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RESEARCH ARTICLE

Genotype×tillage interaction and the performance of winter bread wheat genotypes in temperate and cold dryland conditions

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Abstract

Growing concerns for food security and the alleviation of hunger necessitate knowledge-based crop management technologies for sustainable crop production. In this study, 13 winter bread wheat genotypes (old, relatively old, modern, and breeding lines) were evaluated under three different tillage systems, i.e., conventional tillage (CT, full tillage with residue removed), reduced tillage (RT, chisel tillage with residue retained) and no-tillage (NT, no-tillage with residue retained on the soil surface) in farmer's fields under rainfed conditions using strip-plot arrangements in a randomized complete block design with three replications in the west of Iran (Kamyaran and Hosseinabad locations) over two cropping seasons (2018–2019 and 2019–2020). The main objectives were to investigate the effects of tillage systems and growing conditions on the agronomic characteristics, grain yield and stability performance of rainfed winter bread wheat genotypes. Significant (P<0.01) genotype×tillage system interaction effects on grain yield and agronomic traits suggested that the genotypes responded differently to the different tillage systems. The number of grains per spike and plant height were positively (P<0.0) associated with grain yield under the NT system, so they may be considered as targeted traits for future wheat breeding. Using statistical models, the modern cultivars ("Sadra" and "Baran") were identified as high yielding and showed yield stability across the different tillage systems. As per each tillage system, genotype "Sadra" followed by "Zargana-6//Dari 1-7 Sabalan" exhibited higher adaption to CT; while cultivars "Jam" and "Azar2" showed better performance under the RT system; and cultivars "Varan" and "Baran" tended to have better performance expression in the NT condition. The increased grain yields achieved in combination with lower costs and

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greater profits from conservation agriculture suggest that adapted cultivar and NT systems should be evaluated and promoted more widely to farmers in the west of Iran as an attractive package of crop management technologies. In conclusion, variations in the performance of genotypes and the significant genotype×tillage system interaction effects on grain yield and some agronomic traits assessed in this study suggest that the development and selection of cultivars adapted to the NT system should be considered and included in the strategies and objectives of winter wheat breeding programs for the temperate and cold dryland conditions of Iran.

Keywords: bread wheat, no-tillage, reduced tillage, grain yield, yield stability

1. Introduction

A conventional tillage (CT) system (moldboard, disk and rototiller) is one of the main pillars of conventional agriculture in dryland conditions of semi-arid regions. However, these operations expose the soil to erosion, reduce organic matter and soil fertility and increase unsustainability in crop production systems. Alternative crop management technologies are required to address this issue. Conservation agriculture (CA) is gradually becoming attractive to farmers because it decreases production costs in comparison with CT (De Vita *et al.* 2007; Jat *et al.* 2020). This technology has been widely adopted worldwide as a practical and efficient approach for reducing the adverse effects of environmental pollution, greenhouse gas emissions, and soil erosion (Cavalieri *et al.* 2009; Gathala *et al.* 2020). A no-tillage (NT) system usually reduces crop yields at its initial stage; however, its beneficial impacts on the soil environment may result in equal or greater yields than the CT method in subsequent years (Herrera *et al.* 2013; Pittelkow *et al.* 2015; Page *et al.* 2020). CA is not a common practice in most of the dryland regions of West Asia, but because of some of its advantages and as a more environmentally–friendly approach, it has recently been promoted by the governments and gradually adopted by farmers. Despite the many positive effects of CA, certain constraints arise from zero tillage or NT with residue cover (Honsdorf *et al.* 2019), hence genotypes developed under CT may not necessarily adapt to the CA conditions. Therefore, newly adapted genotypes under CA system conditions should be developed and released (Trethowan *et al.* 2012).

In many studies, the role of CA in increasing crop yields under drought conditions has been emphasized, and it has been considered as one of the strategies for adaptation to climate change in dry conditions (Wang *et al.* 2007; Pittelkow *et al.* 2015; Ruiz *et al.* 2019). Thus, the selected genotypes must meet the productivity criteria and physiological characteristics of high yield and yield stability and resilience to reduce the unpredictable variations of a changing climate (Carranza-Gallego *et al.* 2018). However, CA may induce changes in crop growth by altering the soil moisture content. The yield increase reported in CA under dry climatic conditions is often associated with soil moisture storage (Hemmat and Eskandari 2004, 2006; Araya *et al.* 2012; Soane *et al.* 2012; Steward *et al.* 2018; Page *et al.* 2019). Early planting is also more appropriate in CA systems, due to the reduced time needed for land preparation, which may result in more efficient use of rainfall as well as a reduction in the risk of crop failure due to terminal heat stress (Devkota *et al.* 2019). Improving soil quality and properties as well as reducing pest and disease damage by the inclusion of legumes in the crop rotation are among the other potential reasons which have been reported for increasing yields in CA systems (Nyagumbo *et al.* 2016). Besides these advantages, CA also has adverse effects on crop growth in some cases. For instance, in areas with heavy rainfall and poor drainage due to increased water infiltration and less evaporation in the CA systems, reduced yields may be observed (Nyagumbo *et al.* 2016; Steward *et al.* 2018). Yield reduction also may occur in low-temperature and high-altitude areas due to delays in crop maturity in CA (Wang *et al.* 2007; Soane *et al.* 2012; Zhang *et al.* 2014).

Breeding programs are generally based on the CT system, and most of them develop new cultivars for the CT conditions, thus the yields of different cultivars are generally unknown under the CA system (Taner *et al.* 2015; Ruiz *et al.* 2019). Numerous studies have shown that many germplasms that performed well under CT responded well to NT systems (Hwu and Allan 1992; Maich and Di Rienzo 2014; Honsdorf *et al.* 2018). However, improvements in grain yield may be attainable if genotypes adapted to the CA soil environment are developed (Herrera *et al.* 2013). Therefore, one approach for reducing the negative impact of NT on crops is to develop crop varieties under CA-based production systems (Honsdorf *et al.* 2019). However, this is only possible if significant genotype×tillage interaction effects exist (Hwu and Allan 1992; Joshi *et al.* 2007;

Carena *et al.* 2009; Honsdorf *et al.* 2018), in contrast to the other studies which reported no genotype×tillage interactions (Carr *et al.* 2003a, b; Kumudini *et al.* 2008). Therefore, further studies are necessary to evaluate the combined effects of different conservation tillage systems and genotypes. Such studies would help to identify the agronomic traits associated with superior yield to enhance the genetic improvement of varieties adapted to alternative farming systems (Herrara *et al.* 2013). It is fundamental that the traits conferring adaptation to NT are identified in the breeding programs for this system. Some observations imply that NT can negatively affect the early germination of crops due to more compacted soil, suboptimum soil contact, and lower soil temperature. For example, Herrera *et al.* (2013) has listed many traits for wheat that are associated with crop establishment as the selection criteria for NT adapted genotypes. For instance, kernel weight and embryo size (Ciha 1982; Liang and Richards 2012), coleoptile length and thickness (Rebetzke *et al.* 2004, 2007), vigorous seedlings (Trethowan *et al.* 2005; Kharub *et al.* 2008), and young seedling temperature tolerance are the traits that are potentially useful for improving crop establishment under NT. However, tiller capacity (Kumudini *et al.* 2008), cold-tolerance of seedlings (Cox 1991; Cox and Shelton 1992), higher winter survival (Cox 1991), optimized flowering time (Thompson *et al.* 1987), maturity time (Kumudini *et al.* 2008), and root attributes are other agronomic traits that have the potential to increase the adaptation of genotypes to NT or zero tillage systems (Herrera *et al.* 2013).

