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Plant breeding increases spring wheat yield potential in Afghanistan

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Abstract

Wheat (*Triticum aestivum* L.) is an essential food security crop in Afghanistan. To determine the contribution of wheat breeding to increasing productivity, we analyzed data obtained from 192 trials conducted over 11 locations from 2002–2003 to 2015–2016. Using this data, we estimated annual genetic gains for grain yield, days to heading and plant height over the 14-yr period. We used best linear unbiased estimates to measure genetic gains across CIMMYT Elite Spring Wheat Yield Trials per se and for the top 5 and top 10% performing genotypes relative to checks. Mean realized genetic gain for grain yield was 115 kg ha^{-1} yr^{-1}, whereas the top 10 genotypes achieved annual yield gains of 123 kg ha^{-1}. The continually replaced local check s also contributed an annual genetic gain for yield of 107 kg ha^{-1}. The associated adaptive traits days to heading and plant height varied in their response over time with the top 10 yielding genotypes having a 1.82 d annual reduction in heading date while plant height increased by 0.77 cm yr^{-1} for the same set of genotypes. Results show that continual breeding improvements confer yield gains, contributing to increasing Afghan wheat productivity. This has wider relevance for demonstrating the value of continued investment in public sector plant breeding supporting wheat production and food security in Central Asia.

1 | INTRODUCTION

The International Maize and Wheat Improvement Center (CIMMYT) develops and distributes improved germplasm targeted toward diverse wheat (*Triticum aestivum* L.) growing regions in the developing world. The distribution and testing of CIMMYT-derived advanced wheat breeding lines across environmental zones worldwide has characterized global wheat production into several mega-environments or target population of environments, and its wheat improvement priorities are targeted accordingly (Braun et al., 2010; Rajaram et al., 1993). The target population of environment concept has been recently substantiated by studies showing wide diversity among the sites where CIMMYT's collaborative yield trials have been historically evaluated (Crespo-Herrera et al., 2021). This extensive global environmental

Abbreviations: ARIA, Agricultural Research Institute of Afghanistan; BLUE, best linear unbiased estimate; BLUP, best linear unbiased predictor; CIMMYT, International Maize and Wheat Improvement Center; DTH, days to heading; ESWYT, Elite Spring Wheat Yield Trial; GY, grain yield; IWIN, International Wheat Improvement Network; LC, local check; PTH, plant height.

diversity presents both challenges and opportunities to breeders attempting to develop or select wheat cultivars with both high yield potential and wide adaptation.

Cultivar choice remains the single most important factor in maximising wheat yields. The CIMMYT, together with national wheat programs, operates the Elite Spring Wheat Yield Trial (ESWYT) comprising newly developed high-yielding, disease, and climate resilient wheat germplasm for optimal environments. All countries in South Asia—including Afghanistan, where wheat is the fundamental staple food—participate in this wide international wheat testing network.

Wheat is the most important food crop in Afghanistan with an average annual per capita wheat consumption of over 160 kg, against a global average of 65 kg (FAO, 2013). In Afghanistan, approximately 54% of the population lives below the poverty line (ADB, 2020) and wheat accounts for up to 60% of the calorific intake of an average Afghan (Chabot & Dorosh, 2007). Wheat is grown on over 2.5 million ha in Afghanistan, occupying 80% of the total cereal acreage, and producing 4.5 to 5 million t of wheat per year. Environmental, climatic, and topographical conditions for wheat production vary from a 300 m elevation in the northern Amu river basin to 2,500 m asl in the central highlands. Rainfed wheat accounts for about half of the acreage; however, its contribution to total production is low, ranging from 10 to 30% (APR, 2012). Irrigated environments more reliably contribute to Afghan wheat production, although water deficit and biotic stresses remain a major challenge.

Between 2007 and 2020, data from ESWYT trials has contributed to the release of eight high yielding wheat cultivars in Afghanistan (Obaidi et al., 2011, 2014, 2015; Soofizada et al., 2018). Recent work by Dreisigacker et al. (2019) surveyed wheat cultivars grown on 560 farms in Afghanistan, and used DNA fingerprinting to demonstrate that 74% of farmers were growing cultivars released after 2000, indicating a general trend away from landraces.

World food demand is growing. New wheat cultivars must have higher yield potential, tolerance to warmer temperatures, improved water use efficiency and drought tolerance, and a wide spectrum of disease resistances. Thus, assessing genetic gain in wheat production is of fundamental importance for monitoring breeding progress. Graybosch and Peterson (2010) estimated genetic gain of 0.86 to 1.28% per year over a 50-yr period in two sets of wheat yield trials from the Great Plains of North America. The CIMMYT Global Wheat Breeding Program has periodically monitored the genetic gain of its global wheat improvement programs. This has provided extensive evidence documenting the genetic gain delivered across both selection and target environments (Crespo-Herrera et al., 2017, 2018, 2021; Dreisigacker et al., 2019; Gerard et al., 2020; Lopes et al., 2012; Manès et al., 2012; Mondal et al., 2020; Sharma et al., 2012). In this study, we analyzed multi-environment grain yield (GY) performance and adaptive trait data generated for ESWYT trials in Afghanistan from 2002 to 2016 to quantify genetic gain over time.

Core Ideas

- Genetic gain for yield shows an increase over a 14-yr period, contributing to food security.
- The top performing material in annual nurseries shows increased gain in comparison to checks.
- Adaptive traits also show changes over time indicating fine-tuning to agri-environments.

