Research Article

Exploiting Potential of Production Paradigm to Sustain Rainfed Wheat Yield

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Abstract | Food security is of growing concern around the globe. Wheat, being one of the staple food commodities, is of utmost importance for millions. However, its productivity is determined by various genotypic, environmental and crop management factors. In this study, we elaborated the role of these factors, in rainfed agro-ecology, using data of six genotypes, grown in four sowing windows over six years. The rainfed wheat productivity is predominantly determined by environmental conditions, particularly rainfall induced moisture availability. Hence, the best match between sowing time and the environment prevailed at that time emerged as an important yield determining factor. Overall, grain yield varied between 2.5-4.9 t/ha in these genotypes, between 2.7-4.8 t/h over years and between 2.0-5.1 t/ha across sowing windows. Therefore, greater variation was observed with change in sowing time followed by genotypes. This management strategy holds for up to 67% variations in grain yield and other crop growth and development related parameters. These results highlighted the necessity to have genotypic diversity for best exploitation of the environmental conditions coupled with appropriate crop management strategy. The best match of this genotype × environment × management production paradigm could lead to sustained improvement in wheat grain yield.

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Introduction

Food Security, around the globe, is threatening due to increasing population and diminishing land and other natural resources (Jat et al., 2018). The climate change consequences are further heightening the potential dangers to food security (Campbell et al., 2016; Trnka et al., 2012; Lobell et al., 2011). Wheat, bread and durum together, is the most widely grown crop in the world (Shewry, 2018; Curtis, 2002). As a food source, and its enormous genetic variability in phenological response to photoperiod and temperature, it is grown in almost all regions of the world in locations ranging in altitude from a few meters to more than 3000 m above sea level (Slafer and Satorre, 2000). However, in a given environment, wheat growth, development and yield depends on suitable genotypes, management practices and weather conditions (Studnicki et al., 2016; Hafield and Walthall, 2015; Grausgruber et al., 2000).

Spring wheat, being the staple food crop in Pakistan, is sown over a wide range of sowing dates in various cropping systems of rainfed and irrigated areas. The sowing window of wheat in Pakistan generally starts from mid of October and extends until the end of

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December. Owing to these variations in sowing times, diverse environmental factors affect wheat growth and development (Altenbach et al., 2003), resultantly the average wheat yield varied between <1000 to >4000 kg/ha in various wheat based cropping systems prevailed both in rainfed and irrigated Agro-ecologies. The national average yield however, is 2919 kg/ha (Anonymous, 2018).

The diversity of responses due to genotype-environment interaction and the information regarding some critical crop developmental phases such as grain filling duration is, generally, exploited by the breeders and crop managers to increase yield potential (Mitchell and Sheehy, 2018; Yan and Hunt, 2001; Miralles and Slafer, 2000). However, with the varying genotypic performance over diverse ecologies, improved understanding of the genotype, environment, management, their interaction and attributes is required to exploit yield potential (Dreccer et al., 2007). Moreover, the observed seasonal variations in temperatures and rainfall, and more frequent extreme events necessitate the refinement of genotype × management × environment paradigm (Hunt et al., 2018). This is also important to sustain wheat productivity under the prevailing climatic variability and considering the forecast scenarios associated with climate change phenomenon. So, the present study was conducted to enhance understanding of the components of genotype × environment x management (G × E × M) paradigm for its elaboration to wheat farmers of rainfed agro-ecology.

Materials and Methods

Data generated from a long-term field experiment [laid using Randomized Complete Block Design (RCBD) in triplicate with 4.5 × 10 m plots per sowing per genotype and consisted of 18 rows with row spacing of 25 cm] conducted during 2001-02 crop season (CS) to 2006-07 CS] was utilized for this study. The study site was in Islamabad-Pakistan at 33° 43'N, 73° 06'E and 547 m above sea level having soil characterized as silty loam (Silt:Sand:Clay:73:14:13), alkaline (pH 8.3) with low EC (0.2 dS/m) and Organic Carbon (0.3%)). The details about other factors of this study are given as follows:

Genotypes (G)
A set of six wheat genotypes was included in the study. These are elite breeding material and are denoted as G1 (Parentage: OPATA/RAYON//KAUZ), G2 (Parentage: BUC`S'/FCT`S'), G3 (Parentage: OPATA/BOW'S'), G4 (Parentage: MON'S'/IMU//BAU'S), G5 (Parentage: KAMBARA1) and G6 (Parentage: FRET2) for this study.