The identification of suitable genotypes based on grain yield and other agronomic attributes is one of the key objectives of crop breeding programs. Determining the relationships between crop traits and grain yield as an economic trait can play an effective role in the selection of superior adapted genotypes. The purpose of multi-environment trials (METs) is to evaluate the yield, its stability and adaptability among advanced breeding lines for the development and release of new cultivars. Advanced statistical methods are required to assess the genotype×environment (GE) interaction effects for complex traits and to interpret the METs data. Recently, various biplot-based methods, including biplot of genotype and GE interaction (GGE biplot), have received more attention due to their advantages in analyzing and interpreting the results and overcoming some of the limitations of univariate statistical models. The GGE biplot method provides more detailed sources of variation of the genotype and the GE interaction compared with other methods, as it provides easy and comprehensive solutions for the analysis of the GE interaction data (Yan *et al.* 2007; Rana *et al.* 2020). This method also graphically provides relationships between environments, genotypes, and GE interactions based on the principal component analysis (PCA) for the full exploitation of the MET data. It also provides high efficiency in revealing "which–won–where" patterns to determine mega-environments and crossover GE interactions (Yan *et al.* 2007). Generally, wide adaptation and yield stability of newly released varieties are evaluated under CT in breeding programs, while the crop growth environment would also change by altering soil management, i.e., NT and minimum tillage, hence, the yield stability of the newly released varieties would also be affected by the different tillage practices. Very few reports have evaluated the yield stability of winter bread wheat genotypes under different conservation tillage systems. Ruiz *et al.* (2019) evaluated the specific adaptations of different types of wheat genotypes in which the yield stability of a limited number of winter and spring wheat varieties were studied in both minimum and NT systems under three environments. They concluded that there were differences between these two tillage systems in terms of both adapted varieties and yield stability.

Most studies on the G×T effect have only focused on one climatic condition, one site, a limited number of genotypes and one soil type in research stations (e.g., Herrara *et al.* 2013). However, to understand interaction effects, a wide range of environments, soils, and genotypes must be considered. Little is known about the yield stability of high-yielding winter wheat genotypes under CA in the different climatic conditions of high elevation areas in semi-arid regions. Therefore, it is necessary to understand the performance of different genotypes in different CA systems. In addition, to accelerate the development and promotion of CA systems, on-farm yield trials and the participation of farmers in the selection stream could be set up as a new strategy for evaluating genotypes under CA systems. Because crop residue in high altitude areas, as well as in heavy-textured soils, might act as a physical constraint on crop germination and establishment and provide the basis for cold damage in the early stages of crop growth, a knowledge-based understanding of the responses of winter bread wheat genotypes under the CA system will lead to better adoption of this new technology by farmers in such conditions. To bridge these research gaps, a range of winter bread wheat genotypes, including old, relatively old, modern, and breeding lines, were evaluated under CT, reduced tillage (RT) and NT systems in farmer's field conditions in two high elevation areas (≥1 500 and 1 900 m a.s.l., as temperate and cold, respectively). As the main novelty of this study, not only the genotypes productivity were determined, but also the yield stability and specific adaptation to tillage systems were assessed. With the above considerations, this study aimed to: (i) investigate the interactions between genotypes, cropping seasons, tillage systems, and geographical locations for grain yield and several agronomic traits, and (ii) evaluate rainfed winter bread wheat genotypes in terms of both higher yield and yield stability in each tillage system. The outcomes of this study can provide insights for the promotion and adoption of this package of crop management technologies to further enhance food security and sustainability.

2. Materials and methods

2.1. Plant materials and experimental layout

Thirteen winter bread wheat genotypes, including old, relatively old, modern, and some promising breeding lines (Table 1), were evaluated under three tillage systems, i.e., conventional tillage (CT, full tillage with residue removed), reduced tillage (RT, chisel with residue retained) and no-tillage (NT, no tillage with residue retained on the soil surface) in farmer's fields in two locations in Kurdistan, Iran, Kamyaran (34°49´N; 46°57´E; 1 531 m a.s.l.) as temperate and Hosseinabad (35°10´N; 47°30´E; 1 952 m a.s.l.) as cold, during two cropping seasons (2018–2019 and 2019–2020).

The experiments were performed as strip-plot arrangements in a randomized complete block (RCB) design with three replications with two horizontal (tillage systems) and vertical (genotypes) factors. Each plot consisted of 13-rows with 17 cm inter-row spacing and 20 m length (plot size=44.2 m^2). The RT treatment was implemented by a Chisel at 10–15 cm depth immediately after the harvesting of the previous crop (chickpea in Kamyaran and vetch in Hossainabad), while NT consisted of direct seeding. At both locations, residues were not removed in either of the two systems. CT was implemented by moldboard at 20–25 cm depth followed by two passes of the tandem disk at 10 cm depth. Changing from CT to NT had begun from the two past cropping seasons (2015–2016) in these locations. Wheat–chickpea and wheat–vetch were the two crop rotations in Kamyaran and Hossainabad, respectively. A tine-type direct drill (Askeh-2200 made by Sazeh Kesht Bookan Co., Iran) was used for sowing in the three tillage systems. The winter bread wheat genotypes were seeded in autumn and harvested in early July in Kamyaran and at the end of July in Hossainabad. More information on the field environments is summarized in Table 2. Weeds were managed and controlled using herbicides 2,4-D and clodinafop-propargyl at the tillering stage and hand weeding as required. Fertilizers were utilized at the rates of 60 kg N ha^{-1} (N_{40} at planting and N_{20} as top dressing) and 50 kg P_2O_5 ha^{-1} at the time of planting. Soil samples were taken for analyzing and determining the soil organic carbon content in each plot in each season before planting.

During the growing season, the grain yield and several agronomic traits for each genotype in each plot were recorded. Plant height, number of grains per spike (grains/spike), number of spikes per square meter (spikes m^{-2}), and 1 000-kernel weight (TKW) were recorded for each genotype. Grain yield was measured as kg per plot, and then converted to yield per hectare (kg ha^{-1}).

2.2. Statistical analysis

The MSTAT-C Software was used to perform analysis of variance for grain yield and the other investigated traits. The least significant difference (LSD) test at the

Table 1 The genotypes tested in the study

Code	Name/Cross	Type	Origin[1)]	Growth habit	Earliness
G1	MV 17/Kavir	Promising breeding line	DARI-Iran	Winter	Early
G2	Jam	Modern	DARI-Iran	Winter	Early
G3	Sadra	Modern	DARI-Iran	Winter	Early
G4	Varan	Modern	DARI-Iran	Winter	Early
G5	Baran	Modern	DARI-Iran	Winter	Early
G6	Azar2	Relatively old	DARI-Iran	Winter	Early
G7	Ohadi	Relatively old	DARI-Iran	Winter	Early
G8	Rad	Modern	DARI-Iran	Winter	Early
G9	14075 (Azaran)	Modern	Private Co.-Iran	Winter	Early
G10	Zargana-6//Dari 1-7 Sabalan	Promising breeding line	DARI-Iran	Winter	Early
G11	SPII Gene bank Collection/2010/110	Promising breeding line	DARI-Iran	Winter	Early
G12	YE 2453//PPBB68/C HRC/3/SITTA	Promising breeding line	DARI-Iran	Winter	Early
G13	Sardari	Landrace	SPII-Iran	Winter	Early

[1)] DARI, Dryland Agricultural Research Institute; SPII, Seed and Plant Improvement Institute.

Table 2 Description of the test environments in the study

Environment				Previous crop	Practice management	Sowing date	Soil properties[2)]					Rainfall (mm)	Temperature (°C)		
Cropping season	Location	Tillage system[1)]	Code				OC (%)	K (ppm)	P (ppm)	N (%)	Soil texture		Avg.	Min.	Max.
2018–2019	Kamyaran	CA	Y1KCA	Chickpea	No-till	27 Oct., 2018	0.79	363.7	7.50	0.11	Clay–loam				
		RT	Y1KRT	Chickpea	Stubble Cultivator		0.78	373.3	8.30	0.10	Clay–loam	869.3	12.32	5.32	19.27
		CT	Y1KCT	Chickpea	Plowed with moldboard and disked		0.82	363.4	8.46	0.13	Clay–loam				
	Hosseinabad	CA	Y1HCA	Chickpea	No-till	12 Oct., 2018	0.29	210.1	1.84	0.09	Clay	466.5	7.80	2.38	12.51
		RT	Y1HRT	Chickpea	Stubble Cultivator		0.48	239.1	1.52	0.09	Clay				
		CT	Y1HCT	Chickpea	Plowed with moldboard and disked		0.35	200.8	1.28	0.10	Clay				
2019–2020	Kamyaran	CA	Y2KCA	Chickpea	No-till	24 Oct., 2019	0.81	421.1	6.12	0.11	Clay–loam				
		RT	Y2KRT	Chickpea	Stubble Cultivator		0.78	370.1	7.30	0.11	Clay–loam	467.5	12.68	5.19	20.15
		CT	Y2KCT	Chickpea	Plowed with moldboard and disked		0.82	351.4	8.01	0.13	Clay–loam				
	Hosseinabad	CA	Y2HCA	Chickpea	No-till	10 Oct., 2019	0.33	305.1	2.800	0.10	Clay				
		RT	Y2HRT	Chickpea	Stubble Cultivator		0.50	267.7	3.04	0.10	Clay	396.3	7.10	–0.03	13.70
		CT	Y2HCT	Chickpea	Plowed with moldboard and disked		0.35	277.8	2.24	0.10	Clay				

[1)] CA, conservation agriculture; RT, reduced tillage; CT, conventional tillage.
[2)] OC, organic carbon ; K, potasium; P, phosphate ; N, nitrogen.

