Increasing Grain Yield in Bread Wheat (*Triticum aestivum* L.) by Selection for High Spike Fertility Index

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ABSTRACT

Spike fertility index (SF) has been proposed as a promising selection criterion for increasing grain yield (GY) in bread wheat. Here, changes in GY and related traits after simulated selection (10% intensity) for high SF or high GY *per se* were assessed in two RIL populations: (I) Avalon/Glupro and (II) Baguette 10/Klein Chajá, and in (III) advanced lines from a breeding program. Grain yield, SF, grain number per unit area (GN), grain weight (GW), test weight (TW) and grain protein content (GPC) were determined. Regardless of the environmental conditions, simulated selection for high SF always resulted in GN increases (between 1.6 and 27.4%). Average GY increase observed after selection for high SF (11.5%; N=10; SEM=5.8) did not differ (p=0.92) from the average GY increase observed after

selection for GY *per se* (11.8%; N=10; SEM=4.9). Grain weight, GPC and TW tended to decrease with selection for high SF; however, these trade-offs might be avoided by concurrent selection. Our findings validate the use of SF as a selection criterion for increasing grain yield in bread wheat.

KEYWORDS: grain yield, grain number; fruiting efficiency; breeding; selection; genetic progress

INTRODUCTION

Grain yield is one of the key targets of bread wheat (*Triticum aestivum* L.) breeding programs worldwide. Under a scenario of increased global demand for grains and limited possibilities of expanding cropping areas, breeding efforts must focus on raising annual yield increase rates (CIMMYT, 2019). One way to achieve this is by using yield-related, high-throughput phenotypic variables as selection criteria.

Grain yield in wheat is determined mainly by the number of grains per unit area (GN) and, to a lesser extent, by grain weight (GW). Therefore, variations in GN best explain yield variation (Abbate et al., 1998; Borrás et al., 2004; Elía et al., 2016; Ferrante et al., 2017; Lynch et al., 2017; Shearman et al., 2005; Slafer et al., 1990). However, this is a difficult trait to select for in early generations of a breeding program, in which not enough seed is available. Fischer (1984) proposed that, under non-limiting growing conditions (i.e., without water or nutrient limitations and in absence of pests and diseases), GN is determined by the product of (i) the duration of rapid spike growth period, (ii) crop growth rate during the spike growth period, (iii) dry weight partitioning to spikes during the spike growth period, and (iv) the number of grains per unit of spike dry weight, i.e., a “spike fertility” index (SF) (Abbate et al., 1998) or “fruiting efficiency” (Ferrante et al., 2012). The spike dry weight at anthesis is a complex trait to measure; thus, chaff dry weight at maturity has been proposed as its surrogate (Abbate et al., 2013). Then, the spike fertility index at maturity [also termed fruiting efficiency at

maturity; Fischer and Rebetzke (2018)] is calculated as the number of grains produced per unit of chaff dry weight.

There is extensive evidence in the literature that GN is tightly linked to SF (Abbate et al., 1998; Acreche et al., 2008; Alonso et al., 2018b; Foulkes et al., 2015; Shearman et al., 2005; Terrile et al., 2017). In the reference method (9), SF determination is carried out at anthesis, but this is destructive and very time consuming. A high throughput, non-destructive method for assessing the trait in small samples at maturity has then been proposed (Abbate et al., 2013). In addition, SF at maturity has been shown to have high heritability, substantial genetic variability and low genetic by environment interaction (Alonso et al., 2018b; Martino et al., 2015; Mirabella et al., 2016). Because of all these features, SF has been regarded as a promising selection criterion for increasing GN (and yield) in breeding programs (Abbate et al., 2013; Elía et al., 2016; Fischer, 2007, 2011; Fischer & Rebetzke, 2018; Foulkes et al., 2010; García et al., 2014; González et al., 2011; Lázaro & Abbate, 2012; Martino et al., 2015; Mirabella et al., 2016; Slafer et al., 2015; Terrile et al., 2017). As a matter of fact, Alonso et al. (2018b) have shown that selection for high SF, either solely or in combination with selection for high grain yield, effectively increases yield, resulting in higher and more stable yields than if selecting for high yield *per se*. These encouraging results, obtained with a single RIL population under non-limiting environmental conditions, need further validation before such selection strategies can be implemented in a breeding program. Also, the assessment of possible trade-offs that could arise as a byproduct of these schemes should be carried out. Therefore, the aim of this work was to determine the effectiveness of selection for high SF in raising grain yield and its effect on other variables, by carrying out simulated selection and analyzing the response to this selection in a combination of diverse genetic materials (RILs and advanced lines) and an array of environmental conditions.

