Ecophysiological Yield Components In Wheat Cultivars Under Variable Phosphorus Availability

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Abstract— *Effects of P deficiency and interactions Cultivar x P available, on wheat yield and ecophysiological components were analysed, considering that the grain number* m^{-2} *is the product of the length of spike growth period, crop growth rate during this phase, the proportion of growth for spikes (partitioning) and spike fertility (grain number produced per unit of spike dry weight). Four cultivars with different strategy to generate yield (i.e. combinations of ecophysiological yield components) were compared with and without P fertilization, during two years in Azul, Buenos Aires, Argentina. The soil was moderately P deficient (7-9 mg P* kg^{-1} *soil) and P fertilization treatments (50 kg P* ha^{-1}*) were established at sowing. P deficiencies affected yield and most of its components, the exceptions were: partitioning to spike, spike growth period and radiation use efficiency. The interaction Cultivar x P fertilization was not significant in all cases. The lack of interaction between cultivar and P level suggest that improvements in any crop physiological component will express in both, moderately deficiencies or high P environment.*

Keywords— Ecophysiological yield components, P deficiency, stability yield components.

I. INTRODUCTION

The Phosphorus (P) is one of the most limiting macronutrients for crop production (Ziadi et al., 2013) and today, in many areas of the world it is one of the highest-cost inputs used by farmers to achieve profitable crop yields (Ryan et al., 2012). Under current production conditions there is concern about making a more rational use of P fertilizer application (Ryan et al., 2012). The development of P-efficient crop varieties that can grow and yield better with low P supply is a key in improving crop production. However, current conventional breeding strategies are mainly implemented through yield selection under high fertility soils. Wissuwa et al. (2009) concluded that modern varieties have often been selected under high nutrient input conditions in order to obtain high yield. These varieties may not be the most suitable for conditions of low P supply.

On the other hand, wheat cultivars have different strategies (i.e. combinations of yield crop physiological components) to generate yield. The differences between cultivars would be attributed to a grain number m^{-2} (GN) and/or grain weight. According to Fischer (2007) the GN is a direct function of spike dry weight (SDW) and spike fertility (SF). The SDW is defined as the product of spike growth period (SGP) and the spike growth rate (SGR). The spike growth rate is defined by product of the crop growth rate (CGR) and the proportion assigned to spike (partitioning). Finally, the CGR is the product between the intercepted solar radiation and the radiation use efficiency. Differences between cultivars have been found in: (1) partitioning (Fischer & Stockman, 1986), (2) spike fertility (Abbate et al., 1998; Lázaro & Abbate, 2012), (3) CGR (Montenegro, 2001), (4) RUE (Shearman et al., 2005) and (5) grain weight (Sayre et al., 1997). However, the relative impact that P deficiencies, has on these yield components in different genotypes is not well known. Various authors (Rosa & Camargo, 1991; Manske et al., 2000; Egle et al., 1999 and Manske et al., 2001) found differences in the absorption and utilization of P using different cultivars, but they did not explore the yield components in detail. Gutheim et al. (2001) in the Pampas region of Argentina and Batten et al. (1984) in Australia analyzed the responses to P fertilization of wheat genotypes and did not find genotype x P level fertilization interaction for yield. These authors observed that modern semi-dwarf cultivars had higher yield in both, high and low P, and that these increases were due to a greater GN. However, these studies do not show whether this behaviour is due to a high stability of all GN ecophysiological components or only to some strong interactions cultivar x P availability. On the other hand, Lázaro et al. (2010) and Sandaña & Pinochet (2011) studied the effects of P deficiencies in ecophysiological components but they used only one cultivar. Previous investigations have not analysed in depth whether the effects of P deficiencies differ between wheat cultivars that have different strategies (combinations of yield crop physiological components) to generate yield.

Knowing the stability of physiological attributes to different stress situations, such as P deficiency, can contribute to germplasm improvement, since that can help choose physiological attributes that have an advantage in cropping situations to be transferred to top lines.

This study evaluated whether cultivars with different strategies to generate yield respond similarly to P status, i.e. if yield and crop physiological components are stable to changes in P availability. It should be clarified that stability refers to a dynamic agronomic concept, where the adaptability of a genotype depends, largely on a linear response to environmental variables (Flores et al. 1998). Therefore, a cultivar is stable if its yield is parallel, respect at mean yields of all cultivars in a range of environments of availability P.