5% probability level was used for mean comparisons. A biplot based on PCA and a heat map based on genetic and phenotypic correlations were used to investigate relationships among the studied traits. The genotype main effect and genotype-by-environment interaction (GGE) biplot methodology (Yan 2001) was also applied to assess the yield stability of the genotypes and the GE interaction across environments. Some graphical issues of GGE biplot, including (i) mega-environment investigation, (ii) mean *vs*. stability performance, and (iii) discriminative *vs*. representativeness ability of the test environments, were also applied. We used the R Software packages of MET-R (Alvarado *et al.* 2016).

3. Results

3.1. Climatic conditions

The amount and monthly distribution of precipitation varied from location to location and year to year, which created different growth conditions that resulted in different grain yield potentialities (Fig. 1). The annual precipitation levels at Kamyaran site in 2018–2019 and 2019–2020 were 869.3 and 467 mm, respectively, whereas in Hosseinabad they were 467.5 and 396.3 mm, respectively, suggesting differences between the two environments. For a wheat

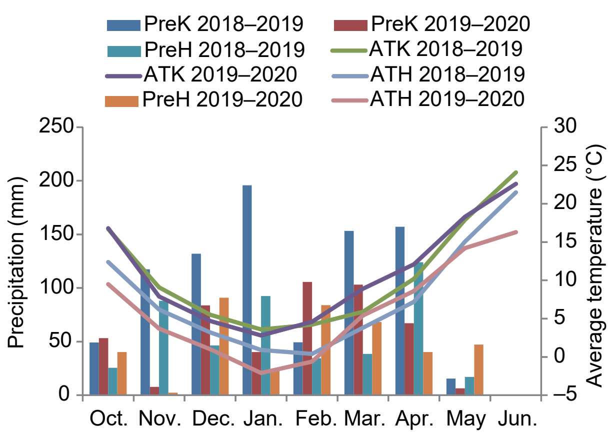


Fig. 1 Monthly rainfall distribution and average temperature during the experiments. PreK, precipitation at Kamyaran; PreH, precipitation at Hosseinabad; ATK, average temperature at Kamyaran; ATH, average temperature at Hosseinabad.

crop with reasonable grain yield, 450 mm is adequate, but most of the precipitation was received in winter so it was not effectively used by the crops. Even though precipitation levels during the growing seasons were equal to or more than the long-term annual average, the crops experienced some degrees of terminal drought due to the rainfall deficiency that coincided with high temperatures during the grain-filling period (Fig. 1). In 2018–2019 and 2019–2020, the average temperatures in Kamyaran were 10.8 and 10.9°C, respectively, and in Hosseinabad they were 7.8 and 6.2°C, showing that the crops in Hosseinabad experienced severe cold conditions during the two seasons.

3.2. ANOVA and mean performance of the treatments

Grain yield was significantly affected by the tillage system, location, and all interaction effects. All other measured traits were also affected by both the main effects and their interactions (Table 3). The genotypes significantly differed for all measured traits; furthermore, genotype interactions with all other sources of variation (tillage, location, year, and all treatment combinations) for all the traits were significant. For grain yield, the contributions of the year×location, location and genotype effects to the total variation were high and accounted for 51.5, 17.9 and 4.28% of the total variation, respectively. The variation explained by treatments varied depending on the traits. For TKW, the effects of year (21.6%), genotype (20.8%), and genotype×tillage (8.01%) contributed the most to the total variation. For spikes m^{-2}, the effects of location (40.6%), year (21.6%) and genotype (8.4%) were the most important sources of variation. In the case of grains/spike, the effects of year×location (51.4%), year (15.4%) and location (3.7%) were the main contributors to the total variation. The greatest variation in plant height was explained by year×location (44.6%), followed by genotype (17.3%) and location (14.4%).

3.3. Tillage system×environment interactions for traits

Significant tillage system×environment interactions for each investigated trait are shown in Fig. 2. The highest productivity was obtained in Kamyaran in 2018–2019, as it received remarkable precipitation (869.3 mm; Table 2; Fig. 1). Under this condition, significant (P<0.05) differences were observed between tillage systems, where the genotypes produced the highest grain yield under CT (3 709 kg ha^{-1}), followed sequentially by NT (3 680 kg ha^{-1}) and RT (3 334 kg ha^{-1}) (Fig. 2-A). In this cropping season, the crops in Hosseinabad received 466.5 mm of precipitation, which was above long-term average precipitation (350 mm) in this location. A significant (P<0.05) difference between tillage systems

Table 3 Combined ANOVA for the 13 wheat genotypes grown under three different tillage systems, at two locations and in two cropping seasons (2018–2019 and 2019–2020) for the investigated traits[1)]