MATERIALS AND METHODS

Field experiments and plant material

Field experiments were carried out at the Balcarce (37º45’ S; 58º18’ W; 130 m a.s.l.) and Marcos Juárez (32°43'S; 62°06'W; 112 m a.s.l.) Agricultural Experimental Stations of the Instituto Nacional de Tecnología Agropecuaria (INTA), Argentina. Characteristics of experiments are summarized in Table 1.

Experiments were conducted under conventional tillage with no nutrient limitations; weeds, pests and fungal diseases were chemically controlled. As described in Table 1, experiments were grouped into Sets I, II and III. In Set I, a biparental population of 90 recombinant inbred lines (RIL) derived from the cross between ‘Avalon’ and ‘Glupro’ was evaluated in experiments BAG15 and BAG16. ‘Avalon’ is a cultivar from the UK with high protein content, whereas ‘Glupro’ is a cultivar from the USA with the introgression of the *GPC-B1* gene (Uauy et al., 2006) for high protein content. In Set II, a biparental population of 146 RIL derived from the cross between ‘Baguette 10’ and ‘Klein Chajá’ (Alonso et al., 2018b; Martino et al., 2015; Mirabella et al., 2016) was evaluated in experiments BFE13, BFE14, BFE15 and MJFE17. Both parents are Argentinean spring bread wheat cultivars of good agronomic performance, with contrasting SF and yield components. In Set III, breeding lines derived from crosses between cultivars of diverse origin (CIMMYT, Europe, Argentina), advanced through a modified bulk selection scheme and selected for grain yield and agronomic performance in a wheat breeding program (INTA Balcarce Experimental Station), were evaluated in experiments BLE16 and BLE17 (28 lines), and BLP17 and BLE18 (36 lines).

Data collection

Grain yield was determined by mechanical harvest of the whole plot (when three-row plots were used) or its five central rows (when seven-row plots were used; Table 1). In the former case, the plot (and harvested) area was 3.5 m^2, with an inter-plot distance of 0.3 m; in the latter case, the harvested area was 5 m^2. Grain moisture was obtained from a grain subsample of each plot to calculate dry grain yield (GY; g/m^2). Grain weight (GW; mg) was determined

by counting a 1000-grain sample with an electronic counter, weighing it and dividing total weight by 1000. Grain number per square meter was then calculated as the quotient between GY and GW × 1000.

Spike fertility index was determined at maturity on a sample of 15-20 spikes drawn at random from the harvestable area of each plot prior to mechanical harvest. Spikes were cut at the lowest spikelet level, counted, weighed, and threshed. Spike chaff dry weight (g) was calculated as the difference between total spike dry weight (i.e. before threshing) and total grain weight. Grains were counted using an electronic counter. Then, SF (grains/g) was calculated as the quotient between the number of grains and spike chaff dry weight per sample (Abbate et al., 2013).

Test weight (TW) was measured using a Schopper chondrometer on a 250 g grain sample and expressed as kg/hl. Grain protein content (GPC; %) was determined indirectly by NIRS using a TEC NIR 256 Inlab NIR in 100 g grain samples, previously cleaned and dried at 60°C to constant weight.

Trait responses after simulated selection

Data from three sets of experiments (Table 1) were used to evaluate responses in GY and other traits after simulated selection for high SF. At each set, the 10% top lines with the highest SF values were selected, based on SF data generated in experiments BAG16 (Set I), BFE13, BFE14, BFE15 and MJFE17 (Set II) and BLE16, BLE17, BLP17 and BLE18 (Set III). This means that, at each set, SF was assessed in only *some* experiments (Table 1). However, the performance of those selected lines and the simulated response after selection (i.e., their differential performance compared with that of the population mean) was evaluated based on data generated in *all* experiments within each set. This also included the experiments in which SF itself was determined, as an independent spike sample was drawn before harvest for SF determination, whereas the response variables were evaluated at harvest. In order to compare the effects of selection for high SF with those for high GY *per se*, a similar approach was followed by carrying out simulated selection for high GY *per se* (10% intensity) and assessing trait responses in all experiments within each set. However, as there is an obvious

bias in assessing GY response after selection for GY *per se* in the same experiment, these cases were excluded from the analysis.

Responses after selection for SF or GY *per se* were calculated for GY and other traits as the difference between the mean values of the 'selected group' and the general mean of the population at each response experiment. They were then expressed as percentage of the population mean. For each set of experiments, an overall response mean was also calculated.

Statistical analysis

Grain yield was analyzed with a linear fixed effects model including experiments and genotypes and genotype by experiment interaction effects nested in sets of experiments. Welch's t-test was used to compare trait responses (in %) after the two simulated selection strategies (i.e., for high SF vs. for high GY *per se*). For this comparison, only those cases that had data for side by side comparisons were used.

