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Wheat Sown with Narrow Spacing Results in Higher Yield and Water Use Efficiency under Deficit Supplemental Irrigation at the Vegetative and Reproductive Stage

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Abstract: A decrease in water resources around the globe in irrigated agriculture has resulted in a steep decline in irrigation water availability. Therefore, management options for efficient use of available irrigation water are inevitable. Deciding the critical time, frequency and amount of irrigation are compulsory to achieve higher crop outputs. Hence, this two-year field study was conducted to assess the role of different row spacings, *i.e.*, 20, 25 and 30 cm, on growth, productivity, and water use efficiency (WUE) of wheat under deficit supplemental irrigation (DSI) at the vegetative and reproductive phase by using surplus supplemental irrigation (SSI) throughout the growing season as the control. DSI at both growth stages, and the reproductive stage in particular, changed the crop allometry, yield and net income of wheat. However, narrow spacing (20 cm) resulted in efficient use of available irrigation water (DSI and SSI) with higher yield, WUE and economic returns. Interestingly, wider spacing resulted in a higher number of grains per spike with higher 1000-grain weight under SSI and DSI, but final yield output remained poor due to a lower number of productive tillers. It was concluded that reducing irrigation during the vegetative stage is less damaging compared with the reproductive phase; therefore, sufficient supplemental irrigation must be added at the reproductive stage, particularly during grain-filling. Further, narrow spacing (20 cm) resulted in efficient utilization of available irrigation water; therefore, wheat must be grown at a narrow spacing to ensure the efficient utilization of available irrigation water.

Keywords: deficit supplemental irrigation; row spacing; wheat; net income

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the three main cereals feeding the world. Global annual production during 2013 was 718.13 million tons, feeding about one-fifth of the human population [1]. The rapidly increasing global population will need double the current global wheat production until 2050 to ensure food supply for future generations [2]. Therefore, the scientific community is working to find comprehensive strategies to eliminate the possible danger of famine due to increasing population pressure. Under the current scenarios of climate change, an increase in the cultivation area without adverse social and environmental impacts is virtually impossible; an increase in yield is the only possible option [3,4]. However, a continuous decline in fresh water availability is a hurdle to the potential to increase production [5,6].

Water is a limited resource, with severe competition among industrial, agricultural and domestic users [7]. Different wheat growing regions rely on fresh water for supplemental irrigation, and future availability of fresh and ground water supply is an unanswered question [5,8]. Moreover, the rising demands of household users for water are further scavenging the supply of water for irrigated agriculture [7,9]. The continuously shrinking supply of water for irrigated agriculture creates a severe deficiency of supplemental irrigation water in different wheat-producing regions [10,11]. Deficit supplemental irrigation (DSI) during different growth phases hampers the productivity of wheat, however; the reproductive stage is more sensitive in this regard [4,12]. Insufficient water supply results in accelerated leaf senescence [13], reduced carbon fixation and assimilate translocation [14], pollen sterility [15–17], reduced grain set and development [18], and reduced sink capacity [19,20] in wheat.

By adopting site-specific agronomic techniques, such as resolving acute nutrient deficiency and the rate and geometry of seeding, yield can be somewhat improved under DSI [4,21].

Despite the severe shortage of water in current and future years, wasting of fresh water is common due to the application of heavy supplemental irrigation [22]. Scheduling irrigation in wheat is the most manageable and viable factor that can be used to maximize water use efficiency (WUE) and the productivity of the crop. Several scientists have already worked on maximizing WUE by scheduling irrigation and decreasing supplemental irrigation during the initial growth stages of different crops such as groundnut [23], wheat [22], maize [24], fruit trees [25] and sunflower [26].

Wheat is generally sown in rows spaced 22.5 cm apart without considering the stature and tillering capability of the cultivars under use. Nonetheless, wheat cultivars behave differently under varying row spacing due to their divergent stature and tillering potential [27,28]. To attain higher resource use efficiency and wheat output, tall and high tillering (among currently available semi-dwarf cultivars) wheat cultivars should be planted under narrow row spacing and vice versa [27,28]. Moreover, crops sown in wider rows compete with weeds and have higher evapotranspiration, thus resulting in inefficient utilization of applied inputs [29]. Higher evaporative losses decrease the WUE due to more available space between crop rows. Therefore, to ensure the efficient use of applied irrigation water, row spacing must be optimized such that it reduces the evaporative losses to a minimum without inducing interplant competition.

Therefore, it is hypothesized that narrow row spacing can improve the output and WUE of wheat subjected to DSI during the vegetative and reproductive phase. Hence, this two-year field study was designed to assess the effects of DSI imposed during the vegetative and reproductive phase on the yield, water use efficiency and net return of wheat sown under divergent row spacing.

