Assessment of Tolerance to Drought Stress of Thirty-five Bread Wheat (*Triticum aestivum* L.) Genotypes Using Boxplots and Cluster Analysis

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Summary

Drought is an acute abiotic stress that limits wheat production worldwide, particularly in arid and semi-arid zones, due to the uneven distribution of rainfall, possibly as a consequence of climate change. In south Asia, including Bangladesh, India and Pakistan, wheat is generally grown under rainfall deficit in winter causing the reduction of wheat yield during this period. This study aimed to characterize the drought tolerance of 35 wheat genotypes of diverse morphologies grown in the field. Plants were grown under drought (irrigation was stopped after the crown root initiation (CRI) stage and the crop was protected from receiving rainfall) and well-watered (control) conditions. Phenological variation on days to first visible awn, days to heading, days to anthesis, days to full expansion of flag leaf, days to awn drying, and days to physiological maturity of all 35 wheat genotypes were significantly different ($p \leq 0.01$) under water deficit (drought stress). Similarly, plant height, tillers m^{-2}, spike length, spikelets $spike^{-1}$, grains $spike^{-1}$, grain weight, grain yield (GY) and straw yield of all 35 genotypes were significantly reduced under water deficit. Among the tested genotypes, nine genotypes i.e., 'BARI Gom 26', 'Sourav', 'BAW 1169' and 'BAW 1158' (GY reduction < 30%), and 'BAW 1151', 'BAW 1157', 'BAW 1159', 'BAW 1161', 'BAW 1165' and 'BAW 1170' (GY reduction < 40%) were classified as tolerant on the basis of minimum variation in phenology, growth and yield attributes, while also considering the lowest yield reduction (< 40%) under drought stress. Genotypes 'Prodip', 'Shatabdi', Gourav, 'Sufi', 'Kanchan', 'Barkat', 'Balaka', 'Aghrani', 'Akbar', 'Protiva', 'Ananda', 'Bijoy', 'BARI Gom 25', 'BAW 1160', 'BAW 1162', 'BAW 1163', 'BAW 1164', 'BAW 1168' and 'BAW 1172' were categorized as moderately sensitive (< 50% GY reduction), while genotypes 'Seri', 'Pavon', 'BAW 1166', 'BAW 1167', 'BAW 1171' and 'BAW 1173' were considered to be highly susceptible to drought (>50% GY reduction). Therefore, among the 35 genotypes, nine may be recommended as drought-tolerant wheat genotypes for cultivation under water deficit (drought) conditions or may be used in a future breeding program to develop drought-tolerant varieties.

Key words

south Asia, deficit water, wheat, phenology, growth, yield

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Introduction

Wheat (*Triticum aestivum* L.) is the world's most important cereal in terms of production area and yield (FAO, 2015), providing 20% of all calories consumed by people worldwide while also significantly contributing to animal feed (Shiferaw et al., 2013; Horváth, 2014; Shewry and Hey, 2015). The world's population of 7.2 billion is projected to increase by 1 billion over the next 12 years and reach 9.6 billion by 2050 (UN Report, 2013). To meet the dietary demand of increasing populations (Timsina et al., 2018), wheat production will bear a crucial weight on food security and the global economy in coming decades (The Guardian, 2014). Therefore, there will be a need to increase wheat productivity by optimizing existing resources such as water, fertilizers and pesticides to overcome the negative impact of climate change and pressure on agriculture caused by rising energy costs (IFDC, 2016). In arid and semi-arid regions of the world, factors such as high temperature, moisture deficit and low soil fertility limit wheat production (Balasubramanian et al., 2012; Chauhan et al., 2012). Soil water deficit, or water stress, limits photosynthates through stomatal closure and early leaf senescence (Chauhan et al., 2012), which ultimately affects processes related to grain development (Zhang et al., 2004; Rajala et al., 2009; Wang et al., 2018).

Wheat is the most important cereal in terms of production and acreage in the world, as well as in countries in SouthAsia (FAO, 2015). In Bangladesh, it is the second most important crop after rice, serving as a staple food crop that is grown on an area of 3.74 million ha with an annual production of 1 million metric tons and an average yield of 3.08 t ha^{-1} (BBS, 2015). However, according to the Bangladesh Agricultural Research Institute (BARI), the range of potential yield of wheat varieties is 4.0–4.5 t ha^{-1} (BARI, 2016) with climatic yield potential as high as 6.0 t ha^{-1} (Timsina et al., 2010, 2018). One of the main reasons is that one third of the total area under wheat production in Bangladesh lies in rainfed regions which can experience episodes of drought, thereby limiting plant growth and productivity (Khaliq et al., 1999). Separately, due to climate change, the amount of rainfall in the world (Dore 2005), including Bangladesh, has decreased in the past few decades (Shahid, 2010; Islam and Hasan, 2012) and is much lower than the amount of water needed for irrigation (Hossain and Teixeira da Silva, 2013). During the wheat-growing season in Bangladesh, monsoon rain is absent and as a result, wheat cultivation is fully dependent on irrigation water, which is already scarce, so any drought spell during its growth cycle may substantially decrease grain yield (GY) (Sarker et al., 2015).

Water shortage between November and March is very common in Bangladesh and this is accentuated by a rapid lowering of the ground water table caused by the intensive cultivation of *Boro* rice. One of the best and most practical solutions to solve the problem of water shortage is to develop wheat genotypes that are tolerant to water deficit and that can withstand water deficit or that require less water but still produce optimum yield. Very few experiments have been performed in Bangladesh to identify drought-tolerant wheat genotypes as a practical way to increase national wheat production. Cognizant of this challenge in Bangladesh, in this research, the drought stress tolerance of 35 wheat genotypes was studied in a bid to differentiate them based on their levels of tolerance. To achieve this, it was necessary to determine genotypic variation in response to drought based on phenology, canopy temperature and yield and to identify promising lines for future wheat breeding programs.

Materials and Methods

Location of the Experiment

The experiment was conducted on upland soil at the research field of the department of Agronomy of Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Salna, Gazipur located in the center of the Madhupur Tract (24° 05" N, 90° 16" E and 8.4 m above sea level) from November to March. Experimental soils are of the Salna soil series of Shallow Red-Brown Terrace, representative of agro-ecological zone 28 (AEZ-28; Madhupur Tract) and with silty clay on the surface and silty clay loam in the sub-surface region (Brammer, 1978; Shaheed, 1984; FAO/UNDP, 1988).