RESULTS

Experiments included in Sets I to III were carried out under different environmental conditions (i.e. different locations, years, growing conditions, plot size, etc.; Table 1). In addition, conspicuous environmental differences between crop seasons due to temperature, radiation and rainfall were observed (Fig. 1). This resulted in significant differences in average grain yield between experiments ($p<0.0001$); GY differences between genotypes ($p<0.0001$) were also evident across experiments (Tables 2 and 3). As a consequence of the observed environmental differences and the genetic constitution of the populations under study, conspicuous phenotypic variation was also observed in the remaining traits (Table 3). When analyzed by set, very different population means for all the variables were observed across experiments in each of the three sets, reflecting environmental variation between years and/or locations (Table 3). A summary of results of simulated selection for high SF carried out in each of the three sets is presented in Table 4 (for responses in GY and GN) and Table S1 (for responses in GW, TW and GPC). Selection of the top 10% lines with the highest SF in experiments BAG16 (Set I), BFE13, BFE14, BFE15 and MJFE17 (Set II) and BLE16 and BLE17, BLP17 and BLE18 separately (Set III) always increased GN, and also increased GY

except for a few cases of slight decrease in Set III. For each set of experiments, the overall mean response (%) in GY and GN after simulated selection for SF is shown in Table 4. Only for set III the overall mean was negative for GY (-2.0%), while it was positive for GN (8.6%). Across the three set of experiments, GY and GN respectively increased by 5.6 and 13.4% as a result of simulated selection for high SF (Table 4), as compared with the population means. On the other hand, selection responses after simulated selection by high GY *per se* ranged between -9.3% and 46.0% in GY and between -6.8% and 51.2% in GN, considering all experiments. As occurred with simulated selection for high SF, responses after selection for high GY *per se* were positive for all cases except for a few in set III (Table 4).

Both simulated selection strategies (i.e., by high SF and by high GY *per se*) were compared in terms of the average response attained in GN and GY (Table 5). As a result, both yielded substantially similar average responses ($p>0.05$) in GN and GY, although the variance was several fold higher when using GY *per se* as the selection criterion for responses in GN.

As for other yield-related traits, simulated selection for high SF consistently lowered GW (overall decrease of 5.3%; Table S1). As for TW, response after selection for high SF was slightly positive in Set I and slightly negative in Set II, but not significant. Grain protein content, only determined in Set I, was decreased by 6.9% as a result of selection for high SF. On the other hand, average responses after simulated selection for high GY *per se* were positive (Table S1).

DISCUSSION

Grain yield increase is of paramount importance in every bread wheat breeding program. However, annual increase rates have been steadily declining and would hardly meet the present and future demand. In a recent review, Fischer and Rebetzke (2018) proposed focusing on a number of breeding targets for accelerating grain yield genetic gains, among which they included fruiting efficiency/spike fertility index (SF). When evaluating several selection strategies under different environmental conditions, Alonso et al. (2018b) found that simulated selection for high SF, either solely or along with selection for high grain yield, always resulted in higher and more stable yields than if selecting for high yield alone. In the

present study, we show that, regardless of the genetic material or the environmental conditions, selection for high SF alone virtually always increases grain yield in bread wheat.

Independently of the set of experiments, selection for high SF always resulted in GN increases (between 1.6 and 27.4%) and in GY increases in most cases, except for a few in Set III (Table 4). These latter cases, however, occurred in a population of advanced breeding lines, which underwent selection in previous generations as opposed to the RIL populations used in sets I and II. Also, this was the population with the least number of individuals (N=28/36; Table 1). The top 10% lines with the highest SF values amounted to only 3-4, which could have increased sampling error. Nevertheless, overall results suggest that one can select lines with high SF on the basis of data collected from a very small spike sample and sometimes in a different environment than the one in which yield is determined (even including lower yield potential locations as it is Marcos Juárez as compared with Balcarce, in this study) (Menéndez & Satorre, 2007) and expect, at the minimum, a meager increase in yield and/or GN.

Regarding the substantial variation in the magnitude of the responses to selection observed across sets and experiments within sets (Table 3), several possible underlying causes could be considered. For instance, variations might have occurred due to unmeasured sampling errors, sample size, and different genetic and genetic by environment interaction effects of the traits under evaluation. In this sense, additional data sets comprising a wider spectrum of germplasm and environments/years of evaluation should be incorporated in the analysis in order to reduce these errors. On the other hand, the heritability of each trait as well as the degree of association between the trait used for selection and the response trait might have been other sources of variation in the observed responses to selection. For instance, in the case of the RIL population of Set II, the heritability values of the traits (h^2_{SF}=0.84; h^2_{GY}=0.28; h^2_{GN}=0.35; Alonso et al. 2018b) and the correlations between the traits, both genetic ($r_{SF\text{-}GY}$=0.36, $r_{SF\text{-}GN}$=0.55; Alonso et al. 2018b) and phenotypic ($r_{SF\text{-}GY}$=0.29, $r_{SF\text{-}GN}$=0.44; Table S2), provide an idea of how these relationships could affect the responses. Spike fertility index, used here as a selection criterion, has high heritability with low environmental influence, which makes it fairly stable across successive generations. The trait response after such selection is expected to be positively correlated with the degree of association between the selection and evaluation traits; indeed, in this study, the response was better in GN than in GY. In turn, the year-to-year variations in the response of these traits are in line with their