2 | MATERIALS AND METHODS

2.1 | Phenotypic data

This study used data from ESWYT trials conducted in the 2002–2003 to 2015–2016 wheat growing seasons throughout Afghanistan. The ESWYT is a replicated yield trial containing new elite spring bread wheat germplasm developed by CIMMYT, and adapted to optimally irrigated, low rainfall areas (Crespo-Herrera et al., 2017). The trial generally contains 50 elite lines selected with data from 2 to 3 yr of yield testing under optimum and stress conditions in Ciudad Obregón, Mexico, as well as data from multiple disease resistance screens, and end-use quality assays. New lines are included annually in each ESWYT trial, providing new elite germplasm for multilocation testing. The 14-yr set analyzed in this study represents approximately 700 unique entries. The ESWYT trials include —three to four CIMMYT checks and a local check (LC), which is generally the top performing commercial cultivar in the testing region. The CIMMYT checks (three to four selected based on stable performance in previous international trials rather than for performance in Afghanistan per se) are updated every few years with overlaps maintained between years (and replaced one at a time to ensure overlap). The analysis included 192 ESWYT trials conducted across 69 site × year combinations. The trials were distributed throughout wheat producing regions (Supplementary Table S1). The ESWYT trials were sown in an α-lattice experimental design with two replicates, following locally recommended agronomic practices in all years. Each entry was sown in six rows of 5-m length at a row-to-row spacing of 20 cm. A fertilizer dose of 120 kg nitrogen and 60 kg phosphorus was applied to all trials. Only trials with complete data for GY (t ha^{-1}), days to heading (number of days from planting; DTH) and plant height (PTH; cm) were used in the analysis and interpretation. The datasets were screened to remove outliers, assess the normality of distribution for continuous traits and to calculate trial CVs and heritabilities. The correlations between the three measured traits (GY, DTH, PTH) were also calculated.

2.2 | Statistical analysis

First, we calculated the best linear unbiased estimate (BLUE) and the best linear unbiased prediction (BLUP) values and used Meta Analysis with R to compute the broad-sense heritability (repeatability) and genetic correlation matrices through a combined analysis of the evaluated lines across sites (Alvarado et al., 2020).

For BLUEs estimation, the following linear mixed model was used:

$$Y_{ijk} = \mu + S_i + R_j\left(S_i\right) + SB_k\left(S_i\ R_j\right) + G_l + S_i \times G_l + \varepsilon_{ijkl} \quad (1)$$

where μ is the general mean, S_i is the fixed effects of the sites (i = 1,…, s), $R_j(S_i)$ is the random effects of the replicates (j = 1, 2) within sites (environment), assumed to be independently and identically normally distributed (IID) with mean zero and variance $\sigma^2_{r(s)}$, $SB_k(S_i\ R_j)$ is the random effects of the sub-blocks (k = 1,…,10) within sites and replicates, assumed to be IID with a mean of zero and the variance $\sigma^2_{sb(r\ s)}$, G_l is the fixed effect of the wheat lines (l = 1,…,50), and $S_i \times G_l$ is the line by site interaction. The term ε_{ijkl} is a random residual associated to the lth wheat line, in the k*th* sub-block of the j*th* replicate of the i*th* site and assumed to be IID with a mean of zero and the variance σ^2_{ε}. The model computing the BLUPs was the same as the model of Equation 1, with the lines now considered as random effects.

The broad-sense heritability was calculated according to Equation 2:

$$H^2 = \frac{\sigma^2_g}{\sigma^2_g + \sigma^2_{ge}/nloc + \sigma^2_{\varepsilon}/(nloc \times nrep)} \quad (2)$$

where σ^2_g, σ^2_{ge}, and σ^2_{ε} are the genotype, genotype by site interaction and the error variance components, respectively, and *nloc* and *nrep* are the number of sites and number of replicates, respectively. The genetic correlation matrices among sites were calculated using equations from Cooper and Delacy (1994): $\rho_{g_{ij}=\frac{\rho_{p_{ij}}}{h_i h_{i'}}}$ where $\rho_{p_{ij}}$ is the phenotypic correlation among sites i, and i' and h_i and $h_{i'}$ are the square roots of the sites i and i', respectively.

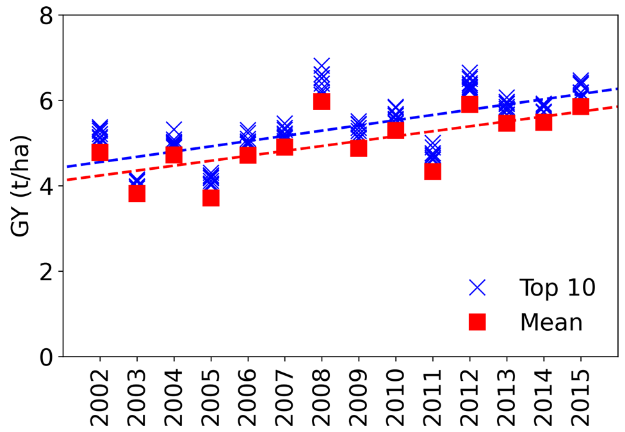

FIGURE 1 Overall increase in grain yield in Elite Spring Wheat Yield Trial trials grown across Afghanistan over a 14 yr trialling period. The yield increase was observed for both the mean performance and top 10 lines per trial (R^2 = 0.45; P < .05). GY, grain yield

2.3 | Computing genetic gains based on best yielding lines compared to LCs

Genetic gains for GY, DTH, and PTH were calculated by regressing the BLUEs of all lines in the ESWYT on the year of testing. Genetic gain was also calculated (a) with the BLUES of all lines across all sites in one particular year, (b) with the BLUES of only the 5 and 10 highest yielding lines recorded in each year, and (c) with the mean of all lines in each year.

In addition, the BLUEs were expressed as percent of the LCs (GYplc), calculated as in Equation 3 as a ratio:

$$\text{GYplc} = (\text{BLUEs}/\text{Mean LC}) \times 100, \quad (3)$$

where BLUEs represents the estimated GY value of a line, and Mean LC represents the estimated GY mean of the LCs. Genetic gain was then calculated using these BLUEs (expressed as GYplc) (a) across all lines across all sites in one particular year, (b) with the BLUES of only the 5 and 10 highest yielding lines recorded in each year, and (c) with the mean of all lines in each year.