Chemical and Physical Properties of Soil

Soils of the experimental sites were analyzed before sowing wheat (Table 1). Soil pH was measured in soil/water (1:2, w/v) using a glass electrode pH meter. Organic carbon was determined by the Walkley and Black oxidation method (Walkley and Black, 1934), total N (nitrogen) by the micro-Kjeldhal method (Jackson, 1958), phosphorus (P), potassium (K) and sulphur (S) by a modified Hunter's method (BARC, 1984), while boron (B) was determined colorimetrically by the Azomethine-H method (Sippola and Ervio, 1977). Soil pH in the experimental plot (AEZ-28) was slightly acidic (5.99) while particle density and bulk density were 2.66 and 1.42 g cm^{-3}, respectively. Soil had 0.69% organic matter, 0.07% total N, 0.15 μg/g B, 10.2 ppm S, 20.5 ppm available P and 0.27 meq 100 g^{-1} soil exchangeable K.

Weather Information at the Experimental Site

The climate of the experimental site is characterized by heavy rainfall from July to September and little or no rainfall for the rest of the year. Monthly maximum and minimum air temperature, soil temperature at different depths, humidity, rainfall as well as evaporation were measured in the experimental site during the experimental period. The HOBO U12 Family of Data Loggers (MicroDAQ.com) was used to record temperature at the meteorological stations of BSMRAU. Rainfall was monitored by a rain gauge (Table 2).

Experimental Design and Treatments

Wheat genotypes were planted under adequate water supply. However, irrigation was stopped after the crown root initiation (CRI) stage (20 days after sowing (DAS)) in the water deficit treatment and the crop was protected from rainfall by a rainout shelter. The well-watered treatment was irrigated four times (at CRI, booting, anthesis and grain-filling stages). The experiment was conducted in a split plot design where water regime was the main plot and wheat genotypes were the sub-plot with three replications. Unit plot size was 6 m^2 (1.2 m × 5 m) and inter-line spacing was 20 cm with continuous sowing.

Table 1. Soil chemical properties of experimental field

Soil properties	pH	Organic matter (%)	Total N (%)	Available P (ppm)	Exchangeable K (meq 100 g^{-1} soil)	Available S (ppm)	B µg g^{-1}
Initial	5.99	0.69	0.07	20.5	0.27	10.2	0.15
Status	SA	VL	VL	M	M	L	VL

SA = slightly acidic, VL = very low, L = low, M = medium

Table 2. Weather data at the experimental site during the course of experimentation

Months	Air temperature (°C)			Soil temperature (°C) at different soil depths			Humidity (%)	Rainfall (mm)	Pan evaporation (mm)
	Max.	Min.	Mean	10 cm	20 cm	30 cm			
November	27.76	23.76	25.76	26.55	26.91	27.33	85.66	0.00	55.06
December	24.80	16.58	20.69	22.72	23.17	23.56	90.70	5.19	208.15
January	22.32	11.53	16.93	18.85	19.34	19.84	89.81	0.00	1.37
February	27.31	13.24	20.28	20.03	20.45	20.83	87.66	0.00	3.60
March	32.58	20.68	26.63	23.53	23.97	24.42	83.94	0.00	4.03

*Data not recorded

Experimental Procedure

Thirty five wheat genotypes comprising some popular varieties, advanced lines and exotic lines provided by the Wheat Research Centre of the Bangladesh Agricultural Research Institute, Nashipur, Dinajpur, Bangladesh, were tested in this study as in Bazzaz et al. (2015) (Table 3).

Land was prepared by four-cross ploughing, followed by laddering to break clods, levelled with a power tiller, and then cleaned to remove debris. To protect run off of irrigation water and fertilizer, 10 cm high ridges were built around each plot.

Genotypes were sown in 20 cm spaced lines with a hand drill using a seeding rate of 120 kg ha^{-1}. To ensure uniform germination, seeds were lightly irrigated just after sowing. Fertilizers were applied at 100-60-40-20-1 kg N-P_2O_5-K_2O-S-B ha^{-1} using urea, triple super phosphate, muriate of potash and gypsum, respectively as sources. Two-thirds of N and the full amount of all other nutrients were applied as the basal dose. The remaining amount of urea was applied as a top dress at CRI and during the second irrigation, split equally. Hand weeding was done by hoe to uproot weeds and break the soil crust at 15 DAS and at 35 DAS, respectively. A detailed description of the experimental procedure is available in Bazzaz et al. (2015).

Data Collection

Phenology

To understand phenological variation under well-watered (control) and drought (water deficit) conditions, data on days to first visible awn, days to heading, days to anthesis, days to full expansion of flag leaf, days to awn drying, and days to physiological maturity were recorded. Days to heading was recorded by counting the number of days from the sowing date until 80% of heads were completely visible in each row of the plot. Similarly, days to anthesis were recorded by counting the number of days from the sowing date until 80% of heads had completed anthesis in each row of the plot. Days to physiological maturity were calculated from sowing to the day when the peduncle and the spike on the tagged main stem became completely yellow (Fig. 1).

Figure 1. Wheat in field at physiological maturity stage

Yield and Yield Attributes

Plants from two 0.4 m lines and 2.5 m in length comprising 1.0 m^2 from each plot were harvested randomly to calculate GY and straw yield (SY). The harvested crop of each plot was bundled separately, tagged and manually threshed on a threshing floor. The bundles were thoroughly dried in bright sunshine before their dry weights were recorded. Data were recorded for plant height (cm), flag leaf length (cm), tillers $plant^{-1}$, spike length (cm), spikelets $spike^{-1}$, grains $spike^{-1}$, 1000-grain weight (g; TGW), GY (t ha^{-1}), SY (t ha^{-1}) and harvest index (HI) (%), all at harvest. GY was recorded at 12% moisture content while SY was calculated on a sun-dry basis (approx. 3% moisture content) (Hellevang, 1995).