heritabilities (low to moderate) and with their great sensitivity to environmental effects. Therefore, selecting for high SF would give stability to the response in GN and GY, whereas these latter traits' low/moderate values of both heritability and genetic/phenotypic correlation with SF would increase variability in such response.

Some trade-offs were observed: in general, GW, GPC and TW tended to decrease with selection for high SF. Nevertheless, genotypes with all high SF, GY, GW, GPC and TW were detected (data not shown); therefore, these trade-offs could be avoided by concurrent selection for all traits. Furthermore, all three populations used in the present study had a relatively low number of individuals if considering the scale of an actual breeding program. Provided that the prerequisite of existence of genetic variability for the traits is met (as it was the case in the present study; Table 3), increasing population numbers is likely to yield even better results when selecting for high SF. This way, while increasing GY and GN, one could concurrently maintain desirable GW, TW and GPC values. Phenotypic correlations between variables were generally positive (Table S2) except for the ones between GN and GW (r=-0.18) and SF and GW (r=-0.2). These low values, however, confirm the idea that the negative relationship between these variables is not complete.

Independently of the genetic constitution of the breeding material and/or the environmental conditions, selections for high SF, as determined in a small spike sample, appear to result in consistently increased grain number per unit area (and yield) in bread wheat. As virtually similar average responses to selection in GN and GY were attained when using SF or GY *per se* as selection criteria (Table 5), selection for SF alone has the potential of increasing the throughput and efficiency of the breeding process, while lowering costs. Spike fertility index determination entails drawing samples in the field, weighing and threshing (which, although cheaper, might be more labor-intensive and time-consuming than GY determination), but it is a process amenable to automation. This could translate into a massive screening of lines for SF in small plots and subsequent multi-environment yield trials that only include a subset of the lines initially screened. This turns SF into a very promising selection target in breeding programs aimed at increasing grain yield. Nevertheless, the effectiveness of carrying out selection for high SF in spaced plants, as it would be the case of early generations of a breeding program, remains yet to be established.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

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Tables

Table 1. Description of field experiments carried out in this study, as organized in Sets of experiments (exps.) I to III. Genetic material included in each set, N (number of individuals), exp. name, location, year, exp. design (RCBD=randomized complete block design; ARCBD=augmented randomized complete block design), No. reps. (number of replications), growing conditions, plot dimensions and data collected (SF=spike fertility index; GY=grain yield; GN=grain number per unit area; GW=grain weight; TW=test weight; GPC=grain protein content). Data from exps. BFE13, BFE14 and BFE15 have been partially published by Alonso et al. (2018a;b).

Set of exps.	Genetic material	N	Exp. name	Location	Year	Sowing date	Exp. design	No. reps.	Growing conditions	Plot dimensions				Data collected					
										Area (m^2)	No. rows	Row length (m)	Inter-row spacing (m)	SF	GY	GN	GW	TW	GPC
I	RIL population	90	BAG15	Balcarce	2015	June 19th	RCBD	2	Rainfed	3.5	3	5	0.2		X	X	X	X	X
	(Avalon/Glupro)	90	BAG16	Balcarce	2016	July 14th	RCBD	2	Rainfed	3.5	3	5	0.2	X	X	X	X	X	X
II	RIL population	146	BFE13	Balcarce	2013	June 23rd	RCBD	2	Irrigated	3.5	3	5	0.2	X	X	X	X	X	
	(Baguette 10/ Klein	146	BFE14	Balcarce	2014	July 25th	RCBD	2	Irrigated	7	7	5	0.2	X	X	X	X	X	
	Chajá)	146	BFE15	Balcarce	2015	July 15th	RCBD	2	Irrigated	7	7	5	0.2	X	X	X	X	X	
		146	MJFE17	Marcos Juárez	2017	June 15th	ARCBD	1	Rainfed	0.9	3	1	0.3	X					
III	Advanced	28	BLE16	Balcarce	2016	August 8th	ARCBD	1	Rainfed	7	7	5	0.2	X	X	X			
	breeding lines	28	BLE17	Balcarce	2017	June 14th	ARCBD	1	Irrigated	7	7	5	0.2	X	X	X			
		36	BLP17	Balcarce	2017	August 6th	ARCBD	1	Rainfed	7	7	5	0.2	X	X	X	X		
		36	BLE18	Balcarce	2018	June 11th	RCBD	2	Irrigated	7	7	5	0.2		X				

Table 2. Analysis of variance for grain yield (g/m^2) across nine experiments. All experiments from Sets I to III (Table 1) were included in the analysis except for MJFE17, which plot size (0.9 m^2) was deemed too small for accurate grain yield determination.