II. MATERIAL AND METHOD

Two experiments were carried out at the Experimental Field of Facultad de Agronomía, Azul, Buenos Aires, Argentina (36° S, 60° W, altitude 137 m a.s.l.) during the 2000/01 (Expt 1) and 2001/02 (Expt 2) growing seasons. The soil was a loamy, illitic, thermic, typical Argiudoll (USDA Soil Taxonomy 2003) with 4.9 g organic matter kg^{-1} soil in the top 20 cm and adequate K fertility (>2.4 mmol $100g^{-1}$). The extractable P concentration in soil (Bray I) was 7 mg P kg^{-1} in Expt 1 and 9 mg P kg^{-1} in Expt 2; these levels are deficient for P, according to critical values for wheat in the Pampas region (García & Berardo, 2006).

The experiments combined cultivars (as main treatments) and two P fertilization levels (low and high as sub-treatments) in a split-plot design with four complete randomized blocks. In these experiments, cultivars with different strategies to generate yield were compared, three spring bread wheat cultivars (Bacanora, Granero INTA, and Buck Ombú) and one spring durum wheat cultivar (Buck Ámbar). Bacanora is known for its high spike fertility index and GN (Sayre et al., 1997; Lázaro & Abbate 2012), Granero by their high partitioning to spike, Ombú by high grain weight and low yield stability and Ámbar by long SGP and grain weight (Lázaro & Abbate, 2012). The results of high P treatments reported in the present paper have been partiality presented previously (Lázaro & Abbate, 2012), but without analyze effects of P deficiencies. The low P level treatments were not fertilized but the high P treatments were fertilized with 50 kg P ha^{-1} as calcium triple superphosphate (0-46-0) in order to ensure non-limiting P availability for crop growth. The P fertilizer was broadcast and incorporated before sowing. The experiments were irrigated, and fertilized with N (200 kg ha^{-1}) as urea (46-0-0) to provide adequate water and N supply. The experiments were free of pests and diseases. The sowing dates were 8 Aug 2000 and 9 Aug 2001 for Expt 1 and Expt 2, respectively, with a density of 350 pl m^{-2}. Each experimental unit consisted of a subplot with 1.4 m wide (seven rows distanced 0.2 m) by 6.0 m long.

Emergence date was considered as the date when half of the plants had their first leaf emerged to approximately 2 cm. Anthesis date was defined as the day on which half of the spikes showed at least one spikelet with an extruded anther. The proportion of spikes at anthesis was computed in 40-50 spikes per plot every 2-3 days, and anthesis date was calculated by linear interpolation of anthesis proportion on calendar time.

The spike growth period (SGP) was computed as the interval during which the spikes weight achieved from a proportion of 0.05 to 1.00 of the non-grain weight that the spike had accumulated until day 7 after anthesis.

Crop and spike dry weights were measured twice around the beginning of the SGP, also at the end of the SGP (7 days after anthesis), and after physiological maturity. Sample size was five innermost rows wide and 50 cm long before anthesis and 70 or 100 cm long after anthesis. A distance of at least 0.35 m was left as borders between adjacent sampling quadrants. A subsample of 20 shoots was dissected into leaf lamina stems (including leaf sheaths) and spikes, when they were higher to 0.5 cm length. At the final sampling of the SGP, the immature grains were removed in a subsample of spikes to determine the dry weight of non-grain spikes. All the weights are expressed on a dry basis.

The crop dry weight at the beginning of SGP was estimated by linear interpolation of crop dry weight throughout calendar time. During the SGP, mean growth rates (g m^{-2} d^{-1}) of crop (CGR) and spikes (SGR) were calculated as the increased of dry weight divided by the number of days between sampling, and mean dry weight partitioning to spikes was calculated as SGR/CGR and expressed as a percentage. Radiation-use efficiency (RUE, g MJ^{-1}) was calculated as the ratio between CGR and the mean IPAR during the SGP.

The daily proportion of incident photosynthetically active radiation (PAR = 0.5 of total radiation) intercepted by the crop (Ri) was calculated as Ri = 1 - PARi/PARo, where PARi was the incident PAR just above the lowest layer of dead leaves, and PARo was the incident PAR above the crop canopy. The values of PARi and PARo were measured with a line quantum sensor of length equal to four inter-rows. The measurements were taken at midday, placing the sensor perpendicularly to the rows. Approximately one recording per meter of plot was taken. Ri was measured every 10 to 15 days from the beginning of the spike growth. The Ri between measurements was obtained by linear interpolation over calendar time. Intercepted PAR (MJm^{-2} d^{-1}) for each day was calculated as the product of the corresponding daily IPAR fraction and daily incident PAR.