Table 3. Pedigree of wheat genotypes used in the study

#	Entry	Cross/pedigree	#	Entry	Cross/pedigree
1.	Prodip	G. 162/BL 1316//NL 297 NC2055-4B-020B-020B-4B-0B	19.	BAW 1157	BAW 923/BAW 1004 BD(DI)1207S-0DI-4DI-010DI-010DI-0DI-DIRC6
2.	Shatabdi	MRNG/BVC//BLO/PVN/3/PJB-81 CM98472-1JO-0JO-0O-1JO-0JO-0R2DI	20.	BAW 1158	BAW 968/SHATABDI BD(JO)358-0DI-1DI-010DI-010DI-DIRC6
3.	Sourav	NAC/VEE CM 64224-5Y-1M-1Y-2M-0Y	21.	BAW 1159	KAN//IAS 63/ALDAN BD(DI) 961S-0DI-62DI-010DI-010DI-0DI-03DI-DIRC5
4.	Gourab	TURACO/CHIL CM 92354-33M-0Y-0M-6Y-0B	22.	BAW 1160	BAW 1004/GARUDA BD(DI)1493-0DI-8DI-6DI-HR3R6DI
5.	Sufi	KAN/6/COQ/F61.70//CNDR/3/OLN/4/PHO/5/MRGN/ ALDAN//CNO BD(JE) 349-X-0JE-9DI-10HR	23.	BAW 1161	BAW 677/BIJOY BD(JA)1365S-0DI-15DI-3DI-HR12R3DI
6.	Kanchan	UP301/C306 1187-1-1P-5P-5JO-OJO	24.	BAW 1162	SOURAV/3/ZSH23/HLB48//NEPAL297 BD(DI)1296S-0DI-2DI-010DI-010DI-2DI-HR18R2DI
7.	Seri	KVZ/BUHO//KAL/BB CM33027-F-15M-500Y-0M-87B-0Y-0BGD	25.	BAW 1163	SHATABDI/BAW 824 BD(JE)1176S-0DI-11DI-010DI-010DI-8DI-HR27R8DI
8.	Pavon	VCM//CNO/TC/3/KAL/BB CM8399-D-4M-3Y-1M-1Y-1M-0Y-0BGD	26.	BAW 1164	BAW 969/BAW 824 BD(JO)403S-0DI-6DI-010DI-010DI-8DI-HR31R8DI
9.	Barkat	BB/GLL//CARP/3/PVN CM 33483-C-7M-1Y-OM-OJO	27.	BAW 1165	SOURAV//SUFI/BAW 805 BD(DI)1334T-0DI-1DI-010DI-010DI-5DI-HR32R5DI
10.	Balaka	RON/TOB CM 7705-3M-1Y-2M-2Y-OY-OJO	28.	BAW 1166	BL 3373 = BL 1923/NL 876 NC99B3131-5B-020B-020B-1B-0B
11.	Aghrani	INIA/3/SON64/P4160E//SON64 PK 6841-2A-1A-OA	29.	BAW 1167	BL 3877=KAUZ/STAR/CMH 81.749//BL 2224 NC 02B3616-5B-020M-020B-3B-0B
12.	Akbar	RON/TOB CM 7705-3M-1Y-2M-2Y-OY-OJO	30.	BAW 1168	BAW 923/BIJOY BD(DI) 1327S-0DI-3DI-1DI-DIRC4
13.	BARI Gom 26	ICTAL123/3/RAWAL87//VEE/HD2285 BD(JOY) 86-0JO-3JE-010JE-010JE-HRDI-RC5DI	31.	BAW 1169	SHATABDI/BAW 923 BD(DI) 1134S-0DI-4DI-010DI-010DI-1DI-DIRC3
14.	Protiva	KU HEAD SELECTION 12	32.	BAW 1170	CHIR7/CBRD//GOURAB BD(DI) 1327S-0DI-3DI-1DI-DIRC4
15.	Ananda	KAL/BB CM 26992-3OM-3OOY-5OOY-OY-OJA-OJA	33.	BAW 1171	CHIR7/CBRD//GOURAB BD(DI) 1335S- 16DI-010DI-010DI-010DI-1DI-DIRC4
16.	Bijoy	NL297*2/LR25	34.	BAW 1172	GOURAB/PAVON 76 NCD99-04-0DI-1DI-0DI-0DI-0DI-0DI-32DI-0DI
17.	BARI Gom 25	ZSH 12/HLB 19//2*NL 297	35.	BAW1173	KAUZ//ALTAR 84/AOS/3/PASTOR/4/TILHI CMSS-97M03915T-040Y-020Y-030M-020Y-040M-12Y-1M-0Y
18.	BAW 1151	SOURAV/KLAT/SOREN//PSN/3/BOW/4/VEE#5. 10/5/ CNO 67/MFD//MON/3/ SERI/6/NL297 BD(DI)112S-0DI-030DI-030DI-030DI-9DI			

Source: FAO (2018)

Boxplot, Cluster and Correlation Analysis

In this study, we used boxplot analysis (McGill et al., 1978; Chambers et al., 2018) to assess variation in yield and yield attributes when plants were grown under water deficit conditions. Cluster analysis (Scott and Knott, 1974) was performed for all wheat genotypes grown under water deficit condition on the basis of grain and biomass yield (SY). Correlation analysis (Cohen et al., 1983) between yield and yield attributes under water deficit conditions was performed. Boxplot, cluster and correlation analysis were performed using R software (R Core Team, 2013).

Statistical Analysis

Collected data were statistically analyzed using R software (R Core Team 2013). Duncan's new multiple range test (DNMRT) at a 5% probability level was used to test differences among mean values (Steel and Torrie, 1984).

Results

Phenological Variation of Wheat under Water Deficit

Phenological traits such as days to heading, days to physiological maturity and days to grain filling were significantly reduced by drought stress (Fig. 2). The following phenological traits took different number days to complete in the control (well-watered) and water deficit treatments, respectively: 51-69 and 50-66 days to peak visible awn, 61-79 and 61-78 days to heading, 67-81 and 64-78 days to anthesis, which indicates that anthesis occurred three days earlier as a result of water stress, 46-64 or 45-62 days for the flag leaf (an important factor for photosynthesis) to expand fully, 91-101 and 87-96 days for the awn of a wheat spike (an important contributor to grain development) to dry, and 102-110 and 93-103 days to reach physiological maturity. However, physiological maturity was achieved seven days earlier