Source of variation	DF	Mean Square	F	P-value
Experiment	8	5155433	530.03	<0.0001
Genotype (set)	236	33324	3.43	<0.0001
Genotype*experiment (set)	499	19126	1.97	<0.0001
Error	693	9727		

Table 3. Mean (x□) and standard deviation (S) of spike fertility index (SF, grains/g), grain yield (GY, g/m^2), grain number per unit area (GN, grains/m^2), grain weight (GW, mg), test weight (TW, kg/hl) and grain protein content (GPC, %) of I: Avalon/Glupro RIL population (N=90, experiments BAG15 and BAG16); II: Baguette 10/Klein Chajá RIL population (N=146, experiments BFE13, BFE14, BFE15 and MJFE17) and III: advanced breeding lines (N=28, experiments BLE16 and BLE17; N=36, experiments BLP17 and BLE18).

Set of Experiments	Experiment	SF		GY		GN		GW		TW		GPC	
		x□	S	x□	S	x□	S	x□	S	x□	S	x□	S
I	BAG15			515.9	125.0	12990	3254	39.9	3.2	79.9	2.4	16.0	1.2
	BAG16	70.5	11.2	314.1	81.9	9788	2554	32.3	3.4	77.1	2.1	14.5	0.7
II	BFE13	98.3	9.2	717.0	185.9	21960	6283	33.0	4.2	77.8	11.5		
	BFE14	91.9	11.7	367.1	89.4	9964	2687	37.4	4.6	73.8	2.2		
	BFE15	89.5	9.5	749.1	123.5	17824	3457	42.5	3.8	80.3	1.8		
	MJFE17	101.7	12.1	432.5	134.9			32.4	4.7				
III	BLE16	81.5	10.2	498.9	108.4	14755	3004	34.2	5.3				
	BLE17	83.9	9.4	448.2	84.9	11302	2139	39.7	4.9				
	BLP17	86.6	11.8	383.9	46.0	11015	1770	35.3	4.1				
	BLE18			618.1	193.6								

Table 4. Response after simulated selection for high spike fertility index (SF) and grain yield (GY) per se *(i.e., selection of the top 10% lines with the highest SF or GY values at each of three sets of experiments (exps.) carried out between 2013 and 2018 in Balcarce and Marcos Juárez, Argentina) in grain yield (GY; g/m^2) and grain number per unit area (GN; grains/m^2). Grain yield responses after selection for GY* per se *in the same experiment are not shown, as they were not included in the analysis (see Materials and Methods).*

Set of Exps.	Selection Exp.	Response Exp.		Selection for high SF		Selection for high GY	
				Response in GY	Response in GN	Response in GY	Response in GN
I	BAG16	BAG16	Population mean (N=90)	313.7	9760		9788
			Mean of 10% lines (N=9) selected for SF or GY in exp. BAG16	396.2	12431		14496
			Response after simulated selection (%)	**26.3**	**27.4**		**48.1**
		BAG15	Population mean (N=90)	515.5	12971	515.5	12971
			Mean of 10% lines (N=9) selected for SF or GY in exp. BAG16	599.5	15176	743.7	17752
			Response after simulated selection (%)	**16.3**	**17.0**	**44.3**	**36.9**
	BAG15	BAG15	Population mean (N=90)				12966
			Mean of 10% lines (N=9) selected for GY in exp. BAG15				19598
			Response after simulated selection (%)				51.2
		BAG16	Population mean (N=90)			313.7	9788
			Mean of 10% lines (N=9) selected for GY in exp. BAG15			458.2	14257
			Response after simulated selection (%)			46.0	45.7
			Mean (±SD) response after simulated selection in set I (%)	**21.3±7.1**	**22.2±7.4**	**45.2±1.2**	**48.5±7.2**
II	MJFE17	BFE13	Population mean (N=146)	719.5	22092		
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17	721.0	24313		
			Response after simulated selection (%)	**0.2**	**10.1**		
		BFE14	Population mean (N=146)	367.4	9978		
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17	419.0	12592		
			Response after simulated selection (%)	**14.0**	**26.2**		
		BFE15	Population mean (N=146)	749.1	17763		
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17	752.0	19387		
			Response after simulated selection (%)	**0.4**	**9.1**		
	BFE13	BFE13	Population mean (N=146)	719.5	22092		22092
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13	772.4	25615.5		30890
			Response after simulated selection (%)	**7.3**	**16.0**		**39.4**
		BFE14	Population mean (N=146)	367.4	9978	367.4	9978
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13	397.2	10811	444	11714
			Response after simulated selection (%)	**8.1**	**8.3**	**20.9**	**17.4**
		BFE15	Population mean (N=146)	749.1	17763	749.1	17763
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13	790.8	19626	772.5	18522
			Response after simulated selection (%)	**5.6**	**10.5**	**3.1**	**4.3**