After physiological maturity, plots were hand-harvested and all spikes of the sample were threshed. The grains were winnowed and afterwards dried and weighed to determine yield. A grain subsample of approximately 1000 grains was taken and manually cleaned, and all grains were counted, dried and weighed to determine dry weight/grain. The GN was calculated by dividing yield by the dry grain weight. The P concentration in the crop dry weight (i.e. biomass) and grains after physiological maturity was determined according to Jackson (1964) after wet digestion of plant material with a mixture of acids (nitric-percloric 3:2). Determinations were made on a subsample of non-grain biomass and mature grains. The spike fertility (SF) was calculated as quotient between GN (measured at maturity) and SDW measured at the end of SGP.

Weather records, on a daily basis, were obtained from a standard meteorological station not further than 500 m from the experimental sites. Mean temperature and incident PAR between July and December 2000 and 2001 and historic values in Azul are presented in Table 1.

The data for each year were analyzed through a variance analysis (ANOVA) which included the effect of the principal treatment (cultivars), the effect of sub-treatment (P availability), and their interaction. To evaluated year effect, data of the two experiments were combined in an ANOVA with year as a fixed factor. Differences between treatment means were established by the least significant difference, when the variance analysis revealed significant differences. The contribution of each variance component to the total square sum of model considering years, cultivar, fertilization level, and their interactions was also calculated for each variable.

The stability of yield and its components for each cultivar were analyzed by the Finlay & Wilkinson´s (1963) methodology based on linear regression. This method defines an environmental index (EI) calculated from the mean of all genotypes in each environment. It uses the regression coefficients of linear relationships between the value in each environment of each genotype and the EI as a stability measure of the genotype. With this methodology, a cultivar with slope equal to 1 has a response to P fertilization equal to the mean of all cultivars; thus, this would be a very stable cultivar. All regressions were calculated with the data of the mean of each treatment. Regressions were computed for each cultivar separately, but when multiple comparisons of individual regression coefficients revealed no significant differences between slopes or intercepts, the pooled mean slope or intercept was calculated by weighting of each slope or intercept for the sum of squares of their independent variables (pooled regression). The critical level of significance used was $P < 0.05$ in all statistical tests.

III. RESULTS AND DISCUSSION

Both years were climatically very different, as suggested by the incident solar radiation and temperature during crop cycle (Table 1). These differences determined that the crop dry weight (CDW) at maturity and yield were greater in Expt 1 (Table 2). Effects of P deficiency on CDW at maturity were significant both years (Table 2). In Expt 1, CDW in P deficiency treatments were 15% lower than in fertilized plots, while in Expt 2 these differences were greater 21 % (Table 2). P uptake (PT) was also affected by P deficiencies; the differences in total P uptake until maturity between treatments with and without fertilization were 28% and 24% for Expt 1 and Expt 2, respectively (Table 2).

Grain yield was affected by P deficiency in both experiments; decrease was 10% and 17% in Expt 1 and 2, respectively. Decrease in yields as a result of P deficiency was mainly associated with reductions of in GN ($r^2 = 0.66$; D.F. = 6; $P \leq 0.05$). Grain weight was not affected by P deficiency (Table 2), but varied between years and cultivars; Bacanora had the lowest weight and Ámbar was the cultivar with highest weight (Table 2).

The SF increased with P deficiency, although this effect was much clearer in Expt 2 than in Expt 1, and differences between cultivars were evident in both experiments, Bacanora presented the highest value (26% above general mean) and Ámbar the lowest (27% below general mean) (Table 3).The SDW at the end of their growth period (i.e. one week after anthesis) was affected by P deficiencies. The reduction was 10% (mean of all cultivars) in Expt 1 and 27% in Expt 2 (Table 3). On the other hand, SDW between cultivars were different, Ámbar had the greatest SDW (Table 3) also the highest SGR and SGP. The SDW was associated linearly with SGR ($r^2 = 0.66$; D.F. = 14; $P \leq 0.001$), and with SGP ($r^2 = 0.58$; D.F. = 14; $P = 0.001$) combining data of cultivars, P levels and experiments.

P deficiency affected SGR, in Expt 1 the reduction was 8%, while in Expt 2 this reduction was greater (23%). Moreover, the SGP was 27 days (general average) and although differences among cultivars were found, Bacanora was the shortest (25 d) and Ámbar the longest (29 d), P deficiencies did not affect the duration of the period. The partitioning to spike was close to 30% (general mean) without differences between cultivars or P levels (Table 3).