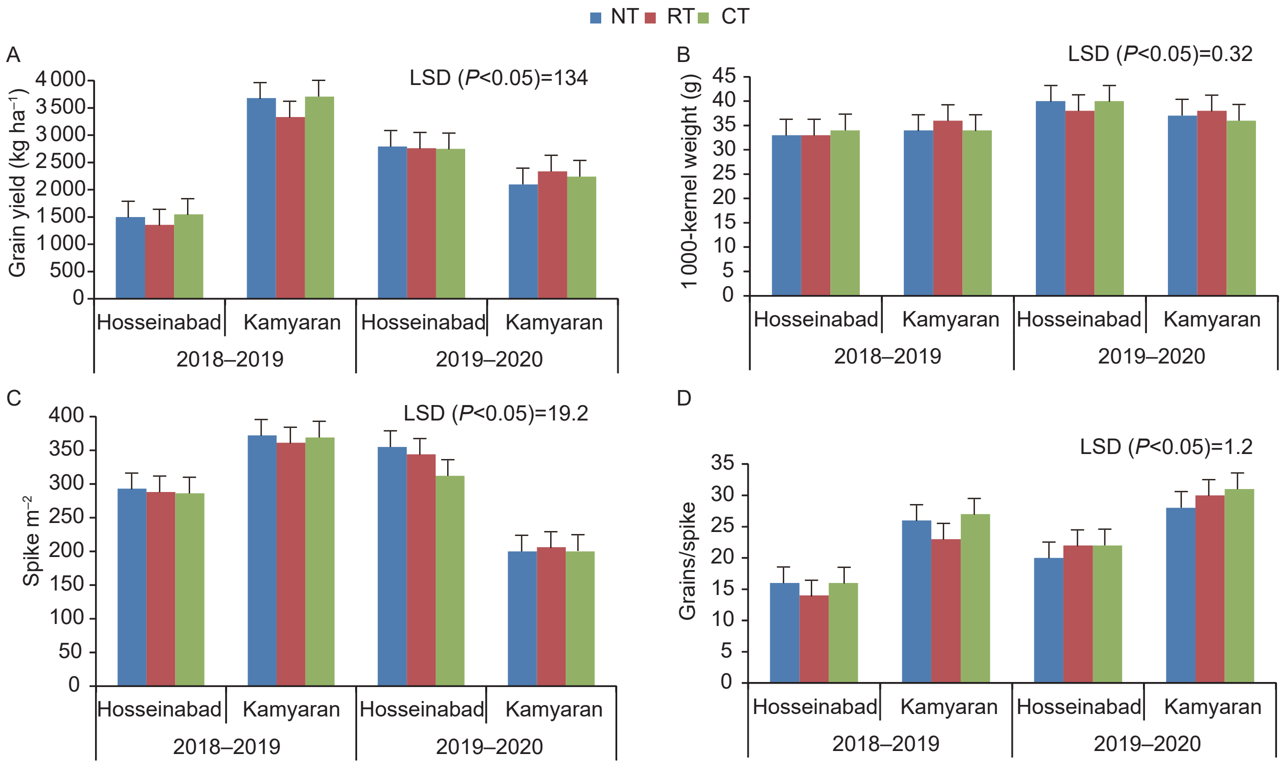
Source	*df*	Grain yield		1 000-kernel weight		Spikes m^{-2}		Grains/spike		Plant height	
		MS	%TSS	MS	%TSS	MS	%TSS	MS	%TSS	MS	%TSS
Year (Y)	1	71015 ns	0.02	1952.9**	21.64	3082.053**	12.90	398475**	15.37	1176.4**	1.21
Location (L)	1	71361532**	17.89	17.3**	0.19	9703.335**	40.60	96607**	3.73	13981.5**	14.43
Y×L	1	205512813**	51.53	448.2**	4.97	59.592**	0.25	1333121**	51.41	43192.3**	44.59
R (LY)	8	584615**	1.17	33.9**	3.01	43.750**	1.46	5088**	1.57	290.6**	2.40
Tillage (T)	2	521366**	0.26	3.9**	0.09	146.583**	1.23	6886**	0.53	94.0**	0.19
T×Y	2	1564945**	0.78	36.6**	0.81	137.566**	1.15	5282*	0.41	310.9**	0.64
T×L	2	62462 ns	0.03	105.6**	2.34	12.989 ns	0.11	5750**	0.44	168.3**	0.35
T×L×Y	2	548247**	0.27	18.0**	0.40	4.297 ns	0.04	3575 ns	0.28	14.6**	0.03
Error	16	51912	0.21	0.3	0.05	3.994	0.27	1067	0.66	14.8	0.24
Genotype (G)	12	1423853**	4.28	156.8**	20.85	167.016**	8.39	3321**	1.54	1398.8**	17.33
G×Y	12	669166**	2.01	49.4**	6.57	27.257*	1.37	4612**	2.13	63.8**	0.79
G×L	12	329082**	0.99	58.1**	7.72	38.623**	1.94	5589**	2.59	282.4**	3.50
G×L×Y	12	954822**	2.87	28.6**	3.81	28.342*	1.42	7874**	3.64	77.0**	0.95
G×T	24	577386**	3.47	30.1**	8.01	30.921**	3.11	2982**	2.76	78.9**	1.95
G×T×Y	24	310226**	1.87	21.6**	5.74	31.256**	3.14	2572**	2.38	92.2**	2.28
G×T×L	24	310826**	1.87	22.4**	5.95	31.290**	3.14	1925**	1.78	95.8**	2.37
G×T×L×Y	24	370484**	2.23	16.8**	4.48	26.644**	2.68	1845**	1.71	57.9**	1.43
Error	288	113791		1.1	3.38	13.954		638	7.08	17.8	
Total	467										
CV (%)		13.5		2.8		8.45		16.3		5.3	

[1)] *df*, degrees of freedom; MS, mean squares; %TSS, percent relative to total sum of squares; CV, coefficient of variation.
* and **, significant at 5 and 1% probability levels, respectively; ns, no significant.

in this location was also observed, where the genotypes performed better under CT (1 550 kg ha^{-1}) and NT (1 498 kg ha^{-1}) than RT (1 335 kg ha^{-1}) conditions. In 2019–2020, the genotypes performed better in Hosseinabad as compared to Kamyaran (2 768 *vs.* 2 224 kg ha^{-1}). No significant differences were observed between tillage systems in Hosseinabad, while the genotypes at Kamyaran performed better under RT (2 338 kg ha^{-1}) than CT (2 239 kg ha^{-1}) or NT (2 096 kg ha^{-1}) conditions.

The highest TKW was obtained in Hosseinabad in 2019–2020 (Fig. 2-B), as it received about 60 mm rainfall in May, which coincided with the commencement of the flowering stage. Significant differences were observed among the tillage systems in each environment. TKW for the tested genotypes was 40 g under CT and NT, and 38 g under RT in Hosseinabad during 2019–2020. In Kamyaran, the highest TKW was observed under RT conditions in both seasons.

Significant ($P<0.05$) differences were observed between tillage systems, locations, and cropping seasons for spikes m^{-2} (Fig. 2-C). The highest spikes m^{-2} was observed in Kamyaran (367 spikes m^{-2}) in 2018–2019, followed by Hosseinabad (337 spikes m^{-2}) in 2019–2020, Hosseinabad (289 spikes m^{-2}) in 2018–2019 and the least was in Kamyaran (202 spikes m^{-2}) in 2019–2020 as the crop suffered from low rainfall in May 2020. The highest number of grains per spike was observed in Kamyaran in 2019–2020 (Fig. 2-D) but it had the lowest spikes m^{-2} (Fig. 2-C), suggesting a negative correlation between the spikes m^{-2} and grains/spike for the tested genotypes in this study. The highest mean grains/spike across tillage systems was observed at Kamyaran (30 grains/spike) in 2019–2020, followed sequentially by Kamyaran (25 grains/spike) in 2018–2019, Hosseinabad (21 grains/spike) in 2019–2020,



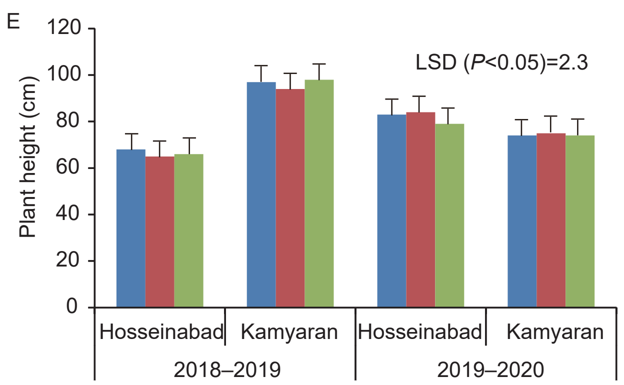


Fig. 2 Performance of rainfed winter bread wheat genotypesunder different tillage systems and location–year combinations for the investigated traits of grain yield (A), 1 000-kernel weight (B), spikes m^{-2} (C), grains/spike (D) and plant height (E) of 13 rainfed winter bread wheat genotypes under rainfed conditions. NT, RT and CT stand for no-tillage, reduced tillage and conventional tillage, respectively. Bars mean SE (n=39).

and Hosseinabad (15 grain/spike) in 2018–2019. The highest grains/spike across locations and seasons was obtained under CT (24 grains/spike) compared to 22 grains/spike in the other two tillage systems.

Significant differences were observed for plant height in the different tillage systems, locations, and cropping seasons (Fig. 2-E). The greatest plant height was recorded at Kamyaran (96 cm) in 2018–2019, followed sequentially by Hosseinabad (82 cm) in 2019–2020, Kamyaran (74 cm) in 2019–2020, and Hosseinabad (66 cm) in the 2018–2019 cropping cycle. The average plant heights across locations and years under NT and RT were 80 cm, and it was 79 cm under CT.

3.4. Genotype×tillage system interaction

A highly significant genotype×tillage system interaction effect on grain yield was observed (Fig. 3; Table 3). Among the examined genotypes, only genotypes G1 and G5 did not significantly interact with the tillage systems. However, the other genotypes differed significantly in their responses to the tillage systems. The highest grain yield (3 138 kg ha^{-1}) was obtained for G3 (Sadra), a new cultivar under CT, and the lowest (1 819 kg ha^{-1}) was for G13 (Sardari), a landrace under the RT condition. The breeding lines G2, G6, G8, and G9 performed best under the RT condition, while G3 (new cultivar), G7 (new cultivar), G10 (breeding line), G11 (breeding line), and G13 (landrace) showed good yields under CT conditions. However, G4 (new cultivar), G5 (new cultivar), and G12 (breeding line) had the highest yields under NT conditions.