Set of exps.	Selection exp.	Response exp.		Selection for high SF		Selection for high GY	
				Response in GY	Response in GN	Response in GY	Response in GN
II (cont)	BFE14	BFE13	Population mean (N=146)	719.5	22092	719.5	22092
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14	763.0	24166	903	29246
			Response after simulated selection (%)	**6.0**	**9.1**	**25.5**	**6.9**
		BFE14	Population mean (N=146)	367.4	9978		9978
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14	430.5	12259		13918
			Response after simulated selection (%)	**17.2**	**22.9**		**39.5**
		BFE15	Population mean (N=146)	749.1	17763	749.1	17763
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14	778.7	19310	759.5	18746
			Response after simulated selection (%)	**4.0**	**8.7**	**1.4**	**5.5**
	BFE15	BFE13	Population mean (N=146)	719.5	22092	719.5	22092
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15	745.8	24528	771.8	23610
			Response after simulated selection (%)	**3.6**	**11.0**	**7.2**	**6.9**
		BFE14	Population mean (N=146)	367.4	9978	367.4	9978
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15	408.5	12294	393	10767
			Response after simulated selection (%)	**11.2**	**23.2**	**7.0**	**7.9**
		BFE15	Population mean (N=146)	749.1	17763		17763
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15	783.4	20006		20816
			Response after simulated selection (%)	**4.6**	**12.6**		**17.2**
			Mean (±SD) response after simulated selection in set II (%)	**6.9± 5.1**	**14.0±6.5**	**10.9±9.9**	**16.1±14.1**
III	BLE16	BLE16	Population mean (N=28)	498.9	14755		14755
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE16	457.1	15962		17905
			Response after simulated selection (%)	**-8.4**	**8.2**		**21.3**
		BLE17	Population mean (N=28)	449.6	11413	449.6	11413
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE16	445.1	12122	407.8	10638
			Response after simulated selection (%)	**-0.1**	**6.2**	**-9.3**	**-6.8**
	BLE17	BLE17	Population mean (N=28)	449.6	11413		11413
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE17	424.6	11600		13563
			Response after simulated selection (%)	**-5.5**	**1.6**		18.8
		BLE16	Population mean (N=28)	498.9	14755	498.9	14755
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE17	565.8	17157	514	15455
			Response after simulated selection (%)	**13.4**	**16.3**	**3.0**	**4.7**
	BLP17	BLP17	Population mean (N=36)	383.9	11015		11015
			Mean of 10% lines (N=4) selected for SF or GY in exp. BLP17	367.4	12195		12793
			Response after simulated selection (%)	**-4.3**	**10.7**		**16.1**
		BLE18	Population mean (N=36)	609.6		609.6	
			Mean of 10% lines (N=4) selected for SF or GY in exp. BLP17	566.6		639.1	
			Response after simulated selection (%)	**-7**		**4.8**	
	BLP18	BLP17	Population mean (N=36)			383.9	11015
			Mean of 10% lines (N=4) selected for GY in exp. BLP18			389.4	11165
			Response after simulated selection (%)			1.4	1.4
			Mean (±SD) response after simulated selection in set III (%)	**-2.0±8.1**	**8.6±5.4**	**0.0±6.3**	**9.3±11.2**
			Overall mean response after simulated selection (%)	**5.6**	**13.4**	**12.9**	**20.1**

Table 5. T test for comparison of the average response in grain number per unit area (GN; grains/m^2) and in grain yield (GY; g/m^2) attained after selection for high spike fertility index (SF) vs. for high GY per se *(data extracted from Table 4; only those cases with available data for side by side comparisons were included).*

Variable	Selection criterion	N	Trait response after selection (%)		DF	T	P-value
			Mean	SEM			
GN	SF	16	13.1	1.73	21	-1.09	0.29
	GY *per se*	16	17.8	3.9			
GY	SF	10	11.5	5.8	17	0.09	0.92
	GY *per se*	10	11.8	4.9			