P deficiencies affected CGR during the SGP; the rate declined 7% in Expt 1 and 23% in Expt 2, but was similar between cultivars (Table 3). Although the crop dry weight reached at end of SGP was different between cultivars, Ámbar was the cultivar that accumulated more biomass, followed by Ombú, Granero and Bacanora. The effect of P deficiency on crop grow at the beginning of SGP was higher than at the end; CDW fell 31% in the non-fertilized treatment respect to the P fertilized treatment at beginning of SGP. Finally, RUE was not affected by P deficiencies and cultivars (Table 3).

For all variables analyzed interaction cultivar x P not was significant and the interaction of cultivar x year was significant in a few cases (Fig. 1). This indicates a high stability to the P availability for cultivars over two seasons. The stability of yields and its components (GN and GW) for the four cultivars, evaluated through different environments generated from differences due to effects on P deficiencies and years are shown in Table 5. RUE and partitioning to spike were exempted from the analysis, because the level of P did not affect these variables. The cultivars had no differences in stability (slopes), except for GN and PARi (Table 5). The stability of GN and PARi were different between cultivars; Bacanora presented slopes greater than 1, while Ombú had an opposite behavior. Bacanora was a cultivar that produced high yields from a high GN (Sayre *et al.*, 1997) through a high SF (Lázaro & Abbate, 2012) and had the highest response in GN when the EI improved, as showed their slope greater than 1 (Table 5).

To get a better idea of what is the importance of P deficiencies on cultivar stability, the ratio of sum of squares of P deficiencies, to the sum of squares of environment (sum of years and P effects) was calculated for yield and their main component and subcomponent of GN (Fig. 2). Except for SGR, the P level contributed less than 50% at environment sum. In these experiments, all cultivars produced higher yield under high P availability, but response to P was moderate with respect to others experiments reported in the literature, that reached around 45% (Lázaro *et al.*, 2010; Melchiori *et al.*, 2004; Manske *et al.*, 2001; Elliot *et al.*, 1997). The moderate response to P fertilization in Azul can be attributed to moderate soil P deficiency; the soil Bray I P concentration in Azul was somewhat higher (between 7 and 9 mg kg^{-1}) than in other previous experiments (Lázaro *et al.*, 2010; Melchiori *et al.*, 2004; Manske *et al.*, 2001; Elliot *et al.*, 1997). However, soil P values of present experiments are typical of the current conditions in the Pampas region. The cultivars differed in yield, although these differences were less apparent in P deficient treatments than in high P availability although the interaction cultivar x P was not significant (Table 2, Fig. 1). Other studies also show the same trend (Batten *et al.*, 1984; Gutheim *et al.*, 2001; Manske *et al.*, 2001; Melchiori *et al.*, 2004). It has been rarely reported that cultivar x P interaction showed significant values, and only Elliot *et al.* (1997) reported a strong interaction cultivar x P, which was caused by differences in yield on high P, while with low P the cultivars did not differ. Manske *et al.* (2001) found that among phenotypic interactions for yield, cultivar x location interaction was more dominant than cultivar x P interaction. In the present experiments, cultivar x P interaction was not important compared with other interactions (Fig. 1). In Australia, Batten *et al.* (1984) analyzed the responses of various wheat genotypes to P fertilization and found that modern semi-dwarf cultivars had higher yield in high as well as low P, and these increases were due to higher GN. On the other hand, P deficiencies did not change significantly the grain weight in any cultivar (Table 2). It can be concluded, then, that there were no cultivars that excelled in yield under low P.

The GN was the yield component that was mostly modified by the effect of differences in P availability, even in cultivars with high grain weight, (e.g. Ombú and Ambar, Table 2). Lázaro *et al.* (2010) and Sandaña & Pinochet (2011), both with only one cultivar, demonstrated that P deficiency decreased yield through GN, since it mainly affected SDW, because of lower SGR, CGR and the amount of radiation intercepted during SGP; with little or no effect on SF, partitioning, duration of SGP, and RUE. These authors found that the functional relationships between GN and SDW, SDW and SGR, SGR and CGR, and CGR and PARi did not change by effects of P deficiencies. Based on GN vs. SDW regressions without nutrient deficiencies from Lázaro & Abbate (2012) for the four cultivars analyzed, the GN and SDW data pairs of low P treatments could be situated within general regressions of each cultivar (Table 4). These results are in accordance with those found in previous work (Lázaro *et al.*, 2010; Sandaña & Pinochet, 2011) where P deficiencies decreased GN by falls in SDW, maintaining the same GN and SDW relationship, independently of stress factor (radiation intercepted or P deficiencies) that caused a decrease of SDW of each cultivar. The exception was the datum of Ombú in Expt 2 where GN fell less than estimated (Esta tabla no está en el trabajo.).