2. Materials and Methods

2.1. Experimental Details

This two-year field study was conducted in the Agronomy Research Area, Bahauddin Zakariya University, Multan, Pakistan (71.43° E, 30.2° N and 122 m a.s.l.) during the winters of 2010–2011 and 2011–2012. The weather data during the growing season and the physiochemical properties of the experimental soil are presented in Figure 1 and Table 1, respectively.

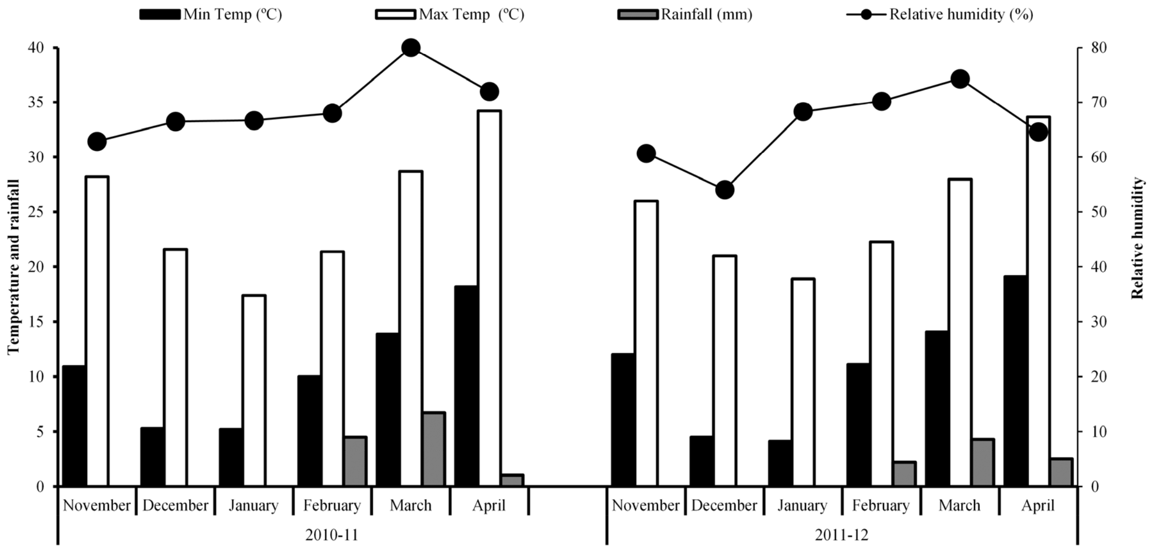

Figure 1. Metrological data for the growing season of the crop during both years of the study.

Table 1. Physio-chemical characteristics of the soil during both years of the experiment.

Characteristic	Unit	Value		Status
		Physical analysis		
		2010–2011	2011–2012	
Sand	%	26.80	23.33	
Silt	%	49.40	57.30	
Clay	%	23.80	19.34	
Textural class		Silty clay loam		
		Chemical analysis		
		2010–2011	2011–2012	
pH		8.60	8.90	Alkaline
Saturation percentage	%	50.84	50.84	
EC	dS m^{-1}	2.42	3.24	High
Organic matter	%	0.64	0.98	Very low
Total nitrogen	%	0.14	0.06	Very low
Available phosphorus	Ppm	4.32	5.13	Low
Available potassium	Ppm	210	278	Medium

The wheat crop was sown under three row spacings, *viz*. 20- (narrow), 25- (medium) and 30-cm (wide), with DSI (50% field capacity) during the vegetative and reproductive growth stages while surplus supplemental irrigation (SSI) (100% field capacity) was provided throughout the growing season as the control. The field capacity was based on the soil moisture content and was maintained by collecting soil samples from depths of 15 and 30 cm on a weekly basis [12]. The saturation percentage of the soil was calculated (soil moisture contents were 50.84% at saturation percentage); half of which was designated as 100% field capacity, and half of the 100% field capacity was considered as 50% field capacity. The field capacity of the soil was maintained by applying a measured amount of water when the moisture level in the soil dropped below the required levels according to the treatments. The vegetative and reproductive growth stages were considered from stages 2–10 and 10–11.4, respectively, according to the Feekes scale [30]. The experiment was laid out in a randomized complete block design (RCBD) with a split plot arrangement. Irrigation treatments were assigned to the main plots while row spacing was randomized in the sub plots. The experimental treatments were replicated three times, with a net plot size of 3 m × 5 m.

2.2. Crop Husbandry

The experimental site received 10 cm of irrigation to make it favorable for seedbed preparation. As soon as the experimental soil attained a feasible moisture regime, the seedbed was prepared by implementing two cultivation practices (10-cm depth) with a tractor-mounted cultivator (Sitara Industries) along with planking. Seeds of the wheat variety Lasani-2008 were obtained from Ayub Agriculture Research Station, Faisalabad, Pakistan. The crop was sown manually by using single-row hand drill to maintain different row spacings with a uniform seed rate of 125 kg ha^{-1} on November 15th and December 3rd during the first and second year of study. Fertilizers were applied at rates of 110 and 92 kg ha^{-1} nitrogen (N) and phosphorus (P), respectively, using urea and triple super phosphate as sources. A full dose of P and half a dose of N were applied at sowing, while the remaining N was applied with the first irrigation. Weeds were controlled using the stale seedbed method. No specific management practices were used for insect and disease control. The mature crop was harvested on April 16th and 23rd during the first and second year of study, respectively.