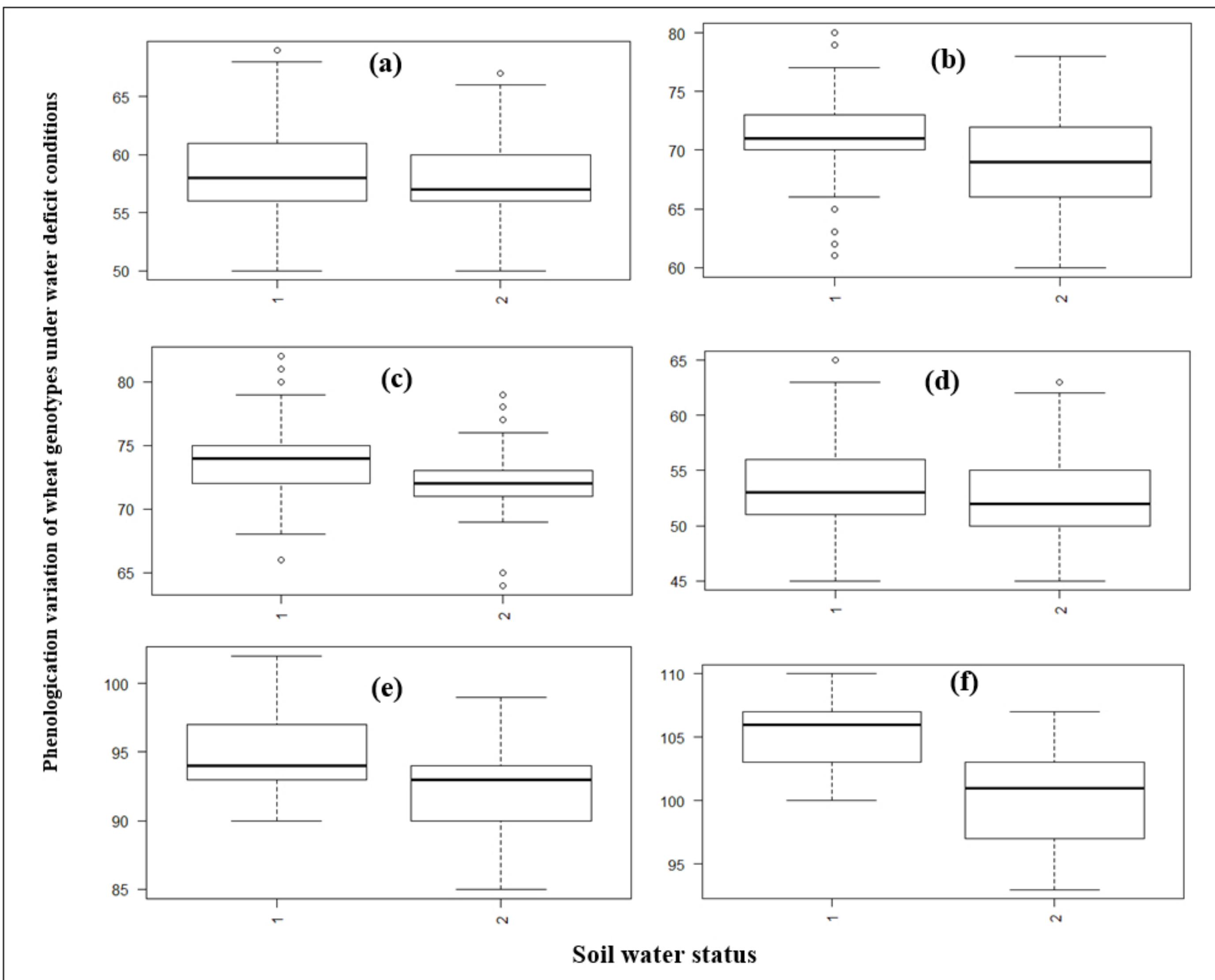

Figure 2. Variation of days to first awn visible **(a)**, days to heading **(b)**, days to anthesis **(c)**, days to full expansion of flag leaf **(d)**, days to awn drying **(e)**, and days to physiological maturity **(f)** of 35 wheat genotypes under well-watered (1) and water deficit (2) conditions.

in drought-stressed 'BARI Gom 25', 'BAW 1167' and 'BAW 1173', but only 1-3 days earlier in 'BAW 1169', 'BARI Gom 26', 'Sourav', 'BAW 1157', 'BAW 1158', 'BAW 1159', 'BAW 1161', 'BAW 1165' and 'BAW 1170', compared to the control.

Boxplot Analysis-based Variation in Yield and Yield Attributes of Drought-stressed Wheat

The yield and yield attributes of 35 wheat genotypes were influenced by water regime (Fig. 3; Table 4). Flag leaf length ranged from 18.60-26.16 cm in drought-stressed plants and from 22.89-30.75 cm in control plants. The highest reduction in flag leaf length was 28.61 cm in 'Seri' and the lowest was 2.62 cm in 'BAW 1165'. The number of tillers plant^{-1} ranged from 1.23-2.10 in the water deficit treatment and from 2.08-2.98 in the control. The highest reduction in number of tillers plant^{-1} due to water deficit was 58.22% in 'Barkat' and the least reduction was 26.78% in 'BAW 1169'.

Spike length ranged from 8.38-11.83 cm in drought-stressed plants and from 9.48-13.18 cm in control plants. However, the highest reduction in spike length due to water deficit was 15.92% in 'Pavon' and the lowest was 3.82% in 'BARI Gom 26'. The minimum and maximum number of grains spike^{-1} were 33.33 and 46.47, respectively under water deficit but 41.73 and 54.83, respectively in the control. The greatest reduction in number of grains spike^{-1} due to water deficit was 24.97% in 'BAW 1167' and the least was 9.15% in 'BARI Gom 26'. Water regime induced considerable variation in TGW which ranged from 34.47-44.80 g and from 43.13-50.47 g in drought and control conditions, respectively. The greatest reduction in TGW due to water deficit was 21.13% in 'BAW 1167' and the least was 8.13% in 'Saurav'. GY ranged from 1.68-4.98 t ha^{-1} and from 4.11-5.81 t ha^{-1} in the drought and control treatments, respectively. SY ranged from 3.23-7.56 t ha^{-1} and from 6.23-9.67 t ha^{-1} in drought and control conditions, respectively (Fig. 3, Table 4).