The SF increased 9 % under P deficiency (mean two experiments, Table 3). For Oasis cultivar, changes in SF were observed when growth slowed due to the effect of shading but not by P deficiencies (Lázaro *et al.*, 2010). However, the differences between cultivars in SF were stable to changes in the environment generated by P deficiencies or by the year effect. This confirms the results of Lázaro & Abbate (2012) who observed in these cultivars an increase in SF when crop growth was reduced during the SGP. However, increases in SF would not compensate the declines in SDW due to shading or P deficiency. On the other hand, SDW just before the start of filling (excluding the weight of grains) is the result of SGP and SGR. P deficiencies had no marked effects on length of this stage (Table 3). Elliot *et al.* (1997) found important delays in anthesis date only in very severe P deficiency, but most of the literature agrees that effects on development at a stage, close to SGP are small (Rodriguez *et al.*, 2000; Sandaña & Pinochet, 2011). Other nutrient deficiencies (N or S) did not produce great effects on this development stage either (Fischer 2007; Salvagiotti & Miralles, 2008). The SGR was one of components affected by P deficiency (Table 3), which determined a decrease in SDW. The partitioning to spike was similar between cultivars (mean value 30%). Differences in partitioning by P availability were not evident (Table, 3) unlike that observed with Oasis cultivar at Balcarce (Lázaro *et al.*, 2010) where the partitioning increased with P deficiencies. However, in the mentioned paper, CGR fell 67 % as a result of P deficiencies, but in the present work CGR decreased only 14 % with P deficiencies (mean of all cultivars, Table 3). RUE remained unchanged despite P deficiencies. Sandaña & Pinochet (2011) also found no differences in RUE between treatments with and without P. These authors also combined data from several studies and concluded that changes in RUE were only detected under severe P deficiencies, when reductions in yield or crop growth are greater than 40%. This happened in experiments analyzed by Rodriguez *et al.* (2000) and Lázaro *et al.* (2010), but not with moderated P deficiencies of our Azul experiments.

While there are numerous methods to study yield stability, the methods of Finlay and Wilkinson (1963) used in this work were largely appropriate for the data available. One of the most severe criticisms of this type of analysis is that it assumes a linear response of genotypes to environments. In our case, this assumption was met, except for RUE and partitioning, variables that did not change by environmental effects, a situation in which the stability analysis is meaningless.

Yield and grain weight stability across environments were very high for all cultivars (no significant differences among slopes, Table 5), whereas, for GN they were more variable (significant differences among slopes, Table 5). The contribution of interactions to total variation was not of great weight, although some were significant (Fig. 1). The clearest interactions, were for SDW and PARi but only in cultivar x year, variables for which the regression in function of the environmental index indicated differences in stability between cultivars (Table 5). The interactions involving cultivar and P (Fig. 1, Tables 3 and 4) were not significant in any of the variables analyzed. This suggests that the variables in question are highly stable, in particular to changes in the P availability. Furthermore, effects of P deficiencies, cultivar and year on RUE or partition to spike were not significant (Table 5). The relationships between GN and its components throughout cultivars were not affected by P deficiencies. Then, P deficiencies operated negatively on PARi, CGR, SGR, SDW and GN; while the RUE, partitioning, SGP and grain weight remained unchanged at moderate stress levels, while the SF increased slightly cushioning the effects of the above. This may be related to the fact that different plant physiological processes have different sensitivity to stress, as with water (Hsiao *et al.*, 1976) or N (Greenwood, 1976) stress. In this sense, Manfreda & Cogliatti (2006) calculated the critical P concentration in individual plants for different growth parameters and found that the most sensitive parameters were aerial biomass and leaf area growth rates, whereas, allometric parameters such as root/stem ratio were more conservative. Among them, the net assimilation rate was the one with lowest critical level. Manfreda & Cogliatti (2006) classified the P deficiencies into several categories: 1) non deficient, when the plants have all growth parameters with in maximum values, 2) moderate, when only the biomass growth rate is below maximum, and 3) severe, when the relative growth rate and net assimilation rate is less than maximum. The existence of different sensitivity levels helps to explain why moderate deficiencies did not affect the RUE related to the net assimilation rate or partitioning and SF that are relative parameters.

Grain weight and most of GN components showed high stability to P availability (Table 5). The Fig. 2 shows that P level contribution on environmental sum of squares of physiological components was less than 50% except SGR, which was slightly higher. The stability of GN and PARi were different between cultivars, Bacanora filed a response to EI higher than the average of the cultivars in both variables. None of the variables analyzed had interaction cultivar x P and the rest of interactions, were also low, so low stability in these variables was due to responses to year and not to P. It was not possible to identify cultivars that represent a clear advantage in terms of P deficiencies Bacanora can be identified as a cultivar that has a clear advantage in high yield environments because of its high GN and SF.