2.3. Measurements

Allometric traits such as leaf area index (LAI), leaf area duration (LAD) and crop growth rate (CGR) were recorded biweekly during both years starting from 75 days after sowing (DAS) to 120 DAS. For recording LAI, two lines with a length of 0.5 m (randomly selected) from each plot of every treatment unit were cut and the fresh weight was recorded. All the leaves in a harvested sample were separated and the leaf area was recorded using a digital leaf area meter (M2 Delta T Devices). LAI was then calculated by dividing the leaf area by the ground area. Leaf area duration (LAD) was calculated from LAI following **Hunt** [31]. To record CGR, the above-mentioned fresh biomass including the leaves was dried in an oven at 70 °C ± 5 °C until a constant dry weight and converted into m^{-2} using a unitary method. CGR was then calculated using the protocol presented by **Hunt** [31].

A randomly selected area of 1 m^2 from three different locations within each experimental unit was selected, and the total number of productive tillers was counted and averaged. Twenty randomly selected spikes were measured for length and averaged to record spike length and then these spikes were threshed manually; the number of grains in each spike were counted and averaged to record the number of grains per spike. Three random 1000-grain samples were obtained after threshing each plot of every treatment for recording grain yield; the grains were weighed and averaged to record the 1000-grain weight. Each experimental plot was harvested manually, tied into bundles and sundried for one week. After sun drying, the total harvest of the plot was tied into bundles and weighed to record the biological yield. The bundles were threshed manually to separate the grains from the straw. The obtained grains from above-described bundles were weighed after manual threshing to record the grain yield and the difference between the biological and grain yield was termed as the straw yield. Afterwards, the biological, grain and straw yields were converted into kg ha^{-1}. The harvest index was calculated as the ratio between grain yield and biological yield. Water use efficiency (WUE) was computed as a ratio between grain yield and water applied [32]. Moreover, a cut-throat flume was used to apply the specific amount of water according to the different irrigation treatments [26].

2.4. Statistical and Economic Analysis

The data collected on the different parameters were statistically analyzed using analysis of variance (ANOVA), and Fisher′s least significant difference test (LSD) at the 5% probability level was used to compare the significance of the treatment means [33]. Moreover, graphical presentations of the data (including the standard error) were constructed using the Microsoft Excel program.

To assess the economic feasibility of the different treatments, an economic analysis was performed. Total expenses incurred during wheat production from sowing to harvesting were calculated. The incurred expanses included existing prices of land rent, seedbed preparation, seed, sowing, fertilizers, irrigation and plant protection measures. Gross income was projected by considering the existing prices of the wheat grains and straw in the local market. Net income was estimated by subtracting the incurred expenses from the calculated gross income, while the benefit: cost ratio (BCR) was computed by dividing the gross income by the total expenses incurred [34].

3. Results

Leaf area index (LAI) and crop growth rate (CGR) progressively increased up to 105 days after sowing (DAS) and then started to decline (Figures 2 and 3). Deficit supplemental irrigation (DSI) imposed at both phenophases curtailed the LAI and CGR compared with SSI; the effect of DSI during the vegetative stage was more obvious at 105 DAS, while the effect of DSI during the reproductive phase was more evident at 120 DAS (Figures 2 and 3). Nonetheless, narrow spacing (20 cm) compared with medium or wider spacing improved the LAI and CGR throughout the entire growth period under SSI and DSI conditions (Figures 2 and 3). Moreover, leaf area duration (LAD) was also significantly decreased under DSI, while narrow row spacing maintained a higher LAD both under optimal and DSI conditions (Figure 4).