Environments (E)
Each year from 2001-02 wheat crop season to 2006-07 crop season was treated as a different environment. This was done because of the reason that each year has different environmental conditions and that wheat crop experienced variable environmental conditions every year (Zhang et al., 2013). Data regarding weather prevailed during the study period was collected from the nearby met station and is summarized in Table 1.

Table 1: *Summarized data of parameters related to environment and crop.*

Variables									
Year	**P**	**AT**	**BSD**	**SR**	**PHt**	**TN**	**TGW**	**SL**	**SlpS**
2001-02	127.5	18.9	1859.1	14.8	92	247	38	10	20
2002-03	423.6	18.0	1898.0	15.0	92	220	39	10	19
2003-04	297.7	18.8	1631.4	15.6	99	271	35	10	19
2004-05	493.6	16.5	1931.6	13.9	98	274	38	11	20
2005-06	278.1	19.2	1891.9	15.1	105	314	38	11	20
2006-07	540.7	18.1	1891.9	15.1	98	262	37	11	20

P stands for total in-season Precipitation (Oct-Apr), AT for Average seasonal Temperature, BSD for total in-season Bright Sunshine Duration, SR for average seasonal Solar Radiations, PHt for Plant Height, TN for Tiller Number/m², TGW for Thousand Grain Weight, SL for Spike Length and SlpS for Spikelets per Spike. The crop data is averaged across years and sowing windows.

Managements (M)
Each year the wheat crop was sown at four different sowing dates, thus creating four different Sowing Windows (SW), to cover the whole range of sowing time. In SW1 sowing was done during October 15-25, while SW2 was completed during November 10-17, SW3 during November 27-December 02 and SW4 during December 10-24. Each SW was considered as a distinctive management option and used in G × E × M interactions.

Parameters studied
Data regarding the studied parameters [namely days to anthesis (DA), days to maturity (DM), plant height (PHt), Spike length (SL), number of spikelets per spike (SlpS), biomass (Bm), thousand grain weight (TGW), number of tillers (TN) and grain yield (GY)] was collected for all genotypes over various

Table 2: *Mean wheat grain yield (t/ha) listed as Genotype × Management and Genotype x Environment two-way data format.*

	Genotypes (G)												Mean	SD	C
	G1		G2		G3		G4		G5		G6				
	GY	%D	GY	%D	GY	%D	GY	%D	GY	%D	GY	%D			
Management (M)															
SW1	4.9	4	5.3	11	4.8	1	4.6	-1	4.4	-6	4.2	-12	4.7	0.4	0.3
SW2	4.7	6	4.8	9	4.4	1	4.6	4	4.0	-9	3.8	-15	4.4	0.4	0.3
SW3	3.5	10	3.5	9	3.2	1	3.2	0	3.1	-1	2.4	-28	3.1	0.4	0.3
SW4	2.1	-2	1.8	-19	2.1	-3	2.3	8	2.4	11	2.1	-1	2.2	0.2	0.2
SD	1.3		1.6		1.3		1.1		0.9		1.0				
C	1.3		1.5		1.2		1.1		0.9		1.0				
Environment (E)															
2001-02	3.7	15	3.4	6	2.4	-34	2.9	-10	3.4	5	3.4	5	3.2	0.5	0.4
2002-03	2.8	-9	2.8	-8	3.1	0	3.5	12	3.2	6	2.9	-4	3.0	0.2	0.2
2003-04	3.7	4	3.1	-15	3.8	6	4.0	10	3.7	4	3.1	-15	3.6	0.4	0.3
2004-05	4.1	3	4.1	3	3.9	-2	3.8	-3	3.8	-4	4.0	2	4.0	0.1	0.1
2005-06	4.3	7	5.0	20	4.7	13	3.9	-3	3.7	-10	2.6	-53	4.0	0.8	0.7
2006-07	4.1	8	4.6	18	3.9	4	3.9	4	3.2	-19	2.9	-30	3.8	0.6	0.5
SD	0.5		0.9		0.8		0.4		0.3		0.5				
C	0.4		0.7		0.6		0.3		0.2		0.4				
Genotypes (G)															
Mean	3.8	5	3.8	6	3.6	1	3.7	2	3.5	-3	3.2	-14	3.6	0.2	0.2
SD	0.8		1.1		0.9		0.7		0.6		0.7				
C	0.5		0.7		5.7		0.4		0.4		0.4				