Figures

Figure 1

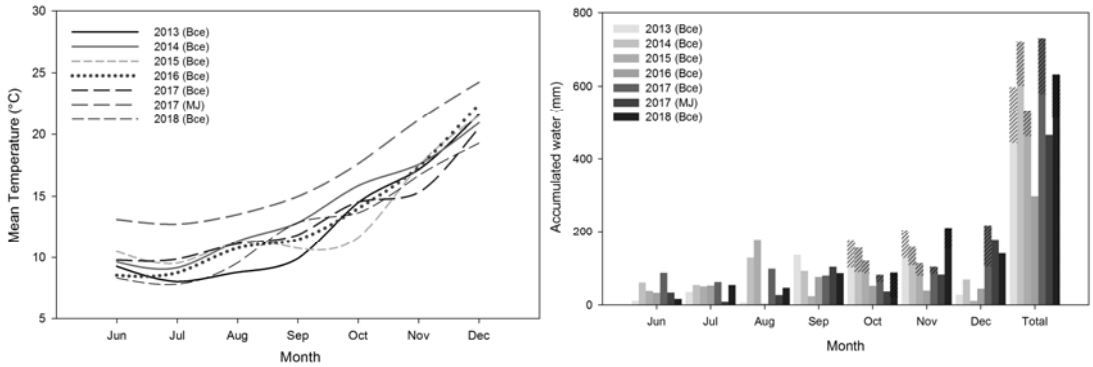

Figure legends

Fig. 1. Mean temperature (left) and accumulated rainfall plus irrigation (right) during the June-December period (wheat growing season) at Balcarce (Bce) in 2013 to 2018 and in Marcos Juárez (MJ) in 2017. Stripped bars show accumulated water by irrigation.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

ACP, MPA and NEM designed the study; ACP, MPA, NEM, JSP, MFF, and ML performed experiments at Balcarce and LSV performed the experiment at Marcos Juárez; MPA, NEM and JSP processed SF samples; NEM, MPA and ACP analyzed the data; MFF prepared all figures of the manuscript; ACP wrote the paper with input from all authors.

Table S1. Response to simulated selection for high spike fertility (SF) or grain yield (GY) per se *(i.e., selection of the top 10% lines with the highest SF or GY values at each of three sets of experiments (exps.) carried out between 2013 and 2018 in Balcarce and Marcos Juárez, Argentina) in spike fertility index (SF; grains/g), grain weight (GW; mg), test weight (TW; kg/hl) and grain protein content (GPC; %).*

Set of exps.	**Selection exp**	**Response exp.**		**Response to selection for high SF**				**Response to selection for high GY**			
				SF	**GW**	**TW**	**GPC**	**SF**	**GW**	**TW**	**GPC**
I	BAG15	BAG15	Population mean (N=90)						39.9	79.9	81.4
			Mean of 10% lines (N=9) selected for GY in exp. BAG15						40.4	83.5	111.1
			Response after simulated selection (%)						**4.6**	**4.6**	**36.5**
		BAG16	Population mean (N=90)					70.6	32.3	77.15	45.1
			Mean of 10% lines (N=9) selected for GY in exp. BAG15					81	32.4	79.4	61
			Response after simulated selection (%)					**14.2**	**0.3**	**2.9**	**35.2**
	BAG16	BAG16	Population mean (N=90)	70.6	32.3	77.1	14.5	70.6	32.3	77.1	45.1
			Mean of 10% lines (N=9) selected for SF or GY in exp. BAG16	89.7	31.6	79.0	13.8	82.2	33.9	80	64.6
			Response after simulated selection (%)		**-2.0**	**2.5**	**-4.9**	**16.5**	**5.0**	**3.7**	**43.3**
		BAG15	Population mean (N=90)		39.9	79.9	16.0		39.9	79.9	16
			Mean of 10% lines (N=9) selected for SF or GY in exp. BAG16		39.8	82.4	14.6		42.3	837	105.6
			Response after simulated selection (%)		**-0.4**	**3.2**	**-9.0**		**5.9**	**4.8**	**29.7**
II	MJFE17	BFE13	Population mean (N=146)		33.0	79.4					
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17		30.6	77.6					
			Response after simulated selection (%)		**-7.2**	**-2.2**					
		BFE14	Population mean (N=146)		37.4	73.8					
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17		34.1	72.3					
			Response after simulated selection (%)		**-8.8**	**-2.0**					
		BFE15	Population mean (N=146)		42.6	80.3					
			Mean of 10% lines (N=15) selected for SF in exp. MJFE17		39.3	79.4					
			Response after simulated selection (%)		**-7.8**	**-1.2**					