IV. FIGURES AND TABLES

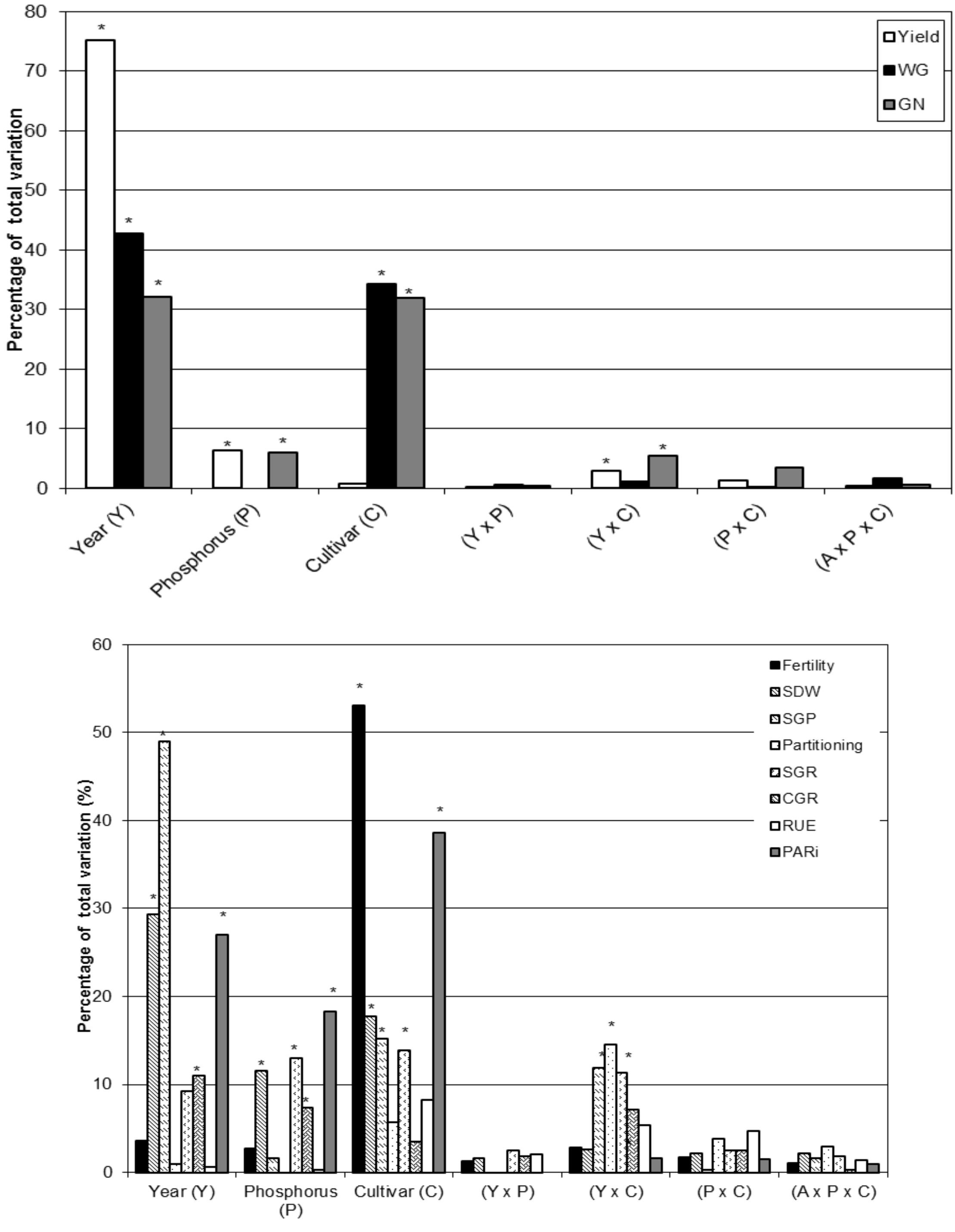

FIGURE 1. A) PERCENTAGE OF TOTAL VARIATION CONTRIBUTED BY THE MAIN EFFECTS OF YEAR (Y), PHOSPHORUS (P), CULTIVAR (C) AND THEIR INTERACTIONS FOR A) YIELD, GRAIN NUMBER (GN) AND GRAIN WEIGHT (WG). B) GRAIN NUMBER SUBCOMPONENTS: SPIKE FERTILITY (FERTILITY), SPIKE DRY WEIGHT (SDW), SPIKE GROWTH PERIOD (SGP), PROPORTION OF CROP GROWTH ASSIGNED TO SPIKE DURING SGP (PARTITIONING), SPIKE GROWTH RATE (SGR), CROP GROWTH RATE (CGR), RADIATION USE EFFICIENCY (RUE) AND INTERCEPTED PHOTO-SYNTHETICALLY ACTIVE RADIATION (FOR TWO EXPERIMENTS, AT AZUL, BUENOS AIRES, ARGENTINA). THE * INDICATE SIGNIFICANT EFFECTS ON THE ANALYSIS OF VARIANCE ($P \leq 0.05$).