3 | RESULTS

3.1 | GY performance and genetic gains increase over time

Significant upward trends were observed for GY over the 14 yr of testing (Table 1), returning a gain of 115 kg ha^{-1} yr^{-1} with a significant R^2 of 0.44 (Figure 1). The overall mean of GY performance in the ESWYT over 14 yr was 5.02 t ha^{-1} and ranged from a low of 3.58 t ha^{-1} (2005–2006) to the highest annual average of 5.97 t ha^{-1} in 2008–09 (Table 1). The geno-

TABLE 1 Yield performance of Elite Spring Wheat Yield Trial (ESWYT) trials grown in Afghanistan from 2002–2003 to 2015–2016 showing increasing grain yield over time along with relatively stable statistical parameters

	Year of testing													
Trial data	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2007–2008**	**2008–2009**	**2009–2010**	**2010–2011**	**2011–2012**	**2012–2013**	**2013–2014**	**2014–2015**	**2015–2016**
ESWYT no.	23	24	25	26	27	28	29	30	31	32	33	34	35	36
n Envs	6	6	7	4	6	5	8	7	5	5	4	5	3	9
H^2	0.37	0.15	0.05	0.19	0.00	0.07	0.53	0.58	0.00	0.62	0.38	0.14	0.16	0.48
Trial mean (t ha^{-1})	4.779	3.814	4.726	3.582	4.704	5.760	5.970	4.881	5.214	4.214	5.936	5.763	4.978	5.851
LSD	0.330	0.136	0.109	0.278	0.015	0.135	0.39	0.334	0.000	0.406	0.393	0.232	0.976	0.311
SE	0.163	0.067	0.054	0.138	0.007	0.067	0.194	0.166	0	0.201	0.195	0.115	0.486	0.155
CV	12.16	11.79	16.42	17.80	16.74	12.09	14.88	12.96	13.36	18.88	12.89	12.63	9.88	11.61
Max yield	5.038	3.868	4.752	3.740	5.253	5.797	6.502	5.220	5.815	4.709	6.221	5.861	5.106	6.141
Min yield	4.374	3.741	4.701	3.407	4.078	5.718	5.391	4.226	4.750	3.403	5.439	5.641	4.868	5.430
G var	0.045	0.006	0.003	0.025	0.000	0.005	0.084	0.068	0.000	0.119	0.064	0.016	0.023	0.048
G × Loc var	0.288	0.092	0.131	0.205	0.214	0.078	0.190	0.148	0.126	0.059	0.130	0.247	0.249	0.239
Res var	0.338	0.202	0.602	0.407	0.620	0.485	0.790	0.400	0.485	0.633	0.586	0.530	0.228	0.461
G sign	0.046	0.488	0.809	0.363	0.998	0.747	0.000	0.000	1.000	0.000	0.040	0.000		0.001
G × E sign	0.000	0.000	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.176	0.009	0.000		0.000

Note. G, gene; G × E, gene × environment; Loc, location; LSD, least significant difference; *n* Envs, number of environments; Res, residual (error); sign, significance; var, variance.

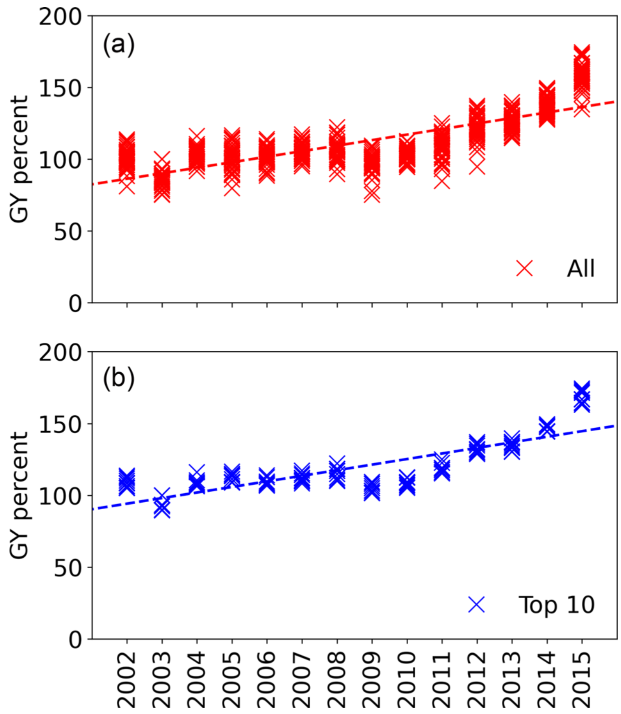

FIGURE 2 Increasing grain yield over time as a percentage of local checks for (a) the full Elite Spring Wheat Yield Trial set ($R^2 = 0.40$, $P < .005$) and (b) the top ten performing lines ($R^2 = 0.66$, $P < .05$) in each set. GY, grain yield

types tested varied significantly in 6 of the 14 yr tested, and there was no clear trend in genetic variance over time. Genotypes interacted significantly with location in 9 of the 14 yr analyzed (Table 1). Grain yield heritabilities of 0.37 or higher were observed in 6 of the 14 yr, with the highest heritability (0.62) observed for 2011–2012. Low GY heritabilities (0.05 or less) were observed in 3 of the 14 yr tested (Table 1).

For the top 10 genotypes in the ESWYT sets, the annual rate of yield gain was 2.7%, representing a gain of 123 kg ha^{-1}yr^{-1} (Figure 1). The slope of the regression was highly significant ($p < .01$; $R^2 = 0.44$). To assess genetic gains for GY over time, we calculated both the per se performance, as well as how the selected group of genotypes performed in relation to local and/or CIMMYT checks. The latter criterion was used as expressing genotype performance relative to a check's performance is a more accurate representation of performance improvement over time compared with performance per se.