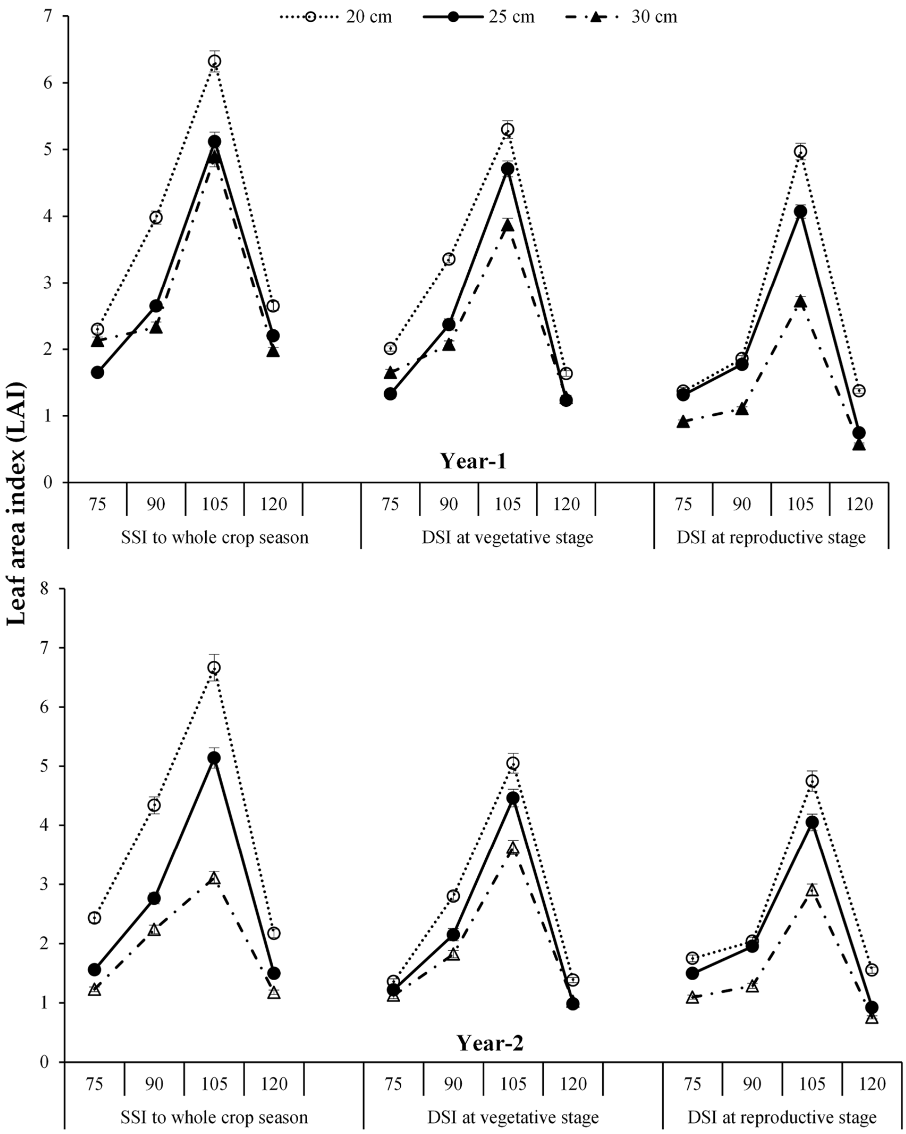

Figure 2. Effect of different row spacings on the leaf area index (LAI) of wheat grown under sufficient (SSI) and deficit supplemental irrigation (DSI) applied at different growth stages. The *x*-axis values are days after sowing. $n = 3$.

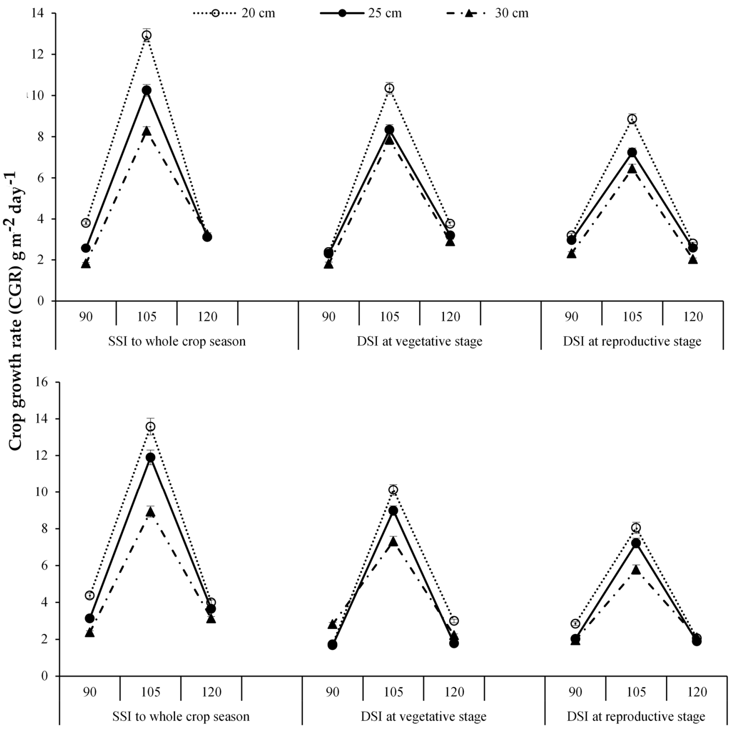

Figure 3. Effect of different row spacings on the crop growth rate (CGR) g m^{-2} day^{-1} of wheat grown under sufficient (SSI) and deficit supplemental irrigation (DSI) applied at different growth stages. The *x*-axis values are days after sowing. *n* = 3.