The results of hierarchical cluster analysis (Fig. 4) for the 13 wheat genotypes and the heat map developed based on grain yields in different tillage systems (Fig. 5) allowed the identification of six distinct genotypic groups that can be further explored as potential genetic materials for rainfed winter wheat breeding programs under different tillage systems. The wheat genotypes expressed different levels of adaptability to the tillage systems. The first genotypic group consisted of G2, G6 and G5, which best performed under the RT system. The second group (G7, G10, G11, and G12) was comprised of genotypes with high adaptation to the CT system. The third genotypic group (G1, G8 and G9) had low to average grain yields across the three tillage systems. The genotypes G3, G4 and G13 tended to separate into individual groups, while G3 exhibited the best performance under CT followed by the NT system, and G4 was the best under the NT system condition. However, G13 showed low performance across all three tillage systems. In general, G3 followed by G10 was better adapted to CT; while G2 and G6 performed well under RT; and G4 and G5 showed higher productivity under NT.

3.5. Relationships among the studied traits

Although there was no significant (P<0.05) difference between tillage treatments in terms of agronomic traits (Table 4), significant genotype×tillage interaction effects were found on plant height, spikes m^{-2}, grains/spike and TKW (Table 3). However, for a better understanding of the relationships among the studied traits, we constructed

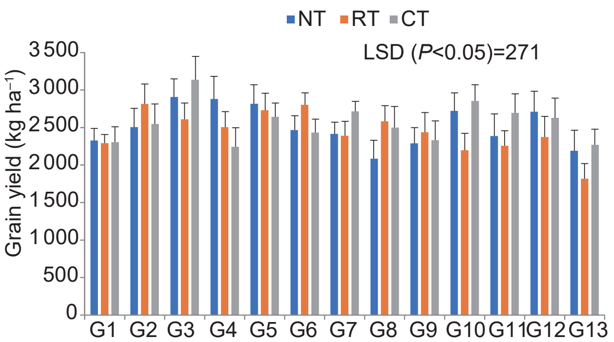


Fig. 3 Genotype×tillage system interaction for grain yield performance (mean) across two locations and over two cropping seasons. NT, RT and CT stand for no-tillage, reduced tillage and conventional tillage, respectively. G1–G13, genotype codes.

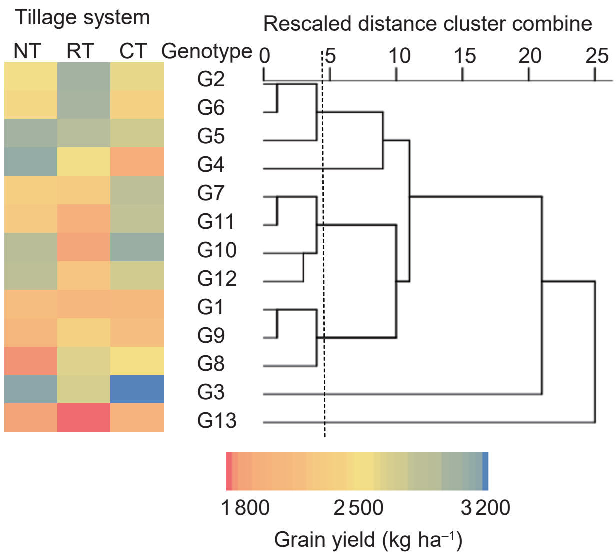


Fig. 4 Heat map developed based on the hierarchical cluster analysis (unweighted pair group method with arithmetic mean (UPGMA) method) of 13 rainfed winter bread wheat genotypes for grain yield using three tillage systems across two locations and over two cropping seasons. The dashed line represents the cut-off line for clusters according to discriminate analysis. NT, RT and CT stand for no-tillage, reduced tillage and conventional tillage, respectively.

a PCA-based biplot analysis using multi-trait data for the 13 wheat genotypes across 12 environments (Fig. 4). The constructed biplot explained 96.82% of the total variation (Fig. 5-A). Grain yield showed either positive or no correlation with the studied traits, as the angles between their vectors were not more than 90°. However, it made an angle of about 90° with TKW, showing that it was not correlated with TKW, but it showed positive correlations with grains/spike, spikes m^{-2}, and plant height. Grains/spike was negatively correlated with TKW due to the obtuse angles between their vectors. In contrast, TKW showed a positive correlation with PLH and spikes m^{-2}. These results also could be verified through the heat map shown in Fig. 3-B, which indicates the phenotypic and genetic correlations between the traits. Significant positive genotypic and phenotypic correlations were observed between grains/spike and grain yield (Fig. 5-B), indicating that selection based on grains/spike may lead to an increase in grain yield under rainfed conditions. The significant negative correlation between grains/spike and spikes m^{-2} suggested a negative correlation between these two-grain yield components once again. Plant height also showed a positive correlation with spikes m^{-2}, which could also be verified by the biplot results (Fig. 5-A).

For a better understanding of the relationships between traits and yield, Pearson correlation analysis was performed for each tillage system. Under the NT system, the plant height (r=0.70**; P<0.01) and number of grains per spike (r=0.66**; P<0.01) were significantly correlated with grain yield (data not shown), showing that selection for these traits as indirect selection criteria would significantly enhance grain yield under the NT condition. Under the RT condition, the number of grains per spike (r=0.81**; P<0.01) was significantly associated with grain yield. Under the CT system, the traits did not show significant correlations with grain yield; however, the highest correlation coefficient (r=0.42) was observed between number of spikes m^{-2} and grain yield.

3.6. Evaluation of genotype×environment interaction based on GGE biplot

According to the "which–won–where" pattern of the GGE biplot for grain yield, the environments were grouped into five sections, and genotypes fell into six sectors (Fig. 6-A). The genotypes G3 and G5 were the best performers in environments Y2KRT, Y2KNT, Y2HRT, and Y1KCT. They were placed in the vertices of the sections in which these environments are located. Genotype G4 was the best yielder in environments Y2HCT, Y2HNT and Y1KNT. G6 was placed on the vertex that was the winner in environment Y2KCT, while genotypes G1 and G7 were

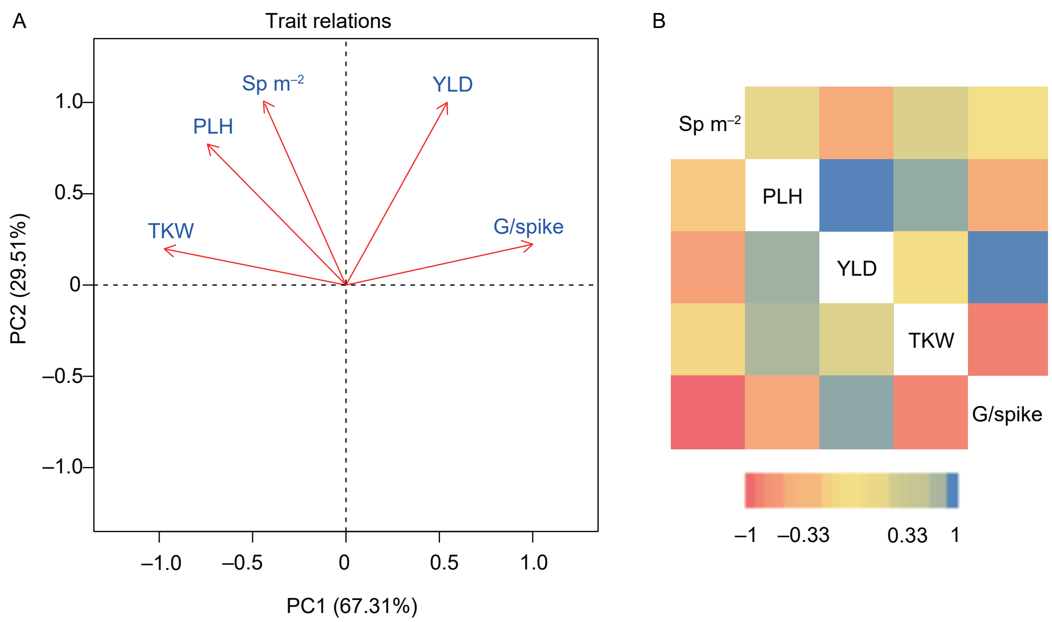


Fig. 5 Traits relationship across environments (combination of tillage systems-year and locations). A, principal component analysis (PCA)-based biplot showing the relationships among the studied traits for 13 rainfed winter bread wheat genotypes across 12 environments. B, phenotypic (below diagonal) and genetic (above diagonal) correlations between grain yield and agronomic traits for 13 examined rainfed winter bread wheat genotypes across three tillage systems in two locations and two cropping seasons under rainfed conditions. YLD, grain yield; TKW, thousand kernel weight; PLH, plant height; Sp m^{-2}, spikes m^{-2}; G/spike, grains per spike.