Set of exps.	Selection exp	Response exp.		Response to selection for high SF				Response to selection for high GY			
				SF	GW	TW	GPC	SF	GW	TW	GPC
II (cont)	BFE13	BFE13	Population mean (N=146)	98.4	33.0	79.4		98.4	33	79.4	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13	112.8	31.9	79.3		100.2	32.8	76.6	
			Response after simulated selection (%)		**-3.5**	**-0.13**		**1.8**	**-0.7**	**-3.5**	
		BFE14	Population mean (N=146)		37.4	73.8		92	37.4	73.8	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13		37.5	74.0		94.1	38.3	74.1	
			Response after simulated selection (%)		**0.3**	**0.3**		**2.3**	**2.4**	**0.5**	
		BFE15	Population mean (N=146)		42.6	80.3		89.4	42.6	80.3	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE13		40.4	79.7		90.8	42.1	80.1	
			Response after simulated selection (%)		**-5.0**	**-0.9**		**1.6**	**-1.1**	**-0.4**	
	BFE14	BFE13	Population mean (N=146)		33.0	79.4		98.4	33	79.4	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14		31.8	78.3		102.7	32.8	76.6	
			Response after simulated selection (%)		**-3.6**	**-1.4**		**4.3**	**-0.7**	**-3.5**	
		BFE14	Population mean (N=146)	92.0	37.4	73.8		92	37.4	73.8	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14	109.4	35.4	73.5		101	37	73.9	
			Response after simulated selection (%)		**-5.5**	**-0.4**		**9.9**	**-1.5**	**0.2**	
		BFE15	Population mean (N=146)		42.6	80.3		89.4	42.6	80.3	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE14		40.5	79.4		95.2	40.6	79.2	
			Response after simulated selection (%)		**-4.9**	**-1.1**		**6.5**	**-4.7**	**-1.5**	
	BFE15	BFE13	Population mean (N=146)		33.0	79.4		98.4	33	79.4	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15		31.4	78.8		103.5	33.4	80	
			Response after simulated selection (%)		**-4.8**	**-0.8**		**5.2**	**1.1**	**0.8**	
		BFE14	Population mean (N=146)		37.4	73.8		92	37.4	73.8	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15		33.8	72.9		96.1	37.1	74.5	
			Response after simulated selection (%)		**-9.6**	**-1.2**		**4.5**	**-0.9**	**1.0**	
		BFE15	Population mean (N=146)	89.4	42.6	80.3		89.4	42.6	80.3	
			Mean of 10% lines (N=15) selected for SF or GY in exp. BFE15	103.9	39.5	79.5		95	41.9	80.5	
			Response after simulated selection (%)		**-7.3**	**-1.1**		**6.3**	**-1.5**	**0.2**	

Set of exps.	Selection exp	Response exp.		Response to selection for high SF				Response to selection for high GY			
				SF	GW	TW	GPC	SF	GW	TW	GPC
III	BLE16	BLE16	Population mean (N=28)	81.5				81.5			
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE16	92.9				84.3			
			Response after simulated selection (%)					**3.4**			
		BLE17	Population mean (N=28)					84.5			
			Mean of 10% lines (N=3) selected for GY in exp. BLE16					89.3			
			Response after simulated selection (%)					**5.7**			
	BLE17	BLE17	Population mean (N=28)	84.5				84.5			
			Mean of 10% lines (N=3) selected for SF or GY in exp. BLE17	98.3				80.5			
			Response after simulated selection (%)					**-4.8**			
		BLE16	Population mean (N=28)					81.5			
			Mean of 10% lines (N=3) selected for GY in exp. BLE17					82.8			
			Response after simulated selection (%)					**1.6**			
	BLP17	BLP17	Population mean (N=36)	86.6	35.3			86.6	35.3		
			Mean of 10% lines (N=4) selected for SF or GY in exp. BLP17	104.5	30.3			77.4	36.7		
			Response after simulated selection (%)		**-14**			**-10.6**	**4.0**		
	BLP18	BLP17	Population mean (N=36)					86.6	35.3		
			Mean of 10% lines (N=4) selected for GY in exp. BLP18					84.9	35.3		
			Response after simulated selection (%)					**-1.9**	**0.0**		
			Overall mean response after simulated selection (sets I, II and III; %)		**-5.6**	**-0.5**	**-7.0**	**3.9**	**0.8**	**0.8**	**36.2**

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Table S2. Pearson correlation coefficients between spike fertility index (SF, grains/g), grain yield (GY, g/m^2), grain number per unit area (GN, grains/m^2), grain weight (GW, mg) and test weight (TW, kg/hl), calculated with data from sets of experiments I, II and III. All coefficients are significant (p<0.05) except where noted (ns).

	GY	GN	GW	TW
SF	0.29	0.44	-0.20	0.00$_{ns}$
GY		0.91	0.24	0.28
GN			-0.18	0.19
GW				0.21