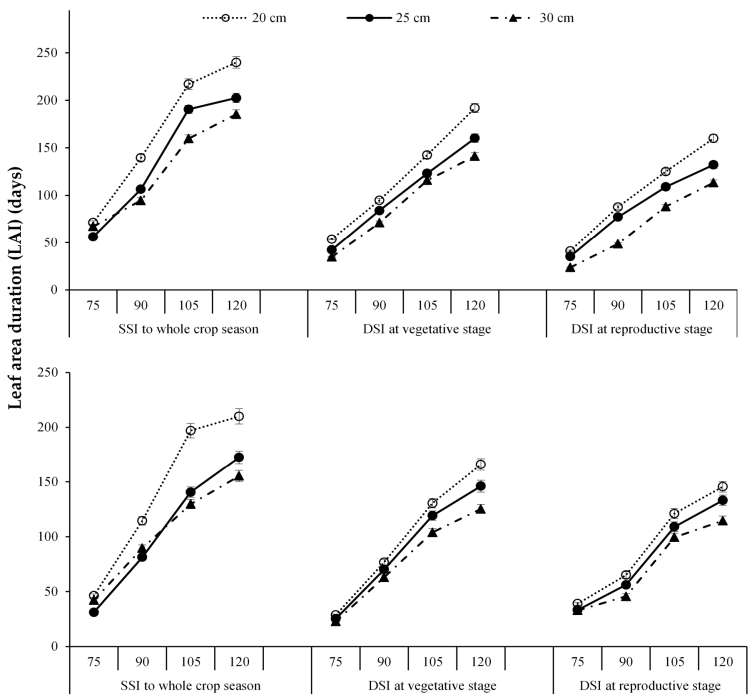

Figure 4. Effect of different row spacings on leaf area duration (LAD) (days) of wheat grown under sufficient (SSI) and deficit supplemental irrigation (DSI) applied at different growth stages. The *x*-axis values are days after sowing. *n* = 3.

Interaction between irrigation levels and row spacings had a significant effect on yield and related traits of wheat during both years of study (Table 2). DSI at different growth stages, and the vegetative stage in particular, decreased the number of productive tillers, while narrow row spacing improved the number of productive tillers both in the well-watered and water deficit environments (Table 3). The highest productive tillers were produced under SSI with narrow row spacing during both years of the trial, while wider row spacing under DSI during the vegetative stage performed poorly in this regard (Table 3). Spike length was notably decreased by DSI, while wider spacing improved spike length under both SSI and DSI (Table 3). The crop sown under wider and narrow row spacing during the first year, and wider row spacing during the second year produced longer spikes under SSI, while medium row spacing under DSI during the reproductive stage resulted in the smallest spikes during each year of study (Table 3).

Table 2. Analysis of variance of growth and yield parameters of wheat grown under DSI during the vegetative and reproductive stages at different row spacings.

Variable	Irrigation		Row spacing		Irrigation × Row spacing	
	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2
Productive tillers m^{-2}	0.002	0.001	0.000	0.002	0.010	0.030
Spike length (cm)	0.003	0.000	0.002	0.000	0.012	0.010
Number of grains $spike^{-1}$	0.001	0.002	0.003	0.001	0.042	0.020
1000-grain weight (g)	0.002	0.000	0.005	0.001	0.043	0.010
Grain yield kg ha^{-1}	0.000	0.000	0.000	0.000	0.040	0.001
Biological yield kg ha^{-1}	0.000	0.042	0.000	0.001	0.043	0.001
Harvest index (%)	0.004	0.000	0.001	0.011	0.031	0.000
WUE (kg m^{-3})	0.000	0.000	0.000	0.001	0.020	0.000

Table 3. Effect of different row spacings on yield parameters of wheat grown under DSI during the vegetative and reproductive stage.