Table 4 Mean grain yield and agronomic traits for winter bread wheat genotypes under different tillage systems[1)]

Trait	Tillage[2)]	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	Mean	LSD 5%
Grain yield (kg ha^{-1})	CT	2305	2548	3138	2245	2643	2434	2716	2500	2331	2855	2695	2629	2270	2562	271.10
	NT	2328	2507	2909	2881	2817	2467	2416	2084	2291	2722	2388	2712	2192	2516	
	RT	2292	2815	2610	2507	2731	2803	2391	2583	2437	2198	2256	2373	1819	2447	
Spikes m^{-2}	CT	303	271	310	256	283	298	296	310	258	302	297	301	309	292	20.29
	NT	320	294	301	308	311	291	306	292	289	329	294	331	299	305	
	RT	305	325	281	291	302	308	300	311	289	286	280	296	323	298	
Grains/spike	CT	21	24	26	24	25	23	24	23	30	25	24	25	18	24	3.01
	NT	18	22	25	25	25	22	22	23	24	23	21	23	21	23	
	RT	22	22	24	26	25	24	21	24	25	29	21	22	16	23	
1 000-kernel weight (g)	CT	37	38	38	35	38	36	38	33	29	39	37	34	39	36	
	NT	39	38	38	35	36	37	38	30	32	39	36	36	34	36	0.82
	RT	35	38	38	34	36	38	38	34	33	37	39	37	35	36	
Plant height (cm)	CT	75	81	82	85	86	82	82	81	60	80	80	77	77	79	
	NT	79	80	88	88	85	86	77	80	68	80	80	82	74	81	3.39
	RT	77	82	84	89	86	89	81	79	60	73	78	79	76	79	

1) G1–G13, genotype codes.
2) CT, conventional tillage; NT, no tillage; RT, reduced tillage.

the winners in environment Y1KRT. For the environments Y1HCT, Y1HNT, and Y1HRT, which grouped in the same section, no winner genotype was identified.

The top-yielding genotypes of G3, G5, G6, G2, and G4, were located on the right-hand side of the biplot (Fig. 6-B). Among these genotypes, G3, G5, G2, and G6 also had high yield stability as they are positioned very near to the average tester coordinate (ATC) abscissa with near-zero PC2 scores. G13 (landrace) had the lowest yield as it was positioned on the left-hand side of the biplot. These results show some genetic gains in grain yield and its stability by developing new cultivars and breeding lines, particularly G3 and G5, compared to the old cultivar (G13).

An ideal environment should be the most "representative" (ability to represent the mega-environment) and "discriminating" (ability to discriminate the tested genotypes). Environments Y2KRT and Y2KNT (both belonging to Kamyaran) were the most representative, as they had a narrow-angle with the ATC and discriminated environments due to their greater vector lengths (Fig. 5-C). Genotypes G3 and G5 showed higher adaptation to these ideal environments. However, Y1HCT, Y1HRT, Y1HNT, and Y1KNT (all belonging to Hosseinabad) were the most discriminating but showed weak representativeness.

3.7. Mean grain yield and stability performance of the genotypes in each tillage system

The mean yields and stability performance of the 13 wheat genotypes in each of the tillage systems were assessed, and the results are shown in Fig. 7. Under the NT system (Fig. 7-A), genotype G3 followed by G4, G5, G10, and G12 produced mean grain yields above the grand mean. G3 was the best genotype in terms of the highest mean grain yield and stability performance. Genotypes G5 and G12 also showed high mean grain yield and yield stability performance under the NT system across environments. G4 and G10 had high mean grain yields but showed specific adaption to the different environments. Under the RT system (Fig. 7-B), genotypes G6, G5, G2, G3, and G8 expressed mean grain yields higher than the grand mean. Among these genotypes, G6 had the best combination of mean grain yield and yield stability under the RT systems across environments. In the case of CT (Fig. 7-C), genotypes G3 followed by G10 were among the genotypes with the highest stability and mean grain yields. However, genotype G3 showed the highest mean grain yield and yield stability under both NT and CT systems, while genotype G6 was identified as the genotype with high mean grain yield and yield stability under RT.

4. Discussion

4.1. Genotype×tillage system interaction effects on grain yield and yield stability

CA has been considered as a reliable solution to prevent soil erosion and increase both soil fertility and adaptation to climate changes, and it is vital for attaining sustainable production in the drylands of arid and semi-arid regional cropping systems. However, depending on the type of soil, crops and climatic conditions, this crop management technology must be adapted and site specific for adoption by farmers.

Typically, the genotypes developed in breeding programs for a CT system may not have the same grain yield and yield stability in the NT system where some constraints may limit proper crop emergence and