Reduction of Grain and Straw Yield of Wheat under Water Deficit

Grain Yield

The relative GY of 35 wheat genotypes was significantly affected by water deficit (Fig. 4). The highest relative GY was obtained in 'BARI Gom 26' (0.91), followed by 'BAW 1158' (0.78), 'Sourav' (0.75), 'BAW 1169' (0.73), 'BAW 1170' (0.70) and 'BAW 1165' (0.67). The lowest relative GY was recorded in 'Pavon' (0.41), followed by 'BAW 1167' (0.44), 'BAW 1166' (0.45), 'Seri' (0.45), 'BAW 1173' (0.47), 'BAW 1171' (0.47) and 'BARI Gom 25' (0.48). The reduction in percentage GY also displayed marked variation among the 35 wheat genotypes under water deficit. The lowest reduction in GY was recorded in 'BARI Gom 26' (9.07%) and the highest in 'Pavon' (59.17%), followed by 'BAW 1167' (56.20%), 'BAW 1166' (55.47%), 'Seri' (55.33%), 'BAW 1171' (53.45%), 'BAW 1173' (53.10%) and 'BARI Gom 25' (52.41%).

Straw Yield

The highest relative SY was obtained in 'BARI Gom 26' (0.83), followed by 'BAW 1170' (0.79), 'BAW 1158' (0.78) and 'BAW 1169' (0.72), and the lowest in 'BAW 1167' (0.50), followed by 'BAW 1172' (0.52), 'Pavon' (0.52), 'Seri' (0.53), 'BAW 1173' (0.53) and 'BARI Gom 25' (0.55) (Fig. 4). Water deficit significantly reduced SY, with the lowest reduction in 'BARI Gom 26' (16.62%) followed by 'BAW 1170' (21.19%), 'BAW 1158' (22.21%), 'BAW 1169' (28.09%) and 'Sourav' (28.55%), while the highest reduction in SY was observed in 'BAW 1167' (49.60%), followed by 'BAW 1172' (48.26%), 'Pavon' (48.08%), 'BAW 1173' (46.85%), 'Seri' (46.82%), 'BARI Gom 25' (44.79%) and 'BAW 1171' (43.28%) (Fig. 4).

Table 4. Range and mean of morphological and yield related parameters of tested wheat genotypes under well-watered and water deficit conditions

Plant characters	Water deficit		Well-watered	
	Range	Mean ± SD	Range	Mean ± SD
Plant height (cm)	68.30-91.45	82.89 ± 5.17	80.76-107.67	94.00 ± 5.67
Flag leaf length (cm)	18.60-26.74	22.89 ± 1.86	22.89-30.75	26.22 ± 1.73
Tillers / plant^{-1} (no.)	1.23-2.10	1.48 ± 0.19	2.08-2.98	2.54 ± 0.22
Spike length (cm)	8.38-11.83	10.23 ± 0.76	9.48-13.18	11.33 ± 0.83
Grains spike^{-1} (no.)	33.33-46.47	40.56 ± 2.97	41.73-54.83	48.75 ± 3.14
1000-grain weight (g)	34.87-44.80	40.28 ± 2.22	43.13-50.47	47.68 ± 1.78
Grain yield (t ha^{-1})	1.68-4.98	3.15 ± 0.67	4.11-5.81	5.32 ± 0.48
Straw yield (t ha^{-1})	3.23-7.56	5.43 ± 0.92	6.23-9.67	8.48 ± 0.85
Harvest index	31.72-41.88	36.78 ± 2.05	36.64-41.51	38.61 ± 1.26