GY stands for Grain Yield while %D is the percent difference between individual genotype mean across all sowing windows and mean of all genotypes in a year, SD is standard deviation, C is the confidence interval for the mean at P < 5% level. Values with special font format indicate best (bold) and worst (italic) performance of genotype(s) in a sowing window (SW) and year.

sowing dates and across years and averaged across the replicate plots. Crop phenology (DA and DM) in terms of days after sowing was measured by selecting ten plants per plot. Bm, TN (head bearing) and GY was taken from the one m^2 area and converted to per hectare (ha). Data regarding PHt (cm), SL (cm), SlpS was recorded from five plants per plot while TGW (g) was randomly taken from each one m^2 harvested sample, which was used for GY.

Statistical analysis

Analysis of variance (ANOVA) was performed by using MSTATC version 1.42 (Freed and Eisensmith, 1991) to test the significant differences between means of various parameters studied for six genotypes (G) across four sowing window managements (M) and years (E). ANOVA was also carried out to determine the G × E × M effect on grain yield, plant height, spike length, spikelet's per spike, tillers per m^2, biomass and 1000 grain weight. Analysis also included all possible interactions among these factors on yield, yield components and other agronomic traits.

Table 3: *Contribution by components of G × E × M paradigm and their interaction in grain yield variance.*

Source of variation	% of total variance						
	GY	TN	Bm	TGW	PHt	SL	SlpS
Management	58	62	66	35	67	11	25
Genotype	<1	<1	<1	2	<1	3	2
G x M	2	2	2	2	2	7	2
Environment	8	6	7	14	5	1	5
M x E	11	11	10	19	16	18	31
G x E	5	2	3	4	2	18	9
G x E x M	7	6	6	7	5	12	7

To find out the best and worst performance of a genotype percent difference between individual genotype mean across all SWs and mean of all genotypes in a year was calculated. Similar calculations