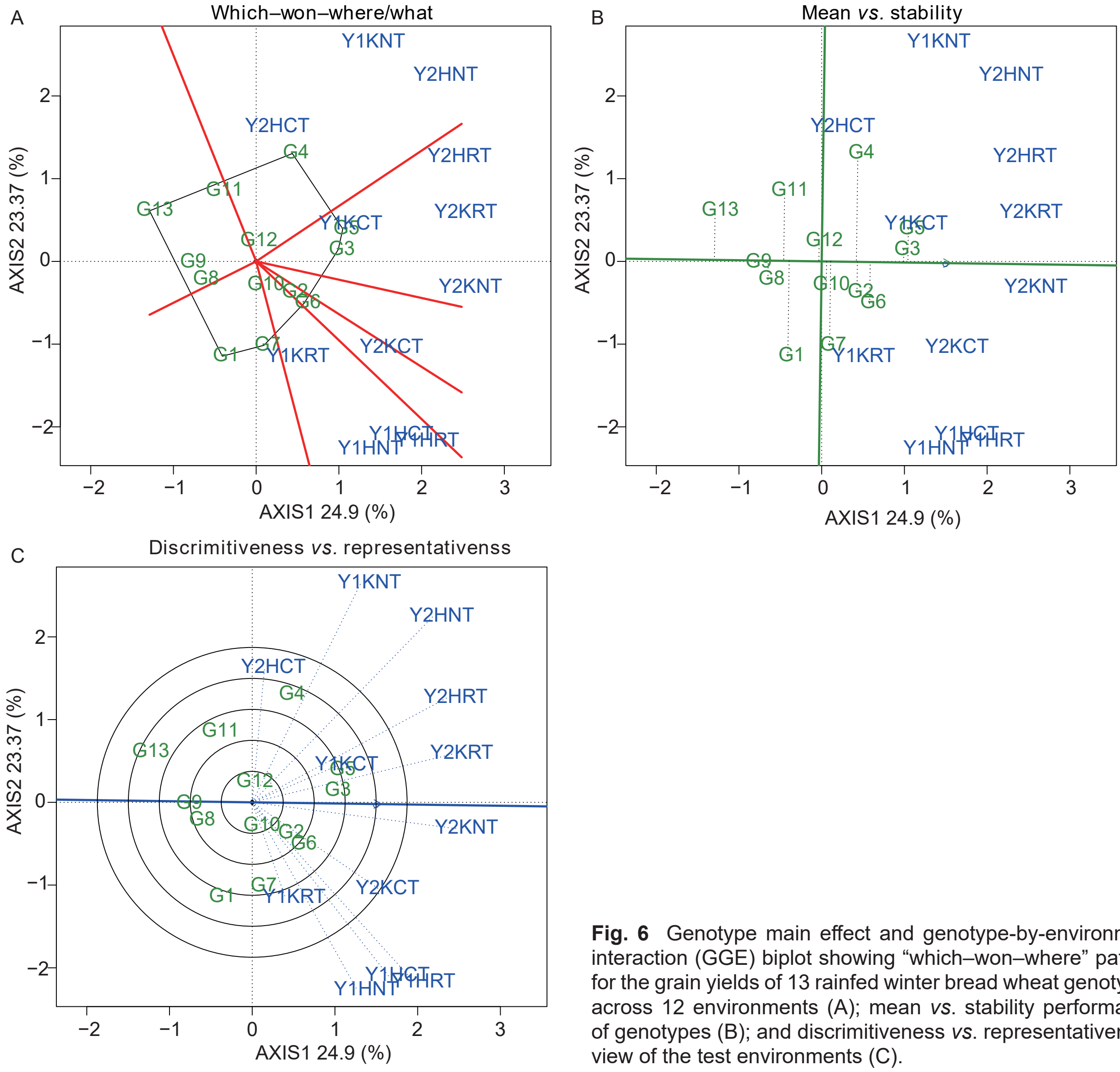
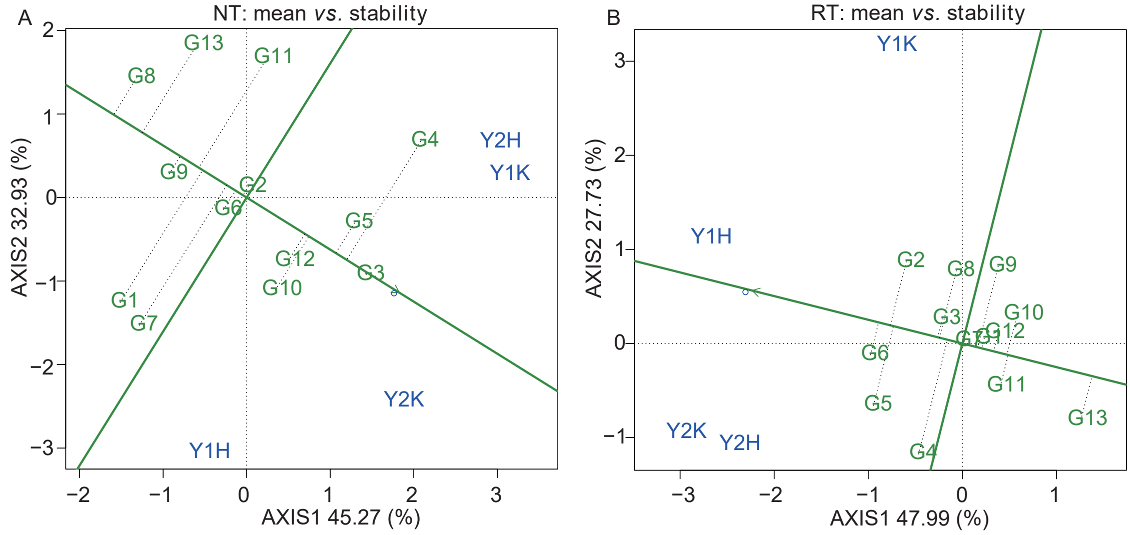


Fig. 6 Genotype main effect and genotype-by-environment interaction (GGE) biplot showing "which–won–where" pattern for the grain yields of 13 rainfed winter bread wheat genotypes across 12 environments (A); mean *vs.* stability performance of genotypes (B); and discrimitiveness *vs.* representativeness view of the test environments (C).

establishment (Honsdorf *et al.* 2019). Therefore, it is important for farmers who are interested in adopting CA to be aware of the genetic potential of available varieties in these conditions, so that they can accept this new crop management technology with more confidence. The results of this study show the behavior and response of the rainfed winter wheat varieties tested under any of the three tillage systems. There were significant (P<0.01) interactions between genotype with year, location, and tillage systems, showing highly remarkable changes in the adaptation of genotypes to different environmental conditions. However, in our experiment, the tested genotypes showed specific degrees of adaptation to the different tillage systems. Under variable environmental conditions, breeding strategies should focus on increasing the yield and its stability. Therefore, genotype evaluation in winter wheat-based cropping systems is a useful approach for the assessment of grain yield and yield stability performance, as well as other agronomic traits.

The high genotype×tillage system interaction affected the performance of the wheat genotypes, indicating that the ranking of genotypes in different tillage systems was not consistent and varied from one tillage option to another. Many studies have reported significant genotype×tillage system interactions for different crops, i.e., wheat (Hwu and Allan 1992; Fischer *et al.* 2002; Joshi *et al.* 2007; Carena *et al.* 2009; Herrera *et al.* 2013; Piggin *et al.* 2015; Honsdorf *et al.* 2018), maize (Herrera *et al.* 2013), barley and chickpea (Yau *et al.* 2010; Piggin *et al.* 2015), safflower (Yau *et al.* 2010) and lentil (Piggin *et al.* 2015). This study showed that among 13 tested genotypes, only the three genotypes of G4, G5 and G12 (less than 23%) showed positive responses to NT (Fig. 3), demonstrating that only a small number of high-yielding rainfed winter



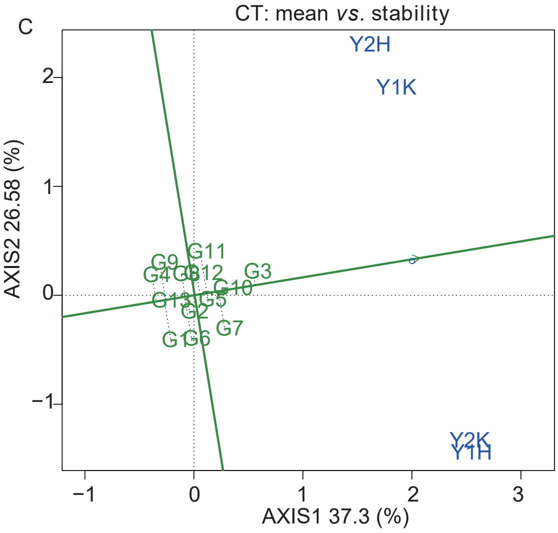


Fig. 7 Mean grain yield *vs.* yield stability performance of rainfed winter bread wheat genotypes in each tillage system. A, no-tillage (NT). B, reduced tillage (RT). C, conventional tillage (CT).

wheat genotypes that were adapted and introduced for CT systems in highland areas responded positively to NT as one of the key components of CA. In contrast to the results of this experiment, Honsdorf *et al.* (2019) did not find significant differences between CIMMYT durum wheat germplasms under two selection streams in CA and CT systems. Those authors pointed out that there is no need for a new breeding program for the screening of durum wheat germplasms under CA. Nevertheless, they reported that the genotype×tillage system interaction is more relevant for bread wheat than for durum wheat because of the larger genetic variation among bread wheat genotypes. However, CA alters crop growth conditions and may cause poor seedling establishment in first years, by creating physical barriers such as increasing of residue retention on the soil surface, increasing soil bulk density and hindering root development, which may be irreparable in highland areas (Honsdorf *et al.* 2019). In this study, genotype G3 followed by G10 exhibited better adaption to CT; while G2 and G6 showed better performance under the RT system; and G4 and G5 tended to have better performance in the NT condition. The relationships among the studied traits in each of the three tillage systems indicated that in the NT system, grain number per spike and plant height were significantly (P<0.01) correlated with grain yield. However, under the RT system, only grain number per spike was significantly associated with grain yield. This leads to the conclusion that selection based on these traits would enhance rainfed winter wheat grain yield under the NT and RT systems. There was no similar trend under the CT system.