Treatments	Productive tillers m^{-2}		Spike length (cm)		Number of grains $spike^{-1}$		1000-grain weight (g)	
	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2
Irrigation levels (I)								
I_1 = SSI throughout whole crop season	701.8 a	563.4 a	17.22 a	17.25 a	47.00 a	45.97 a	44.59 a	42.39 a
I_2 = DSI at vegetative stage	508.5 c	431.6 c	16.05 b	15.81 b	43.63 b	39.67 b	41.30 b	35.27 b
I_3 = DSI at reproductive stage	607.3 b	495.4 b	15.26 c	14.44 c	34.64 c	35.35 c	36.74 c	31.85 c
LSD at 5%	33.90	36.74	0.35	0.31	0.47	1.24	0.70	1.72
Row spacing (S)								
S_1 = 20 cm	701.7 a	555.6 a	16.34 b	15.79 b	42.18 b	39.57 b	42.10 a	36.59 b
S_2 = 25 cm	594.7 b	494.2 b	15.33 c	15.13 c	38.25 c	38.74 b	37.89 b	34.00 c
S_3 = 30 cm	521.3 c	440.7 c	16.85 a	16.58 a	44.83 a	42.67 a	42.64 a	38.92 a
LSD at 5%	27.52	28.16	0.34	0.41	0.68	0.88	1.08	1.21
Interaction between I × S								
I_1S_1	830.0 a	740.0 a	17.56 a	16.88 b	47.44 b	45.31 b	46.06 a	42.65 b
I_1S_2	664.0 b	645.3 b	16.16 c	16.76 bc	42.89 c	44.69 b	41.77 b	39.24 c
I_1S_3	611.3 c	605.0 bc	17.93 a	18.10 a	50.66 a	47.92 a	45.94 a	45.29 a
I_2S_1	603.3 c	586.0 cd	15.99 cd	16.09 c	43.83 c	38.90 d	42.93 b	35.60 de
I_2S_2	482.7 de	532.7 e	15.21 e	14.98 de	40.08 d	38.03 d	37.65 c	33.12 fg
I_2S_3	439.6 e	476.0 f	16.95 b	16.37 bc	46.97 b	42.08 c	43.32 b	37.09 d
I_3S_1	671.7 b	540.7 b	15.47 de	14.39 e	35.27 f	34.51 e	37.31 c	31.53 gh
I_3S_2	637.3 bc	504.7 bc	14.62 f	13.64 f	31.79 g	33.51 e	34.24 d	29.65 h
I_3S_3	513.0 d	441.0 de	15.68 cde	15.28 d	36.86 e	38.02 d	38.65 c	34.37 ef
LSD at 5%	47.67	48.78	0.59	0.71	1.18	1.54	1.88	2.09

Any two means within a column not sharing the same letters are significantly different at p = 0.05; Here, SSI = Surplus supplemental irrigation (100% field capacity) and DSI = Deficit supplemental irrigation (50% field capacity).

The number of grains per spike was substantially decreased by imposing DSI during both stages (the reproductive stage was more sensitive); however, wider row spacing tended to increase the number of grains under SSI and DSI (Table 3). DSI resulted in a significant reduction in the 1000-grain weight during each year of investigation, while wider row spacing improved the 1000-grain weight under both SSI and DSI (Table 3). During the first year, narrow and wider row spacing and wider row spacing during the second year resulted in higher 1000-grain weight while the lowest 1000-grain weight was recorded in narrow row spacing under DSI during the reproductive stage in both years of investigation (Table 3). Grain yield was significantly reduced by DSI during the reproductive stage in particular; however, narrow row spacing improved the grain yield up to certain extent under DSI (Table 4). The highest grain yield was recorded under narrow row spacing with SSI during both years of the study (6828 and 6183 kg ha^{-1} during the first and second year, respectively), while wider row spacing under DSI during the reproductive stage produced the lowest grain yield (2489 and 2762 kg ha^{-1}) during the first and second year (Table 4). Narrowly spaced wheat had 45.89% and 17.37% higher grain yield compared with wider row spacing under DSI during the reproductive phase (Table 4). DSI during the different growth stages, and the reproductive stage in particular, reduced the biological yield, while narrow row spacing improved the biological yield under SSI and DSI (Table 4). The highest biological yield was recorded in the narrow row spacing with SSI, while wider row spacing with DSI during the reproductive stage during the first and second year resulted in the lowest biological yield (Table 4). The harvest index was notably impaired by DSI (23% and 40% reduction by DSI during the reproductive stage in the first and second year, respectively), while narrow row spacing mended the effects of DSI up to a certain extent (Table 4). Narrow row spacing under well-watered conditions resulted in a peak harvest index during each year of investigation, while the lowest harvest index was observed under wider row spacing with DSI during the reproductive stage (Table 4). The crop with SSI and narrow row spacing resulted in the highest WUE, while DSI during the reproductive stage and wider row spacing resulted in low values in this regard during both years of study (Table 4). Regarding the interactions between irrigation and row spacing, SSI and narrow row spacing resulted in the highest WUE, while DSI during the reproductive stage with wider row spacing resulted in the lowest WUE during both years of study (Table 4).

Table 4. Effect of different row spacings on the yield parameters of wheat grown under DSI during the vegetative and reproductive stages.

