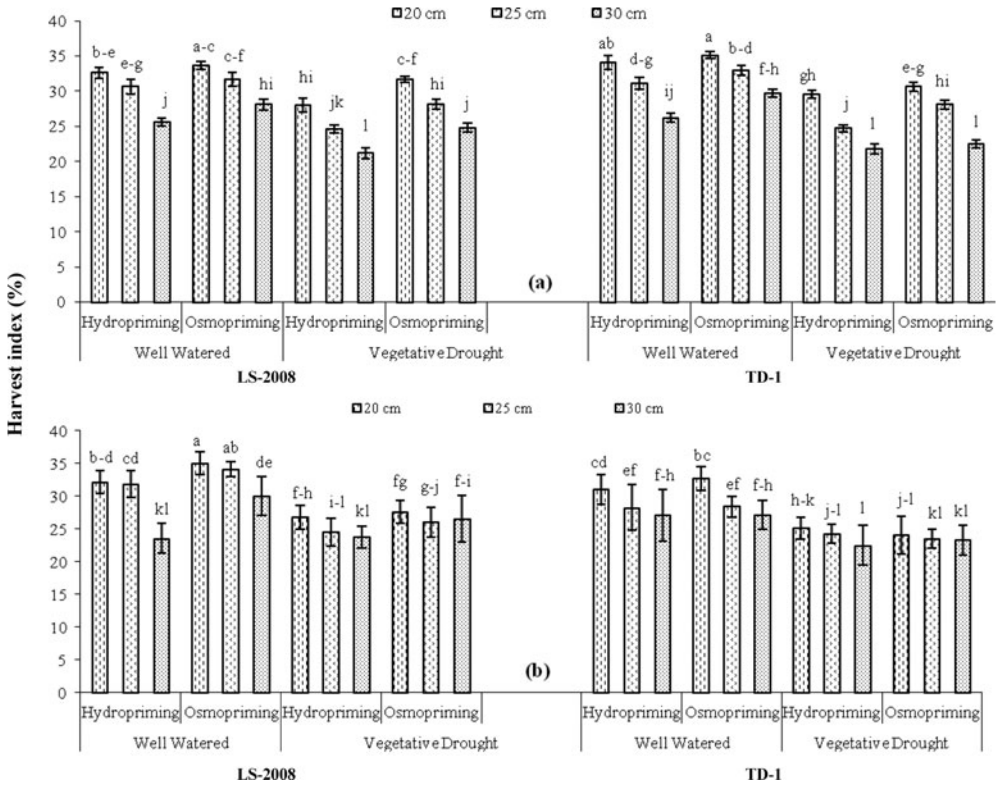

Figure 6. Effect of different seed priming techniques on harvest index of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

season drought caused decrease in number of spikelets (data not given), grains per spike, and grain yield by 27, 73 and 62% (Rizza *et al.*, 2004). In this study, drought-induced decrease in number of grains per spike was principally due to decrease in number of spikelets per spike.

Both cultivars behaved differently under WW and DS conditions. LS-2008 performed better than TD-1 in terms of grain yield. Higher output of LS-2008 was credited to its innate genetic makeup which enabled it to use the available resources (water and nutrients) more efficiently. Nonetheless, due to its medium height, LS-2008 might cover the soil surface more than TD-1 which reduced the evaporation losses under DS and ultimately performed better than TD-1. The genetic variations of wheat for acquiring different resources under same environments is well reported (Alignan *et al.*, 2009; Hussain *et al.*, 2012, 2013).