We also analyzed genetic gains for GY against the performance of LCs as this is the major criterion for varietal registration and release. Compared with LCs, the mean of all genotypes showed a yield gain of 3.85% (Figure 2a) from 2002 to 2015, which translated to 118 kg ha^{-1} yr^{-1}. The LCs also showed a yield gain of 107 kg ha^{-1} yr^{-1} during the same period. The top 10 genotypes brought in a yield gain of 3.88% (Figure 2b), which was 120 kg/ha/yr compared with 103 kg ha^{-1} yr^{-1} of LC. The increase in performance of the top 5% of ESWYT genotypes was 124 kg ha^{-1} yr^{-1} compared with 103 kg ha^{-1} yr^{-1} for LCs, and 125 kg ha^{-1} yr^{-1} for CIMMYT checks (which are selected based on performance in international trials and therefore generally better performing than LCs).

3.2 | Adaptive traits show changes over time

There was significant within-year variation for DTH amongst the ESWYT genotypes in all years, except for 2002—2003 for which no data was available. Days to heading ranged from 99 to 133 ds, with a mean value of 116 d (Table 2). Significant genotype × location interactions were also detected in all 14 yr. The trial heritability for this trait exceeded 62% in 12 of the 14 yr, and in 6 yr the DTH heritability was 80% or higher. Overall, DTH declined significantly over time ($R^2 = -0.45$) by 1.82 d yr^{-1} compared with the ESWYT mean (Figure 3a).

Significant differences were also observed for PTH in 10 of the 14 yr of testing (Table 3), with no data available for 3 yr (2005–2006, 2013–2014, or 2015–2016). However, genotypes interacted significantly with locations in 11 of the 14 yr. Seven of the 14 yr had PH heritabilities of 75% or more, however 2 yr had very low heritabilities of 0.21 or less.

Contrary to DTH, mean PTH increased over time at the rate of 0.74 cm yr^{-1} (Figure 3b). The mean correlations between all three of the analyzed traits (GY, DTH, PTH) and their significance values are given in Supplementary Table S2. Grain yield was positively correlated with PHT in 8 yr with a mean value of 0.05, whereas GY had a positive correlation with DTH in 9 yr with a slightly higher mean positive correlation of 0.10. Plant height and DTH had the highest mean positive correlation of 0.24, with a negative trait correlation recorded in only 1 yr.

4 | DISCUSSION

Afghanistan is a regular wheat importer owing to deficient domestic wheat production. In the absence of strong local wheat breeding programs, the release and widespread cultivation of improved spring wheat cultivars is reliant on improved germplasm from international programs, such as CIMMYT. It is therefore important to monitor and quantify the genetic progress of CIMMYT germplasm introduced to Afghanistan, and its potential to be released there as new cultivars. Periodic estimation of local yield gains is also a measure in determining effectiveness of CIMMYT's delivery of improved material tailored to diverse production environments. This is becoming increasingly important given climatic instability and increasing threats of diseases, including rapidly evolving wheat rusts (Obaidi et al., 2011).

TABLE 2 Days to heading shows a reduction over time from 2003–04 to 2015–16 across Elite Spring Wheat Yield Trial (ESWYT) trial sets

Trial data	Year of testing												
	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
ESWYT no.	24	25	26	27	28	29	30	31	32	33	34	35	36
n Reps	2	2	2	2	2	2	2	2	2	2	2	2	2
n Envs	3	4	4	5	5	8	7	7	5	4	7	4	7
H^2	0.40	0.82	0.66	0.90	0.62	0.91	0.87	0.93	0.71	0.84	0.77	0.62	0.78
Trial mean (d)	133.03	113.90	122.63	129.08	121.93	108.24	106.28	114.54	118.02	98.75	111.25	115.26	110.31
LSD	1.767	1.389	1.640	0.917	1.381	1.338	1.124	0.789	1.230	1.049	1.066	1.246	1.457
SE	0.876	0.686	0.815	0.455	0.684	0.664	0.558	0.391	0.609	0.520	0.530	0.620	0.724
CV	1.07	1.34	2.20	0.65	0.94	1.79	1.35	1.12	1.28	1.43	1.25	1.13	2.47
G var	1.312	2.841	1.998	2.235	1.290	5.504	2.447	2.321	1.343	1.855	1.270	1.040	2.451
G × Loc var	4.861	1.360	0.533	0.859	3.237	2.221	1.596	0.463	1.646	0.359	1.653	1.720	1.224
Res var	2.007	2.346	7.295	0.698	1.327	3.740	2.057	1.632	2.299	2.007	1.948	1.684	7.414
G sign	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G × E sign	0.000	0.000	0.400	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.000	0.000	0.005

Note. G, gene; G × E, gene × environment; Loc, location; LSD, least significant difference; *n* Envs, number of environments; *n* Reps, number of replicates; Res, residual (error); sign, significance; var, variance.