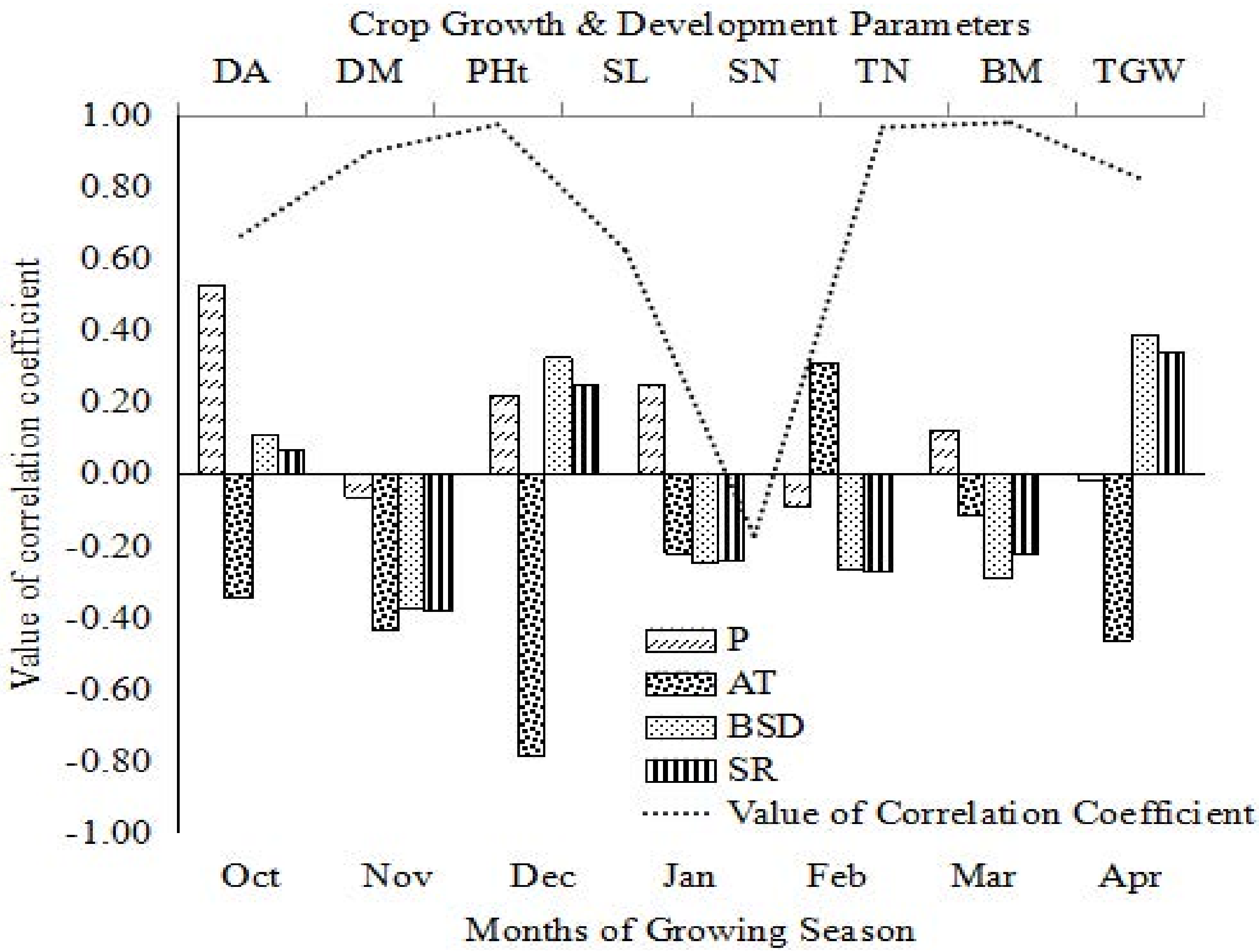

Figure 1: *Correlation of environmental factors (primary x-axis) and crop growth and development parameters (secondary x-axis) with grain yield (for description of crop parameters refer to* Table 1*).*

were done across genotypes for a year and in a sowing window. Correlation analysis was done to estimate the relationship of six genotypes with environmental variables, years and SWs for yield. All these analysis were performed by using STATISTICA version 6 (Stat Soft, 2001).

Results and Discussion

Genotypic (g) performance over years (E) and sowing windows (M)

The studied genotypes (G) performed variably over years (E) and sowing windows (M). GY of all the G, averaged across management (M) options in an Environment (E) varied between 4.9 and 2.5 t/ha (Table 2). During wheat growing season 2001-02, G1 performed better, G4 ranked as top yielded during 2002-03 and 2003-04, while G2 performed better during 2004-07 crop growing season. Over the years, G2 performed better with sowing before mid-November (SW1-2), G1 and G2 provided better GY attaining opportunity with sowing after mid-November (SW3) while, G5 though low yielded but out-performed other genotypes when sown in December (SW4). Hence, the window of opportunity existed for selection of suitable G, corresponding to M options in the given E.

The GY attained by these genotypes varied between 2.7 and 4.8 t/ha over the studied period of time (E). All the genotypes performed better during 2004-06 crop growing seasons with mean GY of 4.0 $\pm$ 0.1-0.8 t/ha averaged across M and G choices as compared to other years. However, 2002-03 wheat growing season was the lowest yielding year with an average yield of 3.0 $\pm$ 0.2 t/ha (Table 2). Hence, significant yearly variations were observed, advocating the selection of suitable G and matching M to sustain productivity.