According to our findings, narrow row spacing improved the productivity of each tested cultivar due to considerable increase in productive tillers under well-watered and vegetative drought during both years. This is probably due to the scarce competition of wheat plants for soil moisture and solar radiation. Narrow row spacing decreased the evaporation losses due to higher canopy shading (i.e. higher LAI, data not given) on

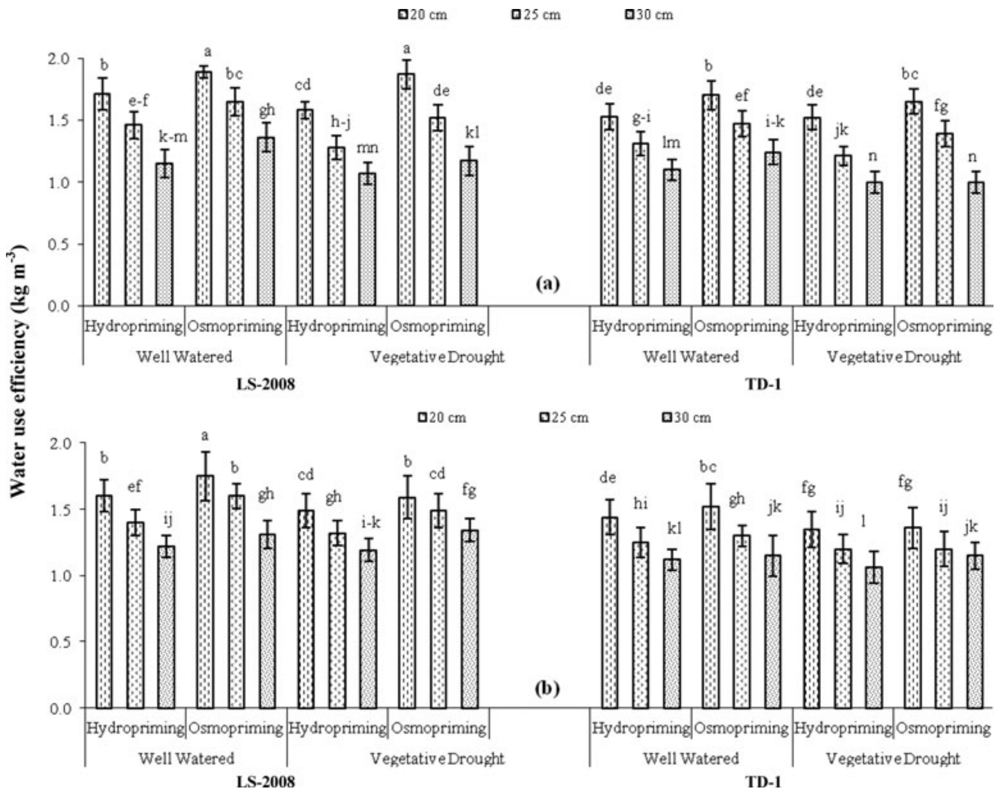

Figure 7. Effect of different seed priming techniques on water use efficiency of wheat genotypes grown at different row spacings under vegetative drought stress during (a) 2010–11 and (b) 2011–12. The vertical bars are standard errors. The means sharing same letter do not differ significantly at $p = 0.05$ ($n = 3$).

soil (Chen and Neill, 2006), specifically under drought (Farooq *et al.*, 2015). Moreover, improved grain outputs of wheat by narrow row spacing have been observed under less than optimum conditions owing to avoidance mechanism. However, grain count and size was better under wider row spacing. More competition in too close rows and more plants per unit area seem the reasons of lower grain count and size under closely spaced rows compared with wider row spacing. Interestingly, higher grain count and size could not counteract the yield loss induced by low number of productive tillers in wider row spacing in both tested cultivars during both years. Improved grain yield under narrow row spacing was probably the effect of lower evaporation caused by high number of tillers and canopy cover. A small soil surface is exposed to sun in this situation in contrast to wider row spacing. Some recent studies have reported higher yield of low tillering dwarf and medium statured wheat cultivars planted under narrow row spacing under optimal and sub-optimal water supply (Farooq *et al.*, 2015; Hussain *et al.*, 2012, 2013).