TABLE 3 Plant height (cm) increased over the period from 2002–2003 to 2015–2016 (no data available for 2005–2006, 2013–2014, or 2015–2016)

Trial data	Year of testing										
	2002–2003	2003–2004	2004–2005	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013	2014–2015
ESWYT no.	23	24	25	27	28	29	30	31	32	33	35
n Reps	2	2	2	2	2	2	2	2	2	2	2
n Envs	2	2	3	3	4	8	7	6	6	5	6
H^2	0.00	0.51	0.75	0.85	0.68	0.81	0.93	0.89	0.84	0.83	0.21
Trial mean (cm)	95.20	86.10	95.69	83.64	81.97	101.84	94.07	94.50	83.16	96.47	97.03
LSD	0.00	4.52	4.11	3.83	4.64	3.07	2.93	2.86	3.20	3.10	2.27
SE	0	2.240	2.028	1.899	2.299	1.523	1.455	1.416	1.583	1.537	1.130
CV	5.81	4.72	3.93	4.93	5.52	5.77	3.92	4.74	5.48	4.84	6.40
G var	0.000	10.361	17.268	25.567	17.704	13.057	29.968	19.587	17.062	14.464	1.681
G × Loc var	20.505	11.940	10.291	4.521	22.550	7.480	9.103	4.931	8.464	4.254	18.031
Res var	30.545	16.546	14.137	16.995	20.458	34.582	13.633	20.062	20.789	21.832	38.533
G sign	1.000	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.272
G × E sign	0.000	0.00	0.000	0.003	0.000	0.000	0.000	0.001	0.000	0.008	0.000

Note. ESWYT, Elite Spring Wheat Yield Trial; G, gene; G × E, gene × environment; Loc, location; LSD, least significant difference; *n* Env, number of environments; *n* Reps, number of replicates; Res, residual (error); sign, significance; var, variance.

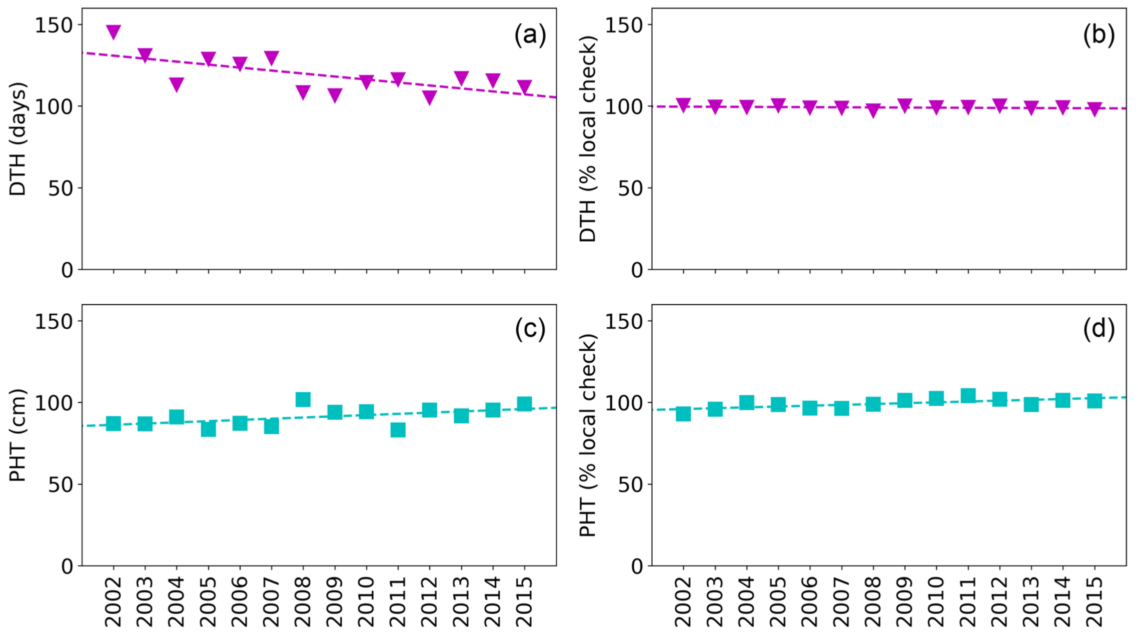

FIGURE 3 Over 14 yr, days to heading reduced by 1.82 d yr^{-1} (a) although did not decrease relative to local checks (b). Plant height increased by 0.74 cm yr^{-1} (c) although the increase relative to checks over the same time period was lower (d). DTH, days to heading; PHT, plant height

Several approaches have been employed to estimate genetic gains for GY. Generally, the choice of a method depends on factors such as available computational and data resources, the structure of the dataset/s and the study objectives (Rutkoski, 2018). In this study, we estimated the rate of breeding progress through introduction of elite genotypes from CIMMYT's international ESWYT evaluated over 14 yr across multiple environments in Afghanistan. The yield gain was calculated both as mean progress per se and the progress for the top five and ten genotypes as compared to the local and/or CIMMYT checks. The checks are used to address the question as to whether observed gains have arisen only from changes in disease resistance. The LCs used by the co-operators are the best resistant cultivars available in the region and are updated over time (Singh et al., 2007). This ensures that comparisons are appropriate to identify superior yielding genotypes with disease resistances that have potential to be released and find farmer acceptance in the region.

In this study, the trends observed in yield gains were consistent, exhibiting highly significant ($p < .01$) regression slopes and genetic gain of over 2.7%, and over 110 kg ha^{-1} yr^{-1} or more in absolute values under all the analyzed scenarios. This finding is in line with previous reports of yield gains over time for CIMMYT germplasm in other parts of the world (Crespo- Herrera et al., 2017; Gerard et al., 2020). Crespo-Herrera et al. (2017), Lopes et al. (2012), Sayre et al. (1997), and Sharma et al. (2012) reported yield gains of 90.1 kg ha^{-1} yr^{-1} and 28.7 kg ha^{-1} yr^{-1} compared with the CIMMYT cultivar 'Attila' and LCs, respectively, from 8 yr of ESWYT across 426 locations. Specific to mega environments, Rajaram et al. (1993) reported yield gains of 102.7 kg ha^{-1} yr^{-1} and 46.65 kg ha^{-1} yr^{-1} compared with CIMMYT and LCs, respectively. More recently, Crespo-Herrera et al. (2021) reported GY gains in India of 118 kg ha^{-1} yr^{-1} for the optimally irrigated North-Western Plains Zone; 46 kg ha^{-1} yr^{-1} for optimally irrigated, heat-stressed North-Eastern Plains Zone; and a high of 123 kg ha^{-1} yr^{-1} for the drought-stressed Central-Peninsular Zone. The CIMMYT's High Rainfall Wheat Yield Trial was also shown to confer relatively variable GY gains across 239 international testing locations (Gerard et al., 2020). In high-rainfall environments, the annual GY genetic gain per se was 160 kg ha^{-1} yr^{-1} and only 65.1 kg ha^{-1} yr^{-1} compared with the LC. The gains in low-rainfall environments were 40 kg ha^{-1} yr^{-1} for GY gain per se and 33.1 kg ha^{-1} yr^{-1} compared with the LC, respectively. In the present study, results segregated on the basis of production zones in Afghanistan could not be recorded as a repeatable delineation of Afghan wheat acreage is yet to be undertaken but should be investigated further in future.