These genotypes, over the years exhibited significant variations in GY with change in sowing time (M). The attained GY varied between 2.0 and 5.1 t/ha and

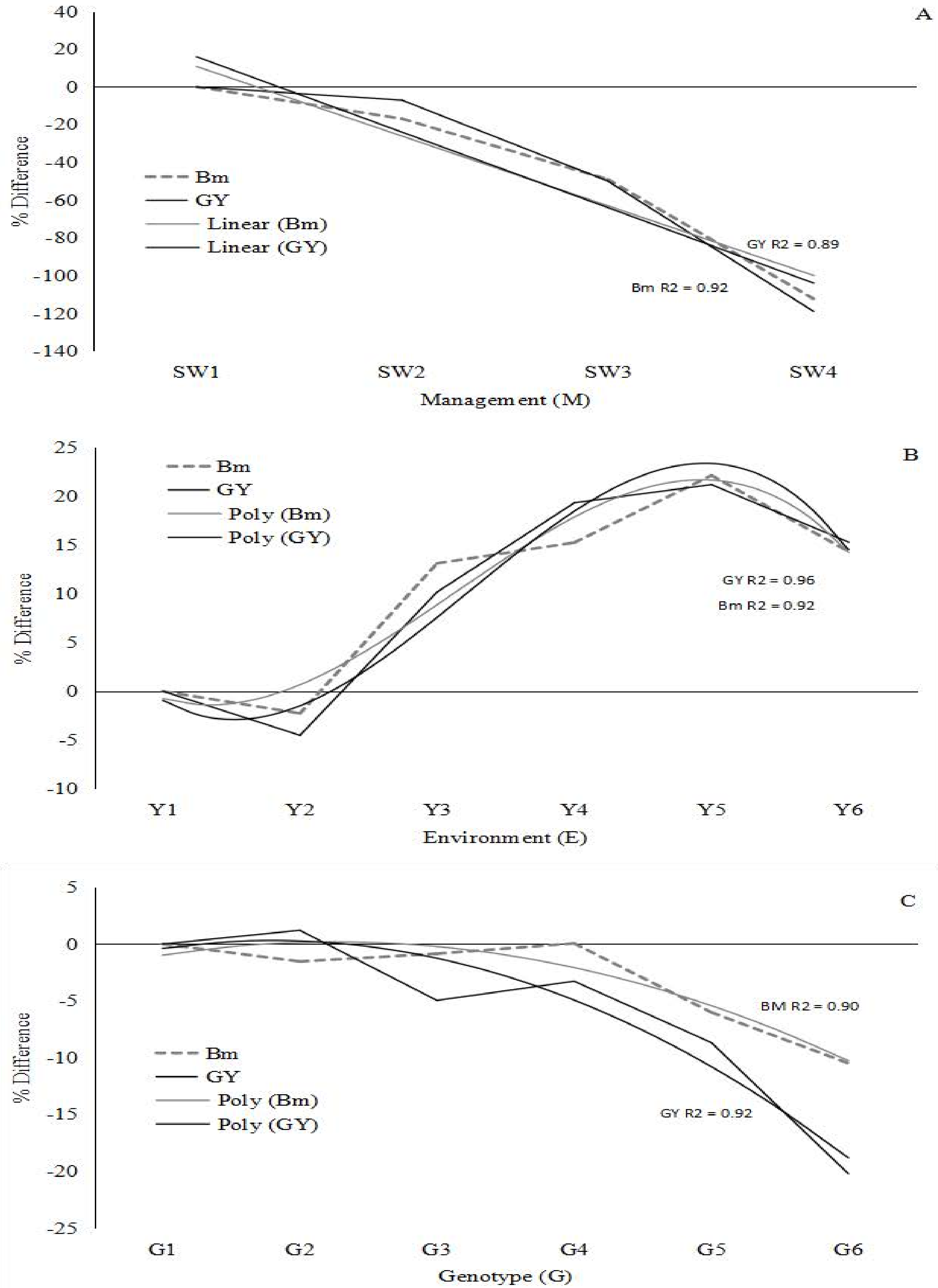

Figure 2: *Variations observed in grain yield (GY) and accumulated biomass (Bm) due to management (A), environment (B) and genotypes (C).*

indicated a very strong influence of M (in terms of selection of sowing time) in this rainfed agro-ecology for sustaining wheat productivity. This was further elucidated by the analysis of variance.