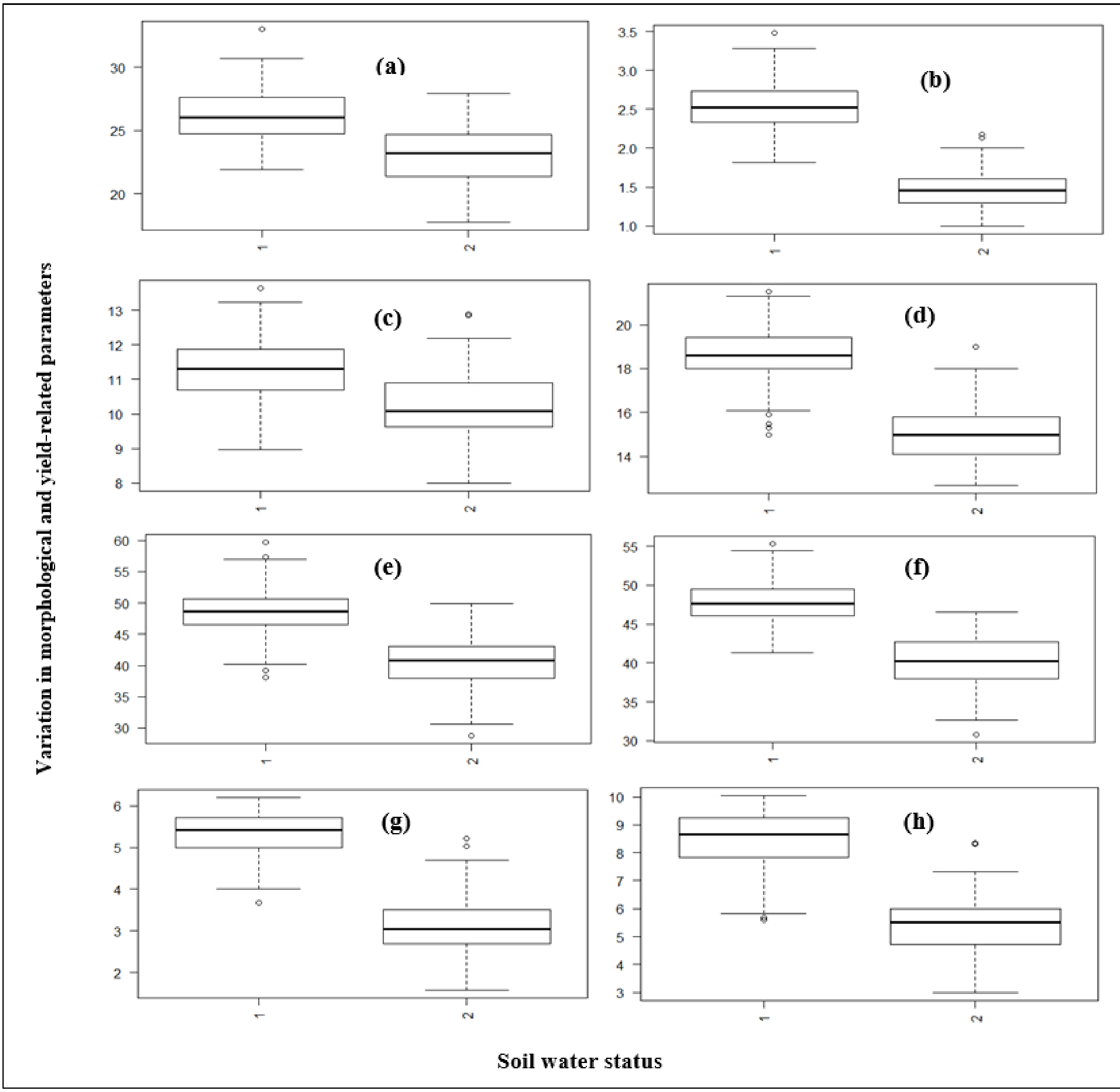

Figure 3. Variation of flag leaf length **(a)**, tillers plant^{-1} **(b)**, spike length **(c)**, spikelets spike^{-1} **(d)**, grains spike^{-1} **(e)**, 1000-grain weight **(f)**, grain yield **(g)** and straw yield **(h)** of 35 wheat genotypes under well-watered (1) and water deficit (2) conditions.

Cluster Analysis of Wheat Genotypes Grown under Water Deficit on the Basis of Grain and Biomass Yield

Cluster analysis was used to arrange variables into different clusters based on their similarity. This was performed by measuring their levels of similarity and Euclidean distance (Everitt, 1993; Eisen et al., 1998). In the resulting dendrogram, cluster I includes two genotypes (7, 8), cluster II includes four genotypes (10, 17, 18, 29), cluster III holds 15 genotypes (1, 2, 3, 4, 11, 15, 16, 22, 24, 26, 28, 30, 33, 34, 35), while clusters IV and V include three (13, 20, 31) and 11 (5, 6, 9, 12, 14, 19, 21, 23, 25, 27, 32) genotypes, respectively (Fig. 5). Cluster I includes genotypes with the fewest genetic differences among them and the highest reduction in yield. Cluster II also showed the lowest variability among them. Clusters III and V contain genotypes with large inter-genotype genetic diversity and medium yield reduction under water deficit. Cluster IV, however, has three genotypes that displayed the lowest reduction in GY and SY. Cluster IV also revealed greater genetic variability among all genotypes and lower reduction in yield attributes such as spike length, number of spikelets spike^{-1}, number of grains spike^{-1}, and TGW. Thus, the genotypes grouped in cluster IV exhibited the fewest differences among themselves.

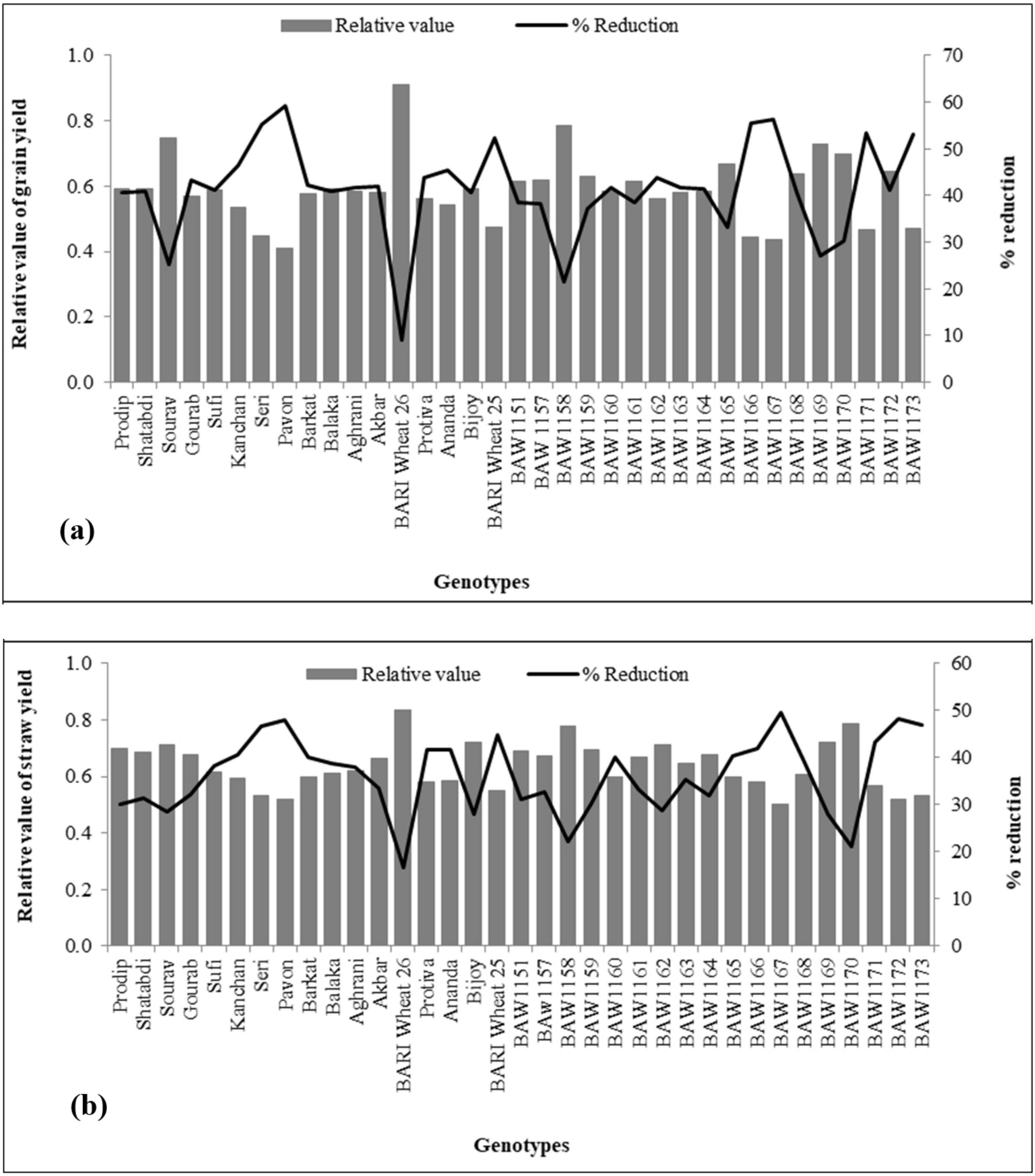

Figure 4. Relative value and percentage of reduction of grain (a) and straw (b) yield of 35 wheat genotypes under variable water regimes