In comparison with yield gains reported in other parts of the world, Thomas and Graf (2014) reported an increase of 1.4% yr^{-1} in on-farm yields in Manitoba, Canada. Hochman et al. (2017) reported closure of yield gaps in Australia created by decline of water limited yield potential over 25 yr with gains achieved by technology which led to an increase in relative yield from 39% in 1990 to 55% in 2015. They attributed this decline to reduced rainfall and rising temperatures while elevated CO_2 prevented a further 4% loss. The Hochman et al. (2017) study however, demonstrated technology overcoming climate driven challenges and still contributing to gains. Another Australian study (Robertson et al., 2016), also cautioned against up to 10% reduction in crop yield potential due to negative impact of climate change. Our study also revealed adaptive changes in ESWYT genotypes over time, reflecting CIMMYT's progress in breeding for phenological and plant architecture that are productive in low rainfall and irrigated environments, such as those in Afghanistan. Understanding how key associated adaptive characteristics change with gains in yield provides insight to potentially guide future breeding efforts (Yao et al., 2019). Across the ESWSYT sets, there was a 1.8 d per year reduction in DTH (Figure 3a). No decrease was observed relative to LCs, indicating a similar trend in reduced duration in Afghan cultivars (Figure 3b). Taken together with GY increases, this demonstrates that despite modest reductions in crop duration (DTH), yield gains were not compromised. Crop durations in many parts of the world will be reduced due to climate-associated stresses (Tanaka et al., 2015), particularly late season heat that impacts final grain quality (Barrero et al., 2020). However, further work is required to understand the actual impact of a 1–2 reduction in DTH and the mitigation of late season (as well as mid-season) stress response. Shorter crop duration may also become increasingly useful to farmers in Afghanistan from the viewpoint of improving crop production logistics (Sheehan & Bentley, 2020).

In contrast to a decrease in the number of DTH, PTH showed an increase of 0.74 cm yr^{-1}, using means for all genotypes (Figure 3c), and of 0.77 cm yr^{-1} for the top ten genotypes. Although a negative correlation between PTH and GY has been reported (Akin et al., 2017; Beche et al., 2014; Yao et al., 2019), this study shows that despite increasing PTH, yield gains continued to increase. Interestingly, the PTH increase was less marked when compared to the LC over the same time period (Figure 3d), indicating that height has increased across wheat germplasm in Afghanistan over the study time period. Increased PTH is often an indicator of higher biomass, which drives higher yield provided lodging tolerance is simultaneously maintained. Wu et al. (2014) analyzed 65 yr of data and suggested that further improvement in the yield potential of wheat would need to involve increasing biomass. Higher biomass is also required in many developing countries, including Afghanistan, to produce straw as a secondary product used as dry fodder feed for livestock although it is not currently a primary selection target in the ESWYT germplasm.

Earlier studies have shown that CIMMYT's major wheat selection and testing location in Ciudad Obregón, Mexico, is correlated to a variable extent with other sites in the southern United States, Middle East, North Africa, southern Africa, and Indian subcontinent where wheat is grown (Braun et al., 1992). Trethowan et al. (2001, 2003) reported clusters of similar performing testing sites located in Mexico, South America, Africa, and South Asia. Lillemo et al. (2005) used CIMMYT's High Temperature Wheat Yield Trial to predict performance in similarly stressed locations across continents. The study reported good ability of data generated from a January planting date in Obregon, Mexico to predict yield performance in many heat-stressed environments. Our results indirectly support these findings as the top five genotypes at Afghan locations and CIMMYT checks returned similar yield gains of 124 and 125 kg ha^{-1} yr^{-1} for the 14-yr period covered by this study. The CIMMYT checks are superior genotypes selected based on their recent international performance (and are generally released as cultivars elsewhere) and the top five genotypes from current trials showed comparable gains. Also, genotypes within each ESWYT set performed consistently across Afghan testing sites as evidenced by high trial heritabilities. This is also evidenced by the fact that at present more than 80% of wheat seed produced in Afghanistan can be traced back to CIMMYT origin varieties (MAIL, 2019), which has also been confirmed by DNA fingerprinting (Dresigacker et al., 2019).

Our study shows continual increases in genetic gains from CIMMYT ESWYT material trialled across Afghanistan over a 14-yr period. This demonstrates the potential of genetically improved germplasm to increase yields, resistance to diseases, and other adaptive traits. Our study makes a case for continued investment in plant breeding and for the collaboration in germplasm evaluation for release in Afghanistan. A continued collaboration is expected to further enhance wheat production and productivity, support the country to reduce its dependence on wheat imports, and ensure future food and nutrition security in Afghanistan.