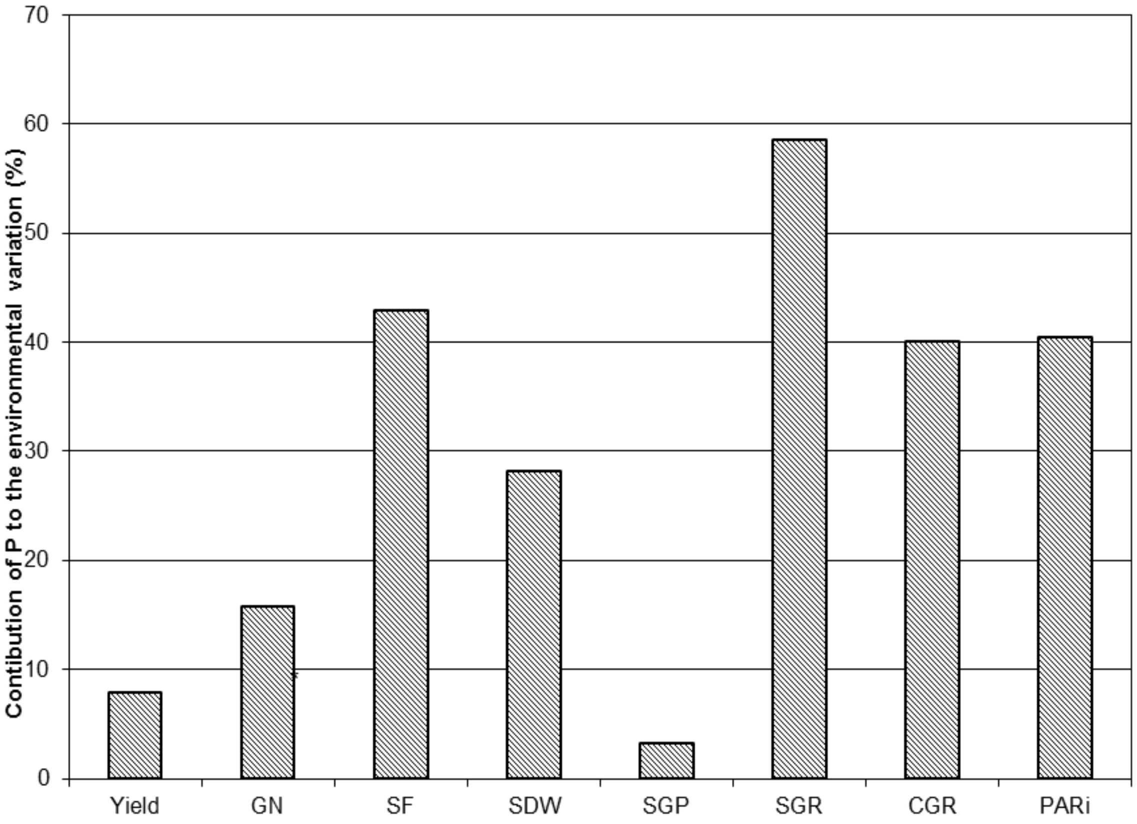

FIGURE 2. SUM OF SQUARES OF P, AS A PERCENTAGE OF THE SUM OF SQUARE OF ENVIRONMENT (SUM OF SQUARES OF YEARS AND P EFFECTS) FOR YIELD (YIELD), GRAINS NUMBER (GN), SPIKE FERTILITY (SF), SPIKE DRY WEIGHT (SDW), DURATION OF SPIKE GROWTH PERIOD (SGP), SPIKE GROWTH RATE (SGR), CROP GROWTH RATE (CGR) AND INTERCEPTED PHOTO-SYNTHETICALLY ACTIVE RADIATION (PARI). VARIANCE COMPONENTS ARE DATA FROM COMBINING TWO EXPERIMENTS, AT AZUL, BUENOS AIRES, ARGENTINA.