4.2. CT *vs.* NT

There are different opinions about the effects of CA on wheat grain yield (Carr *et al.* 2003a, b; Gürsoy *et al.* 2010; Plaza-Bonilla *et al.* 2014; Taner *et al.* 2015; Chaghazardi *et al.* 2016; Santín-Montanyá *et al.* 2017; Khorami *et al.*

2018). Some studies have reported positive effects of NT (Plaza-Bonilla *et al.* 2014; Taner *et al.* 2015; Santín-Montanyá *et al.* 2017), while others have found either negative effects (Chaghazardi *et al.* 2016; Khorami *et al.* 2018) or no significant difference between conventional and NT systems (Carr *et al.* 2003a, b; Gürsoy *et al.* 2010). The reason for this discrepancy is that other factors (e.g., genotypes, climate, etc.) may affect the performance of tillage systems. Across four tested environments (combinations of two locations and two years), the genotypes showed better adaptation to CT than to the other two tillage systems. However, a low percentage of genotypes showed superiority in CT compared to NT (2%) and RT (5%). This better adaptability can be attributed to the environmental conditions where these genotypes were developed, selected, and grown, i.e., CT system. Changing from CT to NT had begun in the two previous crop seasons (2015–2016) in the study locations. Generally, the NT system usually reduces crop yields in the initial stage, however, its advantageous impacts on the soil quality and properties may result in equal or better yields than the CT system in subsequent seasons (Herrera *et al.* 2013; Pittelkow *et al.* 2015; Page *et al.* 2020). Our results showed that in all four of the environments studied, the grain yield in NT was less than in CT. This superiority was more evident in Kamyaran, where remarkable rainfall was received during the 2017–2018 cropping cycle. Under this condition, some genotypes, e.g., Sardari (G13) as a landrace, lodged in response to the heavy rainfall and poorly drained soil, which was more evident in NT than CT (Nyagumbo *et al.* 2016; Steward *et al.* 2018). It appeared that in wet seasons, NT systems were not notably superior to conventional systems (Pittelkow *et al.* 2015; Page *et al.* 2020). However, it is clear that conservation tillage is suitable for dry climatic conditions since it retains soil moisture storage (Hemmat and Eskandari 2004, 2006; Radford and Thornton 2011; Soane *et al.* 2012; Steward *et al.* 2018; Page *et al.* 2019). A global meta-analysis was conducted by Pittelkow *et al.* (2015) based on hundreds of studies which included 48 crops in 63 countries. That study reported an average reduction of 5.1% in grain yield under NT compared to the CT system when NT and residue retention occurred as the two principals of CA. However, it concluded that in dry climates, the grain yield would increase by 7.1%.

4.3. RT *vs*. NT

When farmers want to change from conventional to conservation tillage systems, they often choose reduced or minimum tillage because it offers a more straightforward adaptation in machinery (Ruiz *et al.* 2019). On average, there was no significant difference between the RT and NT systems, with mean grain yields of 2 447 *vs*. 2 517 kg ha^{-1}, respectively (Table 4). Therefore, farmers who are interested in NT can adopt it without worrying about a severe yield reduction in these areas, which is in line with reports by Hemmat and Eskandari (2006) but contradicts the findings of Chaghazardi *et al.* (2016). However, there was a different trend among the tested genotypes regarding the grain yield in NT compared with RT. For example, the grain yields of G2, G6 and G8 were significantly higher in RT than NT. In contrast, G3, G10, G12, and G13 produced higher grain yields in NT, demonstrating the significant genotype×tillage interaction. These differences in response to tillage systems can be considered and exploited in rainfed winter wheat breeding programs for the development and evaluation of germplasm with adaptability to RT and NT systems. The results of the present study are in disagreement with the results obtained by Khorami *et al.* (2019) who reported higher grain yield in RT for five spring wheat genotypes under an irrigation system. However, it must be noted that in most studies a limited number of genotypes were used in environments that might not be sufficient to reveal the G×T interaction in different conditions (Gürsoy *et al.* 2010; Chaghazardi *et al.* 2016; Santín-Montanyá *et al.* 2017).

In Kamyaran, with the temperate climatic conditions and terminal heat stress during grain filling, farmers usually grow wheat after spring chickpea under various CT operations, including moldboard and many passes of tandem disk harrow. These multiple operations for land preparation lead to soil disturbances and a delay in planting time, while wheat seed can be sown in time without any soil disturbance before effective rainfall in NT, which may result in more efficient use of rainfall and a reduced risk of crop failure due to terminal heat stress (Kumar *et al.* 2018; Devkota *et al.* 2019). Early sowing, particularly timely sowing, is the most recommended practice under dryland conditions (Juergens *et al.* 2004; Schillinger *et al.* 2007; Bewick *et al.* 2008; Cann *et al.* 2020). In addition, further advantages of NT might include improving the physical, biological, and chemical soil properties, lower production costs, and minimizing water and wind erosion. Identifying crop traits as criteria for indirect selection based on grain yield for the screening of genotypes is recommended (Fufa *et al.* 2005; Barnábas *et al.* 2008; Monneveux *et al.* 2012). In this study, grains per spike and plant height showed significant positive genetic and phenotypic correlations with grain yield (Fig. 5). Therefore, these traits can be used as indirect selection criteria for development and selection of winter bread wheat genotypes that are adapted to RT and NT systems.

4.4. Grain yield stability

The relative productivity of each genotype was strongly dependent on both tillage system and year. The GGE biplot demonstrated that genotypes G3 (Sadra) and G5 (Baran) had high yielding ranks along with high yield stability. Consequently, these cultivars can be highlighted as the most well-adapted cultivars to different tillage systems in rainfed conditions. Nonetheless, grain yield stability with high mean grain yield is the most critical strategy for selecting cultivars that are widely adapted to variable rainfed growing environments for wheat (Subira *et al.* 2015; Mohammadi *et al.* 2021).

The specific adaptations of some of the tested genotypes to each tillage system revealed that the degrees of adaptability of released rainfed winter bread wheat genotypes to different tillage systems in terms of their high mean grain yield and yield stability were different. For example, the genotypes with high grain yield and yield stability in RT were different from the genotypes in NT and CT. Azar2 (G6), as a relatively old cultivar with high grain yield and yield stability performance under RT, had greater plant height (89 cm), spikes m^{-2} (308 spikes) and grain number per spike (24 grains). A similar trend was found for Sadra (a modern cultivar) in NT and CT (Table 4). Our results showed that these three agronomic traits had more significant correlations with grain yield compared with TKW (Fig. 5-B). A genotype×tillage interaction was also detected (Table 3). Unlike TKW, these traits had more genetic variation and were affected by the tillage systems, suggesting that they can be used as selection criteria for the development of genotypes adapted for such conditions in breeding programs. More spikes per unit area are the result of the proper establishment and increase in tiller survival, which are effective traits for increasing grain yield (Hemmat and Eskandari 2004, 2006). It is clear that by continuous NT and residue retention on the soil surface, the soil moisture content would increase and lead to more crop growth and tillering capacity (Hemmat and Eskandari 2004, 2006). Ruiz *et al.* (2019) identified TKW, grain-filling duration, biomass production and tillering capacity as the target traits for the development of bread wheat and durum wheat under conservation tillage systems in dry environments.

5. Conclusion

The results of this study revealed significant (P<0.01) genotype×tillage system interaction effects on grain yield and related traits, indicating that the genotypes responded differently to different tillage systems. A hierarchical clustering integrated heat map was developed based on grain yield in different tillage systems, which allowed the identification of different trends in the adaptability of rainfed winter bread wheat genotypes to different tillage systems, and these genotypes can be further used as potential genetic materials in rainfed winter wheat breeding programs for different tillage systems. Based on the results of this study, two new cultivars (Sadra and Baran) were high yielding with yield stability across the different tillage systems in the highland cold dryland regions in the West of Iran. These two genotypes also expressed high productivity under the NT system. Thus, these two genotypes can be recommended for the NT system as they can provide resilience and save production costs (i.e., eliminating the attendant costs for ploughing, etc.) in the planting operation, maximizing the chances of achieving high grain yields and profits across variable dryland environments. Furthermore, genotype G3 (Sadra) expressed the highest mean grain yield and yield stability performance across locations and seasons under both NT and CT systems, indicating that in addition to high mean grain yield, the yield stability of this newly released winter wheat variety under both tillage systems should be considered and used in rainfed winter wheat breeding programs. Furthermore, the significant positive correlations of number of grains per spike and plant height with grain yield under the NT system may be considered as targeted traits for the development of new adapted winter bread wheat genotypes in the future. In conclusion, variations in the performance of genotypes and the significant genotype×tillage system interaction effects on grain yield and some agronomic traits assessed in this study suggest that the development and selection of cultivars adapted to the NT system should be considered and included in the strategies and objectives of winter wheat breeding programs for the temperate and cold dryland conditions of Iran.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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