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AUTHOR CONTRIBUTIONS

Rajiv Sharma: Conceptualization; Data curation; Methodology; Project administration; Supervision; Validation; Writing-original draft; Writing-review & editing. Jose Crossa: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Software; Supervision; Validation; Writing-original draft. Najibeh Ataei: Data curation; Investigation; Methodology; Resources; Supervision; Validation; Writing-review & editing. Raqib Lodin: Data curation; Investigation; Methodology; Resources; Validation;

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

ADB. (2020). Basic statistics, Asia and the Pacific. https://data.adb.org/dataset/basic-statistics-asia-and-pacific

Akin, B., Sohail, Q., Unsal, R., Dincer, N., Demir, L., Green, H., et al. (2017). Genetic gains in grain yield in spring wheat in Turkey. *Turkish Journal of Agriculture & Forestry*, *41*, 103–112. https://doi.org/10.3906/tar-1611-50

Alvarado, G., Rodríguez, F. M., Pacheco, A., Burgueño, J., Crossa, J., Vargas, M., Pérez Rodríguez, P., & Lopez-Cruz, M.-A. (2020). META-R: A software to analyze data from multi-environment plant breeding trials. *The Crop Journal*, *8*, 745–756. https://doi.org/10.1016/j.cj.2020.03.010

APR. (2012). Agricultural prospects report.. Ministry of Agriculture, Irrigation & Livestock, Government of Islamic Republic of Afghanistan.

Barrero, J. M., Porfirio, L., Hughes, T., Chen, J., Dillon, S., Gubler, F., & Ral, J.-P. F. (2020). Evaluation of the impact of heat on wheat dormancy, late maturity α-amylase and grain size under controlled conditions in diverse germplasm. *Scientific Reports*, *10*, 17800. https://doi.org/10.1038/s41598-020-73707-8

Beche, E., Benin, G., Da Silva, C. L., Munaro, L. B., & Marchese, J. A. (2014). Genetic gain in yield and changes associated with physiological traits in Brazilian wheat during the 20th century. *European J. of Agron.*, *61*, 49–59. https://doi.org/10.1016/j.eja.2014.08.005

Braun, H.-J., Pfeiffer, W. H., & Pollmer, W. G. (1992). Environments for selecting widely adapted spring wheat. *Crop Science*, *32*, 1420–1427. https://doi.org/10.2135/cropsci1992.0011183X003200060022x

Braun, H.-J., Rajaram, S., & van Ginkel, M. (1996). CIMMYT's approach to breeding for wide adaptation. *Euphytica*, *92*, 175–183.

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

Chabot, P., & Dorosh, P. A. (2007). Wheat markets, food aid and food security in Afghanistan. *Food Policy*, *32*, 334–53. https://doi.org/10.1016/j.foodpol.2006.07.002

Cooper, M., & Delacy, I. H. (1994). Relationships among analytical methods used to study genotypic variation and genotype-by-environment interaction in plant breeding multi environment experiments. *Theoretical and Applied Genetics*, *88*, 561–572. https://doi.org/10.1007/BF01240919

Crespo-Herrera, L. A., Crossa, J., Huerta-Espino, J., Autrique, E., Mondal, S., Velu, G., Vargas, M., Braun, H. J., & Singh, R. P. (2017). Genetic yield gains in CIMMYT's international Elite Spring Wheat Yield Trials by modelling the genotype × environment interaction. *Crop Science*, *57*, 789–801. https://doi.org/10.2135/cropsci2016.06.0553

Crespo-Herrera, L. A., Crossa, J., Huerta-Espino, J., Vargas, M., Mondal, S., Velu, G., Payne, T. S., Braun, H., & Singh, R. P. (2018). Genetic gains for grain yield in CIMMYT's Semi-Arid Wheat Yield Trials grown in suboptimal environments. *Crop Science*, *58*, 1890–1898. https://doi.org/10.2135/cropsci2018.01.0017.

Crespo-Herrera, L. A., Crossa, J., Huerta-Espino, J., Mondal, S., Velu, G., Juliana, P., Vargas, M., Pérez-Rodríguez, P., Joshi, A. K., Braun, H. J., & Singh, R. P. (2021). Target population of environments for wheat breeding in India: Definition, prediction and indirect genetic gains. *Frontiers in Plant Science*, *12*, 756. https://doi.org/10.3389/fpls.2021.638520

Dreisigacker, S., Sharma, R. K., Huttner, E., Karimov, A., Obaidi, M. Q., Singh, P. K., Sansaloni, C., Shrestha, R., Sonder, K., & Braun, H.-J. (2019). Tracking the adoption of bread wheat varieties in Afghanistan using DNA fingerprinting. *BMC Genomics*, *20*, 660. https://doi.org/10.1186/s12864-019-6015-4

FAO. (2013). Food balances. http://www.fao.org/faostat/en/#data/FBS.

Gerard, G. S., Crespo-Herrera, L. A., Crossa, J., Mondal, S., Velu, G., Juliana, P., Huerta-Espino, J., Vargas, M., Rhandawa, M. S., Bhavani, S., Braun, H., & Singh, R. P. (2020). Grain yield genetic gains and changes in physiological related traits for CIMMYT's high rainfall wheat screening nursery tested across international environments. *Field Crops Research*, *249*, 107742. https://doi.org/10.1016/j.fcr.2020.107742

Graybosch, R. A., & Peterson, C. J. (2010). Genetic improvement in winter wheat yields in the Great Plains of North America, 1959–2008. *Crop Science*, *50*, 1882–1890 https://doi.org/10.2135/cropsci2009.11.0685

Hochman, Z., Gobbett, D. L., & Horan, H. (2017). Climatic trends account for stalled wheat yields in Australia since 1990. *Global Change Biology*, *23*, 2071–2081. https://doi.org/10.1111/gcb.13604

Lillemo, M., van Ginkel, M., Trethovan, R. M., Hernandez, E., & Crossa, J. (2005). Differential adaptation of CIMMYT bread wheat to global high temperature environments. *Crop Science*, *45*, 2443–2453. https://doi.org/10.2135/cropsci2004.0663

Lopes, M. S., Reynolds, M. P., Manes, Y., Singh, R. P., Crossa, J., & Braun, H. J. (2012). Genetic yield gains and changes in associated traits of CIMMYT spring bread wheat in a "historic" set representing 30 years of breeding. *Crop Science*, *52*, 1123–1131. https://doi.org/10.2135/cropsci2011.09.0467

MAIL. (2019). *Wheat seed production plan 2019–20: Report of Wheat Seed Production Planning Meeting, October 2019*. Ministry of Agriculture, Irrigation and Livestock.