TABLE 1.
MEAN TEMPERATURE AND INCIDENT PAR (PHOTOSYNTHETICALLY ACTIVE RADIATION) BETWEEN JULY AND DECEMBER 2000 AND 2001 AND HISTORIC VALUES IN AZUL, BUENOS AIRES, ARGENTINA.

	Year	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Mean Temperature (°C)	**2000**	5.2	7.6	10.0	13.1	15.3	19.3
	2001	6.4	11.0	10.9	15.3	16.4	19.5
	Historical*	6.7	9.0	10.9	14.0	16.7	19.7
Incident PAR (MJm^{-2}d^{-1})	**2000**	4.8	6.4	7.6	9.8	13.4	16.2
	2001	3.6	4.6	6.6	7.5	13.2	12.5
	Historical*	3.9	5.2	7.5	10.0	11.8	12.4

*** Mean of 1994-2011 period (Centro Regional de Agrometeorología, FA, UNCPBA).**

Table 2.
Total crop dry weight (CDW), P uptake (PT), yield and their components: grain number (GN) and grain weight (WG), at maturity for four wheat cultivars (Bacanora, Granero INTA, Buck Ambar and Buck Ombú) with (+P) and without (-P) fertilization in two experiments at Azul, Buenos Aires, Argentina.

Cultivar		CDW (g m^{-2})		PT (g m^{-2})		Yield (g m^{-2})		GN (grains m^{-2})		WG (mg)	
		+P	-P	+P	-P	+P	-P	+P	-P	+P	-P
Bacanora	Exp. 1	2076	1714	5.8	4.3	883	772	23439	20689	39.7	37.3
Granero		2058	1586	5.8	3.8	789	655	19215	16469	40.0	41.1
Ámbar		1938	1769	7.5	4.7	754	761	15349	15457	49.5	52.6
Ombú		1994	1801	5.9	5.2	773	689	16040	16412	43.8	46.3
Bacanora	Exp. 2	1410	1027	3.0	2.4	511	400	17369	13663	29.1	29.5
Granero		1529	1262	3.2	3.2	537	466	16127	13752	33.2	33.9
Ámbar		1512	1332	3.2	2.0	481	438	11592	11523	41.5	38.0
Ombú		1615	1196	3.4	2.1	538	417	15059	12741	35.9	33.7
Mean	Bacanora	1743	1370	4.40	3.35	697	586	20404	17176	34.40	33.4
Mean	Granero	1793	1424	4.50	3.50	663	560	17671	15110	36.60	37.5
Mean	Ámbar	1725	1550	5.35	3.35	617	599	13470	13490	45.50	45.3
Mean	Ombú	1804	1498	4.65	3.65	655	553	15549	14576	39.85	40.0
Mean	Exp.1	2017	1718	6.3	4.5	800	719	18511	17257	43.3	44.3
Mean	Exp.2	1517	1204	3.2	2.4	517	430	15037	12920	34.9	33.8
Mean	Year	1867	1360	5.4	2.8	760	474	17884	13978	43.8	34.4
S.E.M. (1 D.F.)[1]		66.9		0.11		19.3		771		0.8	
S.E.M. (1 D.F.)[2]		66.9		0.11		19.3		1294		-	
S.E.M. (3 D.F.)[3]		-		0.33		-		1758		1.4	
Year		*		*		*		*		*	
P		*		*		*		*		ns	
C		ns		*		ns		*		*	
Y x P		ns		ns		ns		ns		ns	
Y x C		ns		ns		*		*		ns	
P x C		*		ns		ns		ns		ns	
Y x C x P		ns		ns		ns		ns		ns	

[1]: SEM: Standard error of mean differences of year. D.F.; degrees of freedom. [2]: SEM: Standard error of mean of P level. [3]: SEM: Standard error of mean of cultivars. SEM only showed if means differences are significant. * P value from ANOVA F-test significative ($P \leq 0.05$), ns: ($P > 0.05$). Y: year; P: Phosphorus; C: Cultivar.

TABLE 3.
CROP TOTAL DRY WEIGHT (CDWb) AT BEGINNING OF SPIKE GROWTH PERIOD, AND SPIKE FERTILITY (SF) AND SPIKE DRY WEIGHT (SDW, EXCLUDING GRAIN WEIGHT), AT THE END OF SPIKE GROWTH PERIOD (SGP); SPIKE GROWTH RATE (SGR), PARTITIONING TO SPIKES (PART), CROP GROWTH RATE (CGR) AND RADIATION USE EFFICIENCY (RUE) DURING THE SGP, FOR FOUR CULTIVARS WITH (+P) AND WITHOUT P (-P) FERTILIZATION IN