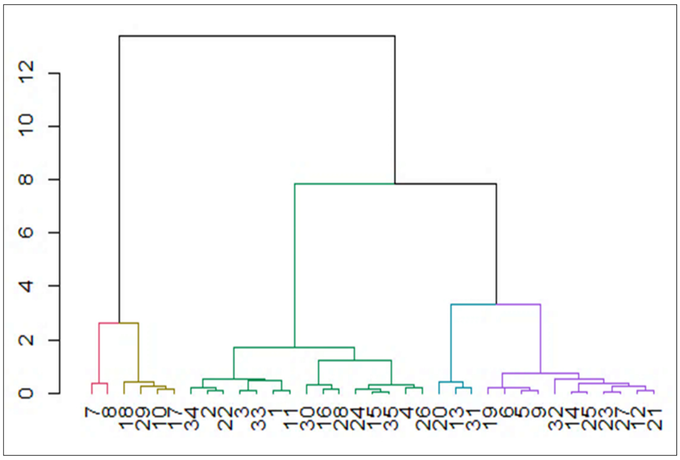

Figure 5. Performance grouping of tested wheat genotypes on the basis of grain and biomass yield grown under water deficit condition. Names of cultivars corresponding to numbers on the X-axis are listed in Table 3.

Range of Mean Grain Yield of Wheat Genotypes Grown in Control and Water Deficit Conditions

Considering the range of mean GY under both environmental conditions, genotypes 13, 20 and 31 produced statistically similar and maximum GY while genotypes 7 and 8 produced the lowest GY in both conditions (Fig. 6, Table 4). Therefore, 'BARI Gom 26', 'BAW 1158' and 'BAW 1169' are recommended for optimal GY and production under both conditions.

Correlation between Yield and Yield Attributes

The correlation between various traits and water regime was positive and significant (Table 5). In particular, GY under water deficit was positively and significantly correlated with tillers plant^{-1}, flag leaf length, spike length, spikelets spike^{-1}, grains spike^{-1} and TGW. Plant height showed no correlation with yield and other yield-contributing attributes under stress but showed a negative correlation with yield in the control. Number of tillers plant^{-1} was significantly and positively correlated with spike length, spikelets spike^{-1}, grains spike^{-1} and TGW, but not with flag leaf length.

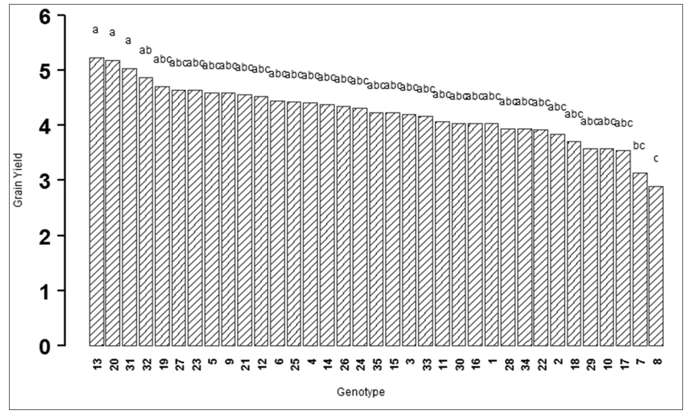

Figure 6. Grain yield of 35 wheat genotypes grown under both well-watered and water deficit conditions. Names of cultivars corresponding to numbers on the X-axis are listed in Table 3.

No correlation was found between flag leaf length and grains spike^{-1} and TGW. A positive and significant correlation was found among spike length, spikelets spike^{-1} and TGW.

Discussion

In our study, we found that water deficit significantly influenced the phenological development of wheat plants in 35 genotypes and decreased the number of days to heading, days to anthesis and days to maturity. Under water deficit, genotypes which matured only 1 to 3 days earlier than well-watered plants showed a lower reduction in yield and may be tolerant to water deficit. The time required for the phenological development of crops is one of the most important factors for yield adaptation in any environment (Motzo and Giunta, 2007). Parchin et al. (2011) and Wang et al. (2018) noted that drought might speed up flowering in wheat but prolonged the process in rice. In principle, the length of the growing period and the phenological development of crops can affect yield by reducing the length of this period (Attarbashi et al., 2002). Compared to well-watered wheat genotypes, drought reduced days to heading (Farooq et al., 2009). This confirmed an earlier study by Bayoumi et al. (2008), while the reduction in days

Table 5. Correlation coefficient among various traits of tested wheat genotypes under well-watered and water deficit conditions

Yield and yield attributes	Yield (well-watered)	Yield (water deficit)	Plant height (cm)	Tillers plant^{-1} (no.)	Flag leaf length (cm)	Spike length (cm)	Spikelets spike^{-1} (no.)	Grains spike^{-1} (no.)	TGW (g)
Yield (water deficit)	0.62**	1.00							
Plant height	-0.28	0.05	1.00						
Tillers plant^{-1}	0.18	0.60**	0.21	1.00					
Flag leaf length	0.28	0.52**	0.18	0.28	1.00				
Spike length	0.30	0.74**.	0.16	0.67**	0.59**	1.00			
Spikelets spike^{-1}	0.39*	0.80**	0.02	0.61**	0.39*	0.71**	1.00		
Grains spike^{-1}	0.33	0.72**	0.09	0.51**	0.26	0.64**	0.72**	1.00	
TGW	0.07	0.59**	0.11	0.54**	0.21	0.65**	0.70**	0.68**	1.00

* Correlation is significant at the 0.05 level; **, Correlation is significant at the 0.01 level.

to maturity confirmed the same trend in Saleem et al. (2007), and the reduction in grain-filling period also confirmed the findings by Sial et al. (2009), all in wheat.

In this study, canopy temperature increased a maximum of 30% in 'BAW 1167' and a minimum of 10% in 'BARI Gom 26' due to water deficit (Bazzaz et al., 2015). This is due to increased respiration and decreased transpiration as a result of stomatal closure (Tasmina et al., 2017). Siddique et al. (2000) also reported that leaf temperature in drought-stressed wheat plants was higher than in well-watered plants at both vegetative and anthesis stages, and that those plants with a lower leaf temperature also had a higher photosynthetic rate. The lower photosynthetic rate in plants exposed to higher temperature might have resulted from an increase in respiration (Jones, 1983; Bakhat et al., 2018). Plants maintain canopy temperature below air temperature in well-watered conditions but canopy temperature exceeds air temperature under water deficit (Buttar et al., 2005).