Treatments	Grain yield kg ha^{-1}		Biological yield kg ha^{-1}		Harvest index (%)		WUE (kg m^{-3})	
	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2
Irrigation levels (I)								
I_1 = SSI throughout whole crop season	5961 a	5490 a	19180 a	15430 a	0.30 a	0.35 a	1.25 a	1.30 a
I_2 = DSI at vegetative stage	4353 b	4109 b	15620 b	13890 b	0.27 b	0.29 b	1.14 b	1.25 b
I_3 = DSI at reproductive stage	3227 c	2974 c	15000 c	13810 b	0.21 c	0.21 c	0.83 c	0.82 c
LSD at 5%	216.80	121.20	521.10	1293.00	0.018	0.030	0.041	0.041
Row spacing (S)								
S_1 = 20 cm	5402 a	4619 a	18030 a	15190 a	0.29 a	0.29 a	1.28 a	1.23 a
S_2 = 25 cm	4580 b	4238 b	16840 b	14410 b	0.26 b	0.29 a	1.09 b	1.14 b
S_3 = 30 cm	3558 c	3716 c	14930 c	13540 c	0.23 c	0.27 b	0.85 c	1.00 c
LSD at 5%	208.8	81.45	408.6	613.1	0.017	0.015	0.045	0.010
Interaction between I × S								
I_1S_1	6828 a	6183 a	20690 a	19480 a	0.33 a	0.31 b	1.43 a	1.47 a
I_1S_2	6041 b	5239 b	19040 b	18010 b	0.31 a	0.29 a	1.26 b	1.34 b
I_1S_3	5047 d	4647 c	17820 c	16200 bc	0.28 b	0.28 bc	1.05 d	1.10 e
I_2S_1	5455 c	4431 d	17250 c	16420 bc	0.31 a	0.26 cd	1.42 a	1.34 b
I_2S_2	4431 e	4156 e	15730 d	16290 bc	0.28 b	0.25 d	1.16 c	1.27 c
I_2S_3	3172 g	3739 f	13870 e	14370 d	0.22 cd	0.26 cd	0.85 e	1.15 d
I_3S_1	3923 f	3242 g	16160 d	15060 cd	0.24 c	0.21 e	1.00 d	0.89 f
I_3S_2	3268 g	2917 h	15760 d	16330 bc	0.20 de	0.17 f	0.84 e	0.81 g
I_3S_3	2689 h	2762 i	13090 f	15450 bcd	0.20 e	0.17 f	0.74 f	0.76 h
LSD at 5%	361.6	141.1	707.6	1303	0.031	0.027	0.079	0.017

Any two means within a column not sharing same letters are significantly different at p = 0.05. Here, SSI = Surplus supplemental irrigation (100% field capacity) and DSI = Deficit supplemental irrigation (50% field capacity).

The economic analysis indicated that wheat with SSI exhibited the highest gross income, net income and BCR, while DSI at different growth stages remained poor in this regard (Table 5). Similarly, among different row spacings, the narrow row spacing had higher net and gross incomes along with higher BCR, while wider row spacing performed poorly with the lowest net income, gross income and BCR (Table 5). With respect to the interaction effect, SSI with narrow row spacing resulted in higher gross and net income and BCR, while wider row spacing with DSI during the reproductive stage resulted in lower net returns and BCR (Table 5) during each year of the trial.

Table 5. Economic analysis of producing wheat by different row spacing and DSI during the vegetative and reproductive stages.

Treatments	Total expenses (US$ ha^{-1})		Gross income (US$ ha^{-1})		Net income (US$ ha^{-1})		BCR	
	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2	Year-1	Year-2
Irrigation levels (I)								
I_1 = SSI throughout whole crop season	713.2	723.1	1838.91	1693.61	1125.68	970.51	2.58	2.34
I_2 = DSI at vegetative stage	693.5	703.4	1342.86	1267.58	649.37	564.23	1.94	1.80
I_3 = DSI at reproductive stage	693.5	703.4	995.50	917.45	302.01	214.09	1.44	1.30
Row spacing (S)								
S_1 = 20 cm	723.10	742.84	1693.61	1424.91	943.36	682.07	2.30	1.92
S_2 = 25 cm	723.10	742.84	1267.58	1307.38	689.78	564.54	1.95	1.76
S_3 = 30 cm	723.10	742.84	917.45	1146.35	374.51	403.50	1.52	1.54
Interaction between I × S								
I_1S_1	742.84	713.23	2106.37	1907.39	1363.52	1194.16	2.84	2.67
I_1S_2	742.84	713.23	1863.59	1616.18	1120.74	902.95	2.51	2.27
I_1S_3	742.84	713.23	1556.95	1433.55	814.10	720.32	2.10	2.01
I_2S_1	723.10	693.48	1682.81	1366.92	959.71	673.43	2.33	1.97
I_2S_2	723.10	693.48	1366.92	1282.08	643.82	588.60	1.89	1.85
I_2S_3	723.10	693.48	978.53	1153.44	255.43	459.96	1.35	1.66
I_3S_1	723.10	693.48	1210.20	1000.12	487.11	306.64	1.67	1.44
I_3S_2	723.10	693.48	1008.14	899.86	285.04	206.38	1.39	1.30
I_3S_3	723.10	693.48	767.83	852.05	44.73	158.56	1.06	1.23

Here SSI = Surplus supplemental irrigation (100% field capacity) and DSI = Deficit supplemental irrigation (50% field capacity).

4. Discussion

This two-year field study showed that DSI applied during both growth stages, and the reproductive stage in particular, reduced the allometric, yield and related traits of wheat. Nonetheless, narrow row spacing improved the yield and WUE under SSI and also reduced the effect of DSI on the final wheat output and WUE. Narrowly spaced wheat exhibited 45.89% and 17.37% more yield and 35.14% and 14.61% higher WUE compared with the wider row spacing under DSI during the reproductive phase (Table 4).