Analysis of Variance

The most significant component among G, E, M and all possible interactions was M for GY and all other growth and development related studied parameters and among yield components for TGW. It accounted for 58% of variance for GY across all G and E circumstances (Table 3). The overwhelming role of M in this rainfed ecology might be attributed to almost negligible contribution of G factor of this G × E × M paradigm. The crop phenology exhibited similar response of all these genotypes. They took around 116 days from sowing to anthesis and 155 days to maturity. Due to this, non-significant differences among genotypes regarding GY and other parameters were observed. M × E interaction hold for 10-31% variance and was emerged as the second important determinant for GY and other parameters (Table 3). Following elaborative analysis highlighted the mechanism of these important components in determining GY.

Relationship of grain yield with studied parameters

Among the studied parameters, Bm emerged as the most important yield determinant in this ecology (Figure 1). Mean Bm presented as E × M two-way data format (Supplementary Table 1) indicated that it varied between 10.1 ± 5.3 t/ha and 13.3 ± 4.1 t/ha during 2001-07 crop growing seasons and between 7.3 ± 2.4 t/ha and 15.5 ± 1.3 t/ha across sowing windows. Hence, a linear reduction was observed from SW1 to SW4 (Figure 2A). This reduction in Bm was corroborative to that of GY. The correlation of these important crop growth and development variables (Bm, TN and PHt) with GY depicted that the GY of these genotypes was interactive with these parameters in the order of Bm>TN>PHt.

Relationship of grain yield with environment, environmental components and management

Among the environmental variables, a moderate to strong positive correlation was observed with amount of precipitation received at the time of crop establishment. The October precipitation is of significance for moisture availability not only for early sown (SW1) crop but also as a residual moisture for subsequent sowing. A very strong negative correlation was observed with average temperature prevailed during the month of December. The fairly positive correlation of Precipitation (P), Bright Sunshine Duration (BSD) and Solar Radiations (SR) in December indicated the role of December temperature in fulfilling the thermal time requirement, particularly for vegetative phase, and the onset of reproductive phase. Similarly, the temperature prevailed during grain filling phase (March-April) is also critical for GY (Figure 1).

The results revealed that the most significant component of G × E × M interaction for GY was M in this rainfed Agro-ecology. The significance of this factor reflected the importance of sowing time and that the selection of optimum sowing time would determine the successful completion of the crop's life cycle and optimal performance of other important growth and development related parameters (Figure 3). Jahan et al. (2018) concluded that being thermo-sensitive, Optimum sowing time could ensure the prevalence of optimum temperature at critical growth stages. Dennett (2000) also included the sufficient water supply, in addition to favorable temperatures, as moderate climatic conditions.

The rainfed wheat farming depends on rainfall for water supply (Asseng et al., 2016). Hence, water availability in the form of rainfall is of immense importance under rainfed conditions. This rainfall induced availability of soil moisture ensured good crop establishment by affecting the germination and emergence. So, the selection of sowing time, suitable for a particular locality or region, became a crucial management option to sustain productivity (Andarzian et al., 2015). The selection of optimum sowing time would also help to ensure the sufficient duration of time for all the crop growth phases, including tiller initiation. Adequate tiller numbers per unit area would result in establishment of good crop stand.