Many processes that determine yield in plants respond to water stress. Yield integrates many of these processes in a complex way. Water deficit leads to a decline in yield-contributing traits such as flag leaf length, tillers plant^{-1}, spike length, grains spike^{-1} and grain weight, regardless of the genotype, compared to well–watered conditions. Leaf expansion depends mostly on cell expansion which is a turgor-dependent process (Taiz and Zeiger, 1991; Khan et al., 2018) and any increase in water stress during the vegetative growth stage limits leaf development in winter wheat, ultimately reducing GY (Musick and Dusek, 1980; Abid et al., 2018). Sangtarash (2010) also reported that flag leaf length in wheat was significantly affected by moisture stress, due to increased respiration and decreased transpiration as a result of stomatal closure (Tasmina et al., 2017). Bayoumi et al. (2008) and Khakwani et al. (2012) found that tillers plant^{-1} were reduced by 36.3% and 35%, respectively in response to drought. Akram (2011) also noted that number of tillers per unit area was significantly affected by different water stress treatments. They also reported that spike length, grains spike^{-1} and GY decreased significantly due to water deficit. Mirbahar et al. (2009) found that spike length in wheat decreased more in stress-susceptible genotypes and less in stress-tolerant ones. Iqbal et al. (1999) imposed water stress on durum wheat at various growth stages and found the maximum reduction in spike length under water stress imposed at the flowering stage. Khanzada et al. (2001), Qadir et al. (1999), and Ullah et al. (2018) reported that water stress throughout vegetative and reproductive development caused a significant reduction in number of grains spike^{-1} in wheat. Some researchers observed a maximum reduction in number of grains spike^{-1} in wheat due to deficit moisture when the stress was imposed at the flowering stage (Warrier and Bhardwaj, 1987; Iqbal et al., 1999).

Khannachopra et al. (1994) observed a reduction in number of grains spike^{-1} in wheat under water stress, but the extent of reduction depended on the genotype. Elhafid et al. (1998) demonstrated that drought stress resulted in reduced pollination and reduced number of grains spike^{-1}. The decrease in GY under drought stress might be induced by a disturbance in nutrient uptake efficiency and photosynthate translocation (Iqbal et al., 1999) resulting in shriveled grains by accelerating the maturity of the plant. This is possible due to a shortage of moisture, forcing the plant to form grains in less time (Blum, 2011; Basu et al., 2016). Mirbahar et al. (2009) observed a decrease in TGW in wheat during terminal drought followed by post-flowering drought. This result was also observed by Khan et al. (2005) and Qadir et al. (1999) who observed that TGW in wheat was reduced mainly due to an increase in water stress. Jaynes et al. (2003) also reported that cluster analysis sequestrated genotypes into clusters which exhibited high homogeneity within a cluster and high heterogeneity between clusters. Although cluster analysis grouped genotypes together with greater morphological similarity, the clusters did not necessarily include all genotypes from the same origin. Ahmad et al. (2008) and Ali et al. (2008) also reported the lack of an association between morpho-agronomic traits and origin.

The GY of any genotype is influenced by the contribution of yield attributes and phenological traits which are in turn influenced by soil moisture. Wheat genotypes that were evaluated in this study showed a significant difference in GY. A relatively low reduction in GY under water deficit was found in 'BARI Gom 26', 'Sourav', 'BAW 1157', 'BAW 1158', 'BAW 1159', 'BAW 1161', 'BAW 1165', 'BAW 1169' and 'BAW 1170', and might be due to a lower relative reduction in tillers m^{-2}, spike length, grains spike^{-1} and GY. Even though the genotypes have distinctly different inherent yielding ability, lower losses in GY under water deficit may be considered as drought tolerance. The average reduction in GY of wheat was 43.2% (Bayoumi et al., 2008) or 50% (Nouri-Ganbalani, 2009) under drought stress. Khakwani et al. (2012) and Edmeades et al. (1994) estimated an average loss in GY of 58-82% and 17-70%, respectively due to drought stress. Adequate water at or after anthesis not only allows the plant to increase the rate of photosynthesis but also gives it extra time to translocate carbohydrates to grains (Zhang and Oweis, 1998), improving grain size and thus GY. The GY of any variety is dependent on its yield components, including plant height, spike length and grains spike^{-1} (Sheron et al., 1986). Shamsuddin (1987) and Khakwani et al. (2012) reported that the number of spikes plant^{-1}, number of grains spike^{-1}, TGW, HI and biological yield were directly related to the GY of wheat.

Conclusion

Water deficit significantly affects the phenology, yield, yield attributes and canopy temperature of wheat genotypes. Physiological maturity was observed in 'BARI Gom 25', 'BAW 1167' and 'BAW 1173' due to water deficit seven days early, and in 'BAW 1169', 'BARI Gom 26', 'Sourav', 'BAW 1157', 'BAW 1158', 'BAW 1159', 'BAW 1161', 'BAW 1165' and 'BAW 1170' when water deficit was only 2-3 days early, compared to well-watered plants. All yield-contributing characteristics such as spike length, grains spike^{-1}, and TGW decreased significantly due to water deficit stress. Regardless of the genotype, GY decreased significantly except for 'BARI Gom 26', which was affected less. Similarly, water deficit increased canopy temperature in all 35 genotypes compared to well-watered plants. Thus, based on physiological maturity, 'Sourav', 'BARI Gom 26', 'BAW 1157', 'BAW 1158', 'BAW 1159', 'BAW 1161', 'BAW 1165', 'BAW 1169' and 'BAW 1170' displayed a reduction in GY and an increase in canopy temperature. Thus, these genotypes can be considered to be tolerant to water deficit and recommended for growth in severe drought-prone areas or for use in breeding programs.

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Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

M.M. Bazzaz, Akbar Hossain, Q.A. Khaliq and M.A. Karim designed, carried out the research and also wrote the manuscript. Muhammad Farooq and Jaime A. Teixeira da Silva helped to assess the data, conducted an intensive scientific revision, and assisted with writing the manuscript.

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