Manès, Y., Gomez, H. F., Puhl, L., Reynolds, M., Braun, H. J., & Trethowan, R. (2012). Genetic yield gains of the CIMMYT international semi-arid wheat yield trials from 1994 to 2010. *Crop Science*, *52*, 1543–1552. https://doi.org/10.2135/cropsci2011.10.0574

Mondal, S., Dutta, S., Crespo-Herrera, L., Huerta-Espino, J., Braun, H. J., & Singh, R. P. (2020). Fifty years of semi-dwarf spring wheat breeding at CIMMYT: Grain yield progress in optimum, drought and heat stress environments. *Field Crops Research*, *250*, 107757. https://doi.org/10.1016/j.fcr.2020.107757.

Obaidi, M. Q., Osmanzai, M., Singh, R. P., Pena, J., Braun, H. J., & Sharma, R. (2011). Development of four new Ug99 resistant wheat varieties for Afghanistan. *Wheat Information System*, *112*, 4–10.

Obaidi, M. Q., Habibi, A., Azmatyar, M. H., Ahmadzada, Z., Mohmand, E., Qayum, A., & Sharma, R. (2014). A new high yielding, disease resistant winter wheat variety for Afghanistan. *Wheat Information System*, *117*, 9–12.

Obaidi, M., Azmatyar, M., Mohmand, E., Habibi, A., Qayum, A., & Sharma, R. (2015). Lalmi 04: A new rainfed wheat variety for Afghanistan. *Triticeae Genomics and Genetics*, *6*, 1–3. https://doi.org/10.5376/tgg.2015.06.0001

Rajaram, S., Van Ginkel, M., & Fisher, R. A. (1993). CIMMYT's wheat breeding mega-environments (ME). In Z. S. Li & Z. Y. Xin (Eds.), *Proceedings of the 8th International Wheat Genetic Symposium* (pp. 19–24). China Agric. Sciencetech Press. P.

Robertson, M., Kirkegaard, J., Rebertzke, G., Llewellyn, R., & Wark, T. (2016). Prospects for yield improvement in the Australian wheat industry: A perspective. *Food & Energy Security*, *5*, 107–122. https://doi.org/10.1002/fes3.81

Rutkoski, J. (2018). Estimation of realized rates of genetic gain and indicators for breeding programme assessment. *bioRxiv*. https://doi.org/10.1101/409342 bioRxiv

Sayre, K. D., Rajaram, S., & Fischer, R. A. (1997). Yield potential progress in short bread wheats in northwest Mexico. *Crop Science*, *37*, 36–42. https://doi.org/10.2135/cropsci1997.0011183X003700010006x

Sharma, R. C., Crossa, J., Velu, G., Huerta-Espino, J., Vargas, M., Payne, T. S., & Singh, R. P. (2012). Genetic gains for grain yield in CIMMYT spring bread wheat across international environments. *Crop Science*, *52*, 1522–1533. https://doi.org/10.2135/cropsci2011.12.0634

Sheehan, H., & Bentley, A. (2020). Changing times: Opportunities for altering winter wheat phenology. *Plants, People, Planet*, *3*(2), 113–123. https://doi.org/10.1002/ppp3.10163

Singh, R. P., Huerta-Espino, J., Sharma, R., Joshi, A. K., & Trethowan, R. (2007). High yielding spring bread wheat germplasm for global irrigated and rainfed production systems. *Euphytica*, *157*, 351–363. https://doi.org/10.1007/s10681-006-9346-6

Soofizada, Q., Mohmand, E., Azmatyar, M. H., & Sharma, R. (2018). Two new rainfed wheat varieties for Afghanistan. *Wheat Information Service*, *125*, eWIS125.2.

Tanaka, A., Takahashi, K., Masutomi, Y., Hanasaki, N., Hijioka, Y., Shiogama, H., & Yamanaka, Y. (2015). Adaptation pathways of global wheat production: Importance of strategic adaptation to climate change. *Scientific Reports*, *5*, 14312. https://doi.org/10.1038/srep14312

Thomas, J. B., & Graf, R. J. (2014). Rates of yield gain of hard red spring wheat in western Canada. *Canadian Journal of Plant Science*, *94*, 1–13. https://doi.org/10.4141/cjps2013-160

Trethowan, R. M., Crossa, J., Ginkel, M., & Rajaram, S. (2001). Relationships among bread wheat international yield testing locations in dry areas. *Crop Science*, *41*, 1461-1469. https://doi.org/10.2135/cropsci2001.4151461x

Trethowan, R. M., Ginkel, M., Ammar, K., Crossa, J., Payne, T. S., Cukadar, B., Rajaram, S., & Hernandez, E. (2003). Association among twenty years of international bread wheat yield evaluation environments. *Crop Science*, *43*, 1698–1711. https://doi.org/10.2135/cropsci2003.1698

Wu, W., Li, C., Ma, B., Shah, F., Liu, Y., & Liao, Y. (2014). Genetic progress in wheat yield and associated traits in China since 1945 and future prospects. *Euphytica*, *196*, 155–168. https://doi.org/10.1007/s10681-013-1033-9

Yao, Y., Lv, L., Zhang, L., Yao, H., Dong, Z., Zhang, J., Ji, J., Jia, X., & Wang, H. (2019). Genetic gains in grain yield and physiological traits of winter wheat in Hebei Province of China, from 1964 to 2007. *Field Crops Research*, *239*, 114–123. https://doi.org/10.1016/j.fcr.2019.03.011

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