Seed priming is pre-germination treatment, which results in synchronous, uniform and quick emergence and makes the emerging seedling more vigourous. Osmopriming significantly improved the grain yield of both tested cultivars owing to substantial

Table 1. Economic analysis for the effect of different seed priming techniques on the wheat genotypes grown at different spacings under early season drought stress.

	Gross Income (US\$ ha^{-1})		Net Field Benefits (US\$ ha^{-1})		Net income (US\$ ha^{-1})	
Treatments	2010–11	2011–12	2010–11	2011–12	2010–11	2011–12
$W_1V_1P_1S_1$	1900.52	1694.99	1788.65	1576.01	1173.38	945.99
$W_1V_1P_1S_2$	1632.80	1497.35	1520.93	1378.36	905.66	748.34
$W_1V_1P_1S_3$	1312.45	1310.86	1200.58	1191.87	585.31	561.85
$W_1V_1P_2S_1$	2093.02	1850.88	1955.72	1705.45	1340.45	1075.43
$W_1V_1P_2S_2$	1829.59	1695.28	1692.29	1549.85	1077.02	919.83
$W_1V_1P_2S_3$	1535.84	1411.54	1398.54	1266.11	783.27	636.09
$W_1V_2P_1S_1$	1703.45	1536.25	1591.58	1417.26	976.30	787.24
$W_1V_2P_1S_2$	1479.49	1347.47	1367.62	1228.48	752.35	598.46
$W_1V_2P_1S_3$	1261.54	1211.32	1149.67	1092.34	534.39	462.31
$W_1V_2P_2S_1$	1887.08	1621.49	1749.78	1476.06	1134.51	846.04
$W_1V_2P_2S_2$	1647.10	1394.38	1509.81	1248.95	894.53	618.93
$W_1V_2P_2S_3$	1404.84	1245.93	1267.54	1100.50	652.27	470.48
$W_2V_1P_1S_1$	1421.43	1268.53	1330.91	1173.95	715.64	543.93
$W_2V_1P_1S_2$	1176.01	1129.23	1085.50	1034.65	470.23	404.63
$W_2V_1P_1S_3$	997.82	1029.12	907.31	934.54	292.03	304.52
$W_2V_1P_2S_1$	1661.97	1349.76	1546.04	1228.74	930.76	598.72
$W_2V_1P_2S_2$	1369.08	1271.10	1253.15	1150.08	637.87	520.06
$W_2V_1P_2S_3$	1085.34	1151.83	969.41	1030.81	354.13	400.79
$W_2V_2P_1S_1$	1369.08	1155.55	1278.57	1060.97	663.30	430.95
$W_2V_2P_1S_2$	1111.66	1032.84	1021.15	938.26	405.87	308.24
$W_2V_2P_1S_3$	941.47	929.30	850.96	834.72	235.69	204.70
$W_2V_2P_2S_1$	1480.63	1165.56	1364.70	1044.54	749.42	414.52
$W_2V_2P_2S_2$	1262.11	1037.70	1146.17	916.68	530.90	286.66
$W_2V_2P_2S_3$	942.90	998.23	826.97	877.21	211.69	247.19

W_1 = Well Watered; W_2 = Vegetative drought; V_1 = LS-2008; V_2 = TD-1; P_1 = Hydropriming; P_2 = Osmopriming, S_1 = 20 cm; S_2 = 25 cm and S_3 = 30 cm.

increase in productive tillers, number of grains and size during both years. Similarly, osmopriming was better than hydropriming under well-watered conditions. As a result of early and highly uniform emergence, the seedlings produced by osmoprimed seeds used the available resources more efficiently. Thus, these seedlings performed well through the entire growing period under both well-watered and drought stress. Drought stress at vegetative stage had no influence on WUE during 1st year and it had slightly decreased the WUE during 2nd year of experiment; as yield decline under drought stress was recompensed by low moisture supply in drought stressed plots. The tested treatment individually are classified in terms of their importance for improving grain yield and WUE under DS as narrow row spacing > medium and wider row spacing and osmopriming with $CaCl_2$ > hydropriming as all treatments received equal water supply.