The optimum sowing time also resulted in increased GY due to the prevalence of optimum environmental conditions during critical growth phases, such as grain filling period (Jahan et al., 2018; Bannayan et al., 2013). Studnicki et al. (2016) indicated the strong impact of environmental conditions and less impact of genotypes on grain yield in spring wheat. Similar to that finding, we also observed much lower impact of genotypes on grain yield. Possible reason,

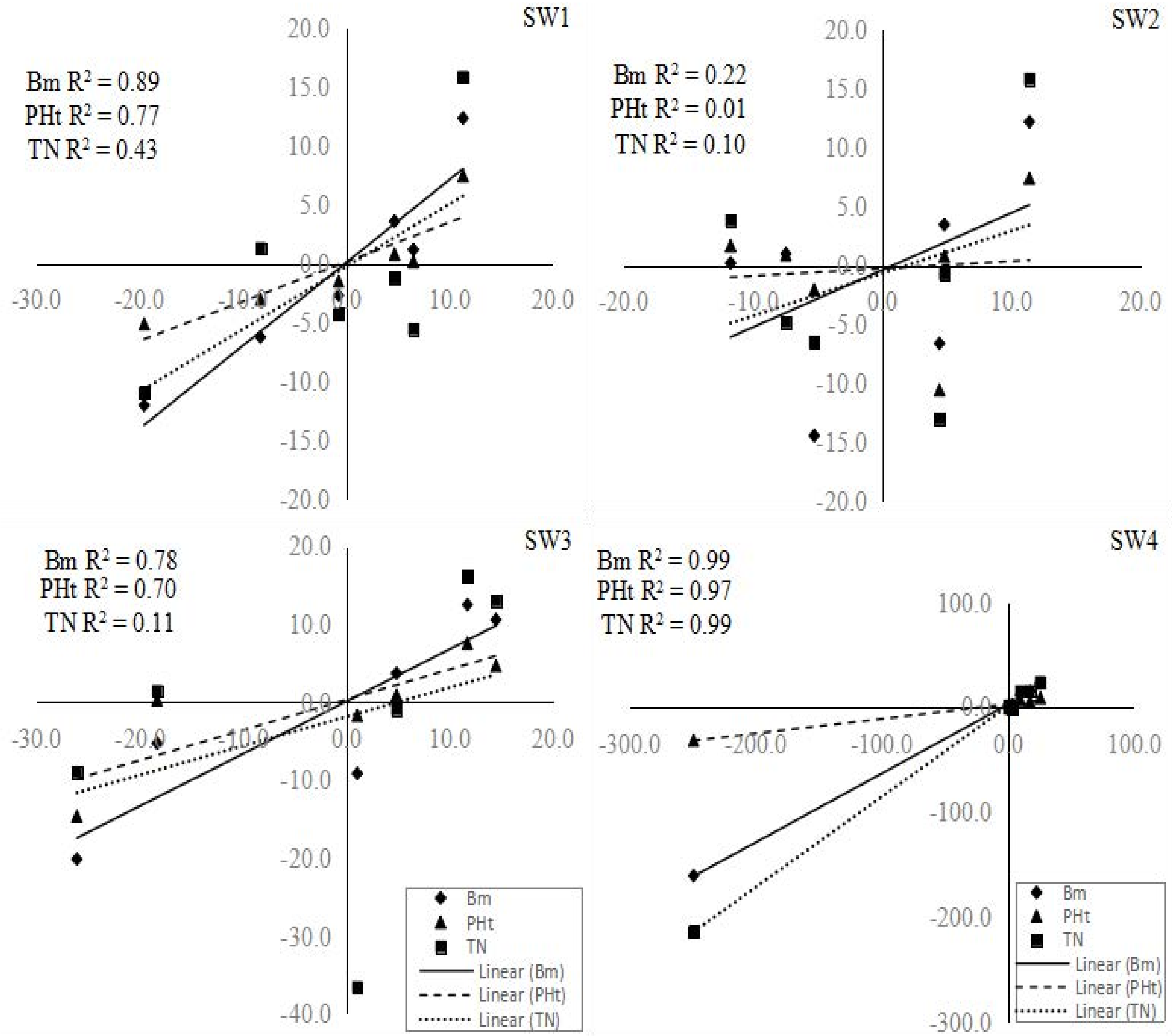

Figure 3: *Mean variations in grain yield (x-axis) and the corresponding deviations in biomass (Bm), plant height (PHt) and tiller (TN) (y-axis) over years across sowing windows (SW1-4).*