The grain yield of wheat represents the cumulative effects of its yield components, such as the population of productive tillers, grains per spike and grain size observed in a particular environment. DSI applied during both phenophases lowered the wheat yield under all tested row spacings due to substantial reduction in yield-related traits such as the number of productive tillers, grain size and count (Tables 3 and 4). Impaired water supply (DSI) during both phenophases reduced the LAI and thus the growth of the crop due to a decrease in turgor pressure as a result of less available moisture [35,36]. The leaves are the plant's assimilatory system unit; therefore, decreased LAI under DSI may be the possible cause of the lower CGR of each tested cultivar due to a low accumulation of assimilates during each year of the experiment (Figures 2 and 3). This low accumulation of assimilates under DSI during both phenophases reduced the grain number and weight (Table 3). Heading and grain-filling are the most critical stages of wheat, during which it exhibits more sensitivity to water scarcity [4]. Moreover, earlier reports indicate that moderate deficit water supply during the reproductive stage reduced wheat grain yield up to 30%, whereas a severe water deficit during the reproductive phase reduced the yield by between 58% and 92% [4,12,37,38]. A shortened grain-filling period in combination with a reduced grain-filling rate due to reduced photosynthesis, accelerated leaf senescence and sink limitations might be responsible for the low grain count and small size under DSI during the reproductive stage [4,39–41]. DSI during the reproductive phase also lowered the harvest index of wheat, similar to a previous report [42], due to inefficient portioning of assimilates to the developing grains. Similarly, the results of another study [43] indicated that DSI during the reproductive stage decreased the grain number rather than the grain size, which largely accounts for the decline in wheat yields under drought stress.

This two-year field study indicated that narrow row spacing (20 cm) enhanced the wheat yield under SSI and DSI during the vegetative and reproductive phase (Table 4) due to a significant increase in the population of productive tillers (Table 3). Several earlier studies reported that increased wheat yield with narrow row spacing was due to a significant increase in the population of productive tillers [44–46]. It is likely that the competition for moisture and solar radiation was not too intense among the wheat plants in our study. Further, it is assumed that narrow row spacing minimized the evaporation losses due to higher canopy shading (*i.e.*, higher LAI) [44], especially under DSI [12]. However, a higher grain count and size was noted under wider row spacing (Table 3). Greater competition resulting from rows spaced too close together and more plants per unit area might be the reasons for the lower grain count and size in the closely spaced rows compared with the wider row spacing (Table 3). Improved grain yield under narrow row spacing is likely the effect of less evaporation due to the higher number of tillers and canopy cover (*i.e.*, higher LAI), and the small soil surface exposed to the sun relative to the wider row spacing. The positive effects of narrow row spacing in improving wheat outputs have also been previously reported by different researchers [12,27,28,44–46]. They also reported that in wider row spacing, an improvement in the number of grains per spike and the 1000-grain weight was due to less competition for light and resources among plants compared with narrow row spacing. Nonetheless, even a higher grain count and 1000-grain weight under wider row spacing could not compensate for the yield losses of wheat due to the reduced plant population under SSI and DSI conditions in this study and in several previous studies [12,44–47].

Higher WUE under SSI and narrow row spacing might be attributed to higher wheat yield (Table 4). Narrow row spacing might lessen the evaporative water loss under DSI during both phenophases due to a more extensive canopy (higher LAI) and less available space between rows compared with wider spacing, resulting in more efficient utilization of available moisture, leading to higher WUE (Table 4). The effects of narrow row spacing in improving the WUE of wheat have already been reported under deficit water supply during the reproductive stage [12].

The adoption of any new technology by farmers depends on its returns and economic feasibility [48]. In this study, SSI and DSI during the vegetative stage were clearly dominant over DSI during the reproductive stage, with higher gross and net income and BCR (Table 5). Further, among the different row spacings tested, the higher BCR and economic returns resulting from the narrow row spacing in this study (Table 5) and in previous studies [45] indicate that it is a viable agronomic tool to improve wheat outputs in water-limited environments. Similar results regarding improvements in gross income, net income and BCR under water deficit during the reproductive stage with narrow row spacing have recently been reported [12].

5. Conclusions

It is concluded that DSI applied during different growth stages, and the reproductive stage in particular, severely reduced wheat productivity, whereas narrow row spacing tended to ameliorate the effects of drought stress up to a certain extent. Therefore, to manage supplemental irrigation in wheat under the current scenarios of water shortages, irrigation can be decreased during the initial growth phases, whereas decreasing the irrigation during the reproductive stage is lethal and results in significant yield losses. Moreover, among the different row spacings practiced in wheat crops, narrow row spacing (20 cm) resulted in efficient utilization of irrigation water and can therefore be adopted to achieve higher outputs.

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