Commercial adoption or success of any new technology or technique among farming community is linked with its economic feasibility (Hussain *et al.*, 2012; Meinke *et al.*, 2001). Economic analysis of this study indicated the dominance of well-watered conditions over vegetative drought, medium statured cultivar LS-2008 over dwarf

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cultivar TD-1, narrow row spacing (20 cm) over medium and wider (25 and 30 cm) row spacing and osmopriming over hydropriming to realize higher net income due to substantial increase in grain yield.

CONCLUSION

In conclusion, drought stress at vegetative stage substantially decreased grain yield of both tested wheat cultivars; however, planted osmoprimed seeds in narrowly spaced rows helped in minimizing the drought induced yield losses of both tested cultivars. Osmoprimed seeds of medium statured cultivar LS-2008 planted under 20 cm spaced rows were better able to produce higher grain yield under vegetative drought and well-watered environments.

SUPPLEMENTARY MATERIALS

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0014479716000053.

REFERENCES

Alignan, M., Roche, J., Bouniols, A., Cerny, M., Mouloungui, Z. and Merah, O. (2009). Effects of genotype and sowing date on phytostanol–phytosterol content and agronomic traits in wheat under organic agriculture. *Journal of Food Chemistry* 117:219–225.

Braun, H. J., Atlin, G. and Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. *Climate change and crop production*, 115–138 (Ed. M. P. Reynolds). CABI Climate Change Series: UK.

Brown, M. E. and Funk, C. C. (2008). Food security under climate change. *Science* 319:580–581.

Byerlee, D. (1988). *From agronomic data to farmer's recommendations, an economic training manual.* Centro Internacional de Maiz Y Trigo: Mexico. 23–33.

Chaves, M. M. and Davies, B. (2010). Drought effects and water use efficiency. *Functional Plant Biology* 37:3–4.

Chen, C. and Neill, K. (2006). Response of spring wheat yield and protein to row spacing, plant density and nitrogen application in Central Montana. Fertilizer Fact: No. 37. Montana State University, Agricultural Experiment Station and Extension Service.

FAO. (2012). Faostat, food and agriculture organization of the united nations (FAO) statistical databases (2014) last updated 15 Aug 2014 Available online at: www.fao.org.

FAOSTAT. (2010). Data, 2007, Food and Agricultural commodities production, Rome, Italy. Available online at: http://faostat.fao.org.

Farooq, M., Basra, S. M. A., Rehman, H. and Saleem, B. A. (2008). Seed priming enhances the performance of late sown wheat (*Triticum aestivum* L.) by improving the chilling tolerance. *Journal of Agronomy and Crop Sciences* 194:55–60.

Farooq, M., Hussain, M. and Siddique, K. H. M. (2014). Drought stress in wheat during flowering and grain-filling periods. *Critical Reviews in Plant Sciences* 33:331–349.

Farooq, S., Shahid, M., Khan, M. B., Hussain, M. and Farooq, M. (2015). Improving the productivity of bread wheat by good management practices under terminal drought. *Journal of Agronomy and Crop Sciences* doi:10.1111/jac.12093.

Gleditsch, N. P., Furlong, K., Hegre, H., Lacina, B. and Owen, T. (2006). Conflicts over shared rivers: resource scarcity or fuzzy boundaries? *Political Geography* 25:361–382.

Hendrix, C. S. and Glaser, S. M. (2007). Trends and triggers: Climate, climate change and civil conflict in Sub-Saharan Africa. *Political Geography* 26:695–715.

Hussain, M., Khan, M. B., Mehmood, Z., Zia, A. B., Jabran, K. and Farooq, M. (2013). Optimizing row spacing in wheat cultivars differing in tillering and stature for higher productivity. *Archives of Agronomy and Soil Sciences* 59:1457–1470.

Hussain, M., Mehmood, Z., Khan, M. B., Farooq, S., Lee, D.-J. and Farooq, M. (2012). Narrow row spacing ensures higher productivity of low tillering wheat cultivars. *International Journal of Agriculture and Biology* 14:413–418.

Jafar, M. Z., Farooq, M., Cheema, M. A., Afzal, I., Basra, S. M. A., Wahid, M. A., Aziz, T. and Shahid, M. (2012). Improving the performance of wheat by seed priming under saline conditions. *Journal of Agronomy and Crop Sciences* 198:38–45.

Khan, M. B., Ghurchani, M., Hussain, M., Freed, S. and Mahmood, K. (2011). Wheat seed enhancement by vitamin and hormonal priming. *Pakistan Journal of Botany* 43:1495–1499.

Large, E. C. (1954). Growth stages in cereals illustration of the Feekes scale. *Plant Pathology* 3:128–129.

Lobell, D., Burke, M., Tebaldi, C., Mastrandera, M., Falcon, W. and Naylor, R. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607–610.

Ludwig, F. and Asseng, S. (2010). Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. *Agriculture Systems* 3:127–136.

Manickavelu, A., Kawaura, K., Oishi, K., Shin-I, T., Kohara, Y., Yahiaoui, N., Keller, B., Abe, R., Suzuki, A., Nagayama, T., Yano, K. and Ogihara, Y. (2012). Comprehensive functional analyses of expressed sequence tags in common wheat (*Triticum aestivum*). *DNA Research* 19:165–177

Meinke, H., Baethgen, W., Carberry, P., Donatelli, M., Hammer, G., Selvaraju, R. and Stöckle, C. (2001). Increasing profits and reducing risks in crop production using participatory systems simulation approaches. *Agriculture Systems* 70:493–513.

Milad, S. I., Wahba, L. E. and Barakat, M. N. (2011). Identification of RAPD and ISSR markers associated with flag leaf senescence under water-stressed conditions in wheat (*Triticum aestivum* L.). *Australian Journal of Crop Sciences* 5:337–343.

Portmann, F. T., Siebert, S. and Döll, P. (2010). MIRCA2000—global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling Glob. *Biogeochemical Cycles* 24:GB1011.

Rizza, F., Badeck, F. W., Cattivelli, L., Lidestri, O., di Fonzo, N. and Stanca, A. M. (2004). Use of a water stress index to identify barley genotypes adapted to rainfed and irrigated conditions. *Crop Science* 44:2127–2137.

Sadaqat, H. A., Tahir, M. H. N. and Hussain, M. T. (2003). Physiogenetic aspect of drought tolerance in canola (*Brassica napus*). *International Journal of Agriculture and Biology* 5:611–614.

Schneekloth, J., Bauder, T. and Hansen, N. (2012). Limited irrigation management: Principles and practices. http://www.ext.colostate.edu/pubs/crops/04720.html.

Sivamani, E., Bahieldin, A., Wraith, J. M., Al-Neimi, T., Dyer, W. E., Ho, T. D. and Qu, R. (2000). Improved biomass productivity and water use efficiency under water deficit conditions in transgenic wheat constitutively expressing the barley*HVA1* gene, *Plant Science* 155:1–9.

SIWI. (2001). Water harvesting for upgrading of rain-fed agriculture: Problem analysis and research needs. SIWI Report 11, ISBN 91-974183-0-7, SIWI, Sweden.

Steel, R. G. D., Torrie, J. H. and Dicky, D. A. (1997). *Principles and Procedures of Statistics, a Biometrical Approach*. 3rd edn. 352–358. New York, USA: McGraw Hill, Inc. Book Co..

Tuberosa, R. and Salvi, S. (2006). Genomics-based approaches to improve drought tolerance of crops. *Trends in Plant Sciences* 11:405–412.

Viets, F. G. (1962). Fertilizers and the efficient use of water. *Advances in Agronomy* 14:223–264.