in this study, might be the same duration taken by these genotypes to attain the crop maturity. So, the thermal time requirement for these was the same. Zimmermann et al. (2017) highlighted the potential role of sowing time and thermal time requirements in achieving grain yield in a given environment. The non-significant differences among these genotypes corroborated their findings and that of Studnicki et al. (2016). Erdemci (2018), in an investigation on chickpea genotypes, also concluded similar sort of contribution by the genotypes. Thus, all these genotypes, by attaining crop maturity at the same time in a sowing window, were exposed to the same set of environmental conditions. This argued for developing diverse genotypes with varying thermal time requirements. The availability of such diverse genotypes provided an option of selecting suitable genotype(s) corresponding to management and environment prevailed during that season. Coventry et al. (2011) demonstrated use of similar approach in Haryana, India. The best match of optimum sowing time with the most suitable genotype, provided an opportunity for wheat crop to avoid terminal heat stress (Coventry et al., 2011), have optimal growing duration (Jahan et al., 2018) and attain potential grain yield.

The other factor, emerged as important in this study, was the interaction of sowing time with year. Asseng et al. (2016) demonstrated the yearly variations observed in Australian rainfed wheat productivity. Similar variations were also observed in this study.

Furthermore, the trend indicated a possible shift towards early November sowing (SW2). This might be attributed to pre-sowing rainfall variability and the resultant moisture availability for a good crop establishment, as highlighted by Asseng et al. (2016).

The option of late November (SW3) and December (SW4) sowing was unproductive and might possibly result in crop failure or significant loss due to exposure of reproductive and/or grain filling phase to less conducive environment (Hunt et al., 2018; Jat et al., 2018). This corroborated the findings of earlier studies (like Luo et al., 2018; Coventry et al., 2011) to have a wider selection opportunity for wheat farmers with genotypes having varying thermal time requirements. So, by regulating the wheat growth phases, this can be achieved. The same was demonstrated by Peake et al. (2018) and Zeleke and Nendel (2016).

While working on this tactical option, due consideration needs to be given to traits of economic importance. In the presented study, plant height, tillers per unit area and resultantly biomass accumulation are important yield determinants in this agro-ecology (Figure 3). These results are corroborative to similar earlier studies like those of Mohammadi et al. (2015) and Cai et al. (2014). Kaya et al. (2015) also concluded as positive contribution of plant height towards grain yield in rainfed agro-ecologies. Several other studies also suggested the role of productive tillers per unit area in determining the wheat grain yield (Hai-cheng et al., 2015) which is also associated with plant height (Mohammadi et al., 2015) and the accumulated biomass as photosynthetic reserves during grain filling (Marti et al., 2016).

The results of the presented study highlighted the important components of G × E × M paradigm and that the availability of appropriate and diverse genotypes with the optimal crop management could better exploit the erratic climate and attain potential grain yield in rainfed agro-ecology.

Conclusions and Recommendations

Wheat productivity in rainfed agro-ecology is predominantly determined by the environmental conditions. Among these, rainfall at appropriate time and in optimum quantity is of prime importance. Though it is being governed by natural phenomena, its best match with other factors belonging to production paradigm could lead to sustained improvement in grain yield. The demonstrated selection of optimum sowing time provided an opportunity for the farmers of the rainfed areas towards having better crop establishment and stand by improving utilization of available soil moisture. This crop management option needs to be coupled with appropriate genotypes for yield sustainability. The presented study highlighted important yield determinants for rainfed agro-ecology. However, further studies using crop simulation models in conjunction with innovative seasonal forecasting tools with improved capabilities are suggested to study these three factors in a more holistic way and propose optimum crop designs for this ecology.

Author's Contribution

Muhammad Asim: Performed field experiments, data analysis, interpretation and wrote the manuscript.
Asghari Bano: Design of the manuscript and data interpretation.
Sikander Khan Tanveer: Data analysis.
Muhammad Umair Aslam: Data entry and analysis.

Supplementary Material

There is supplementary material associated with this article. Access the material online at: http://dx.doi.org/10.17582/journal.pjar/2020/33.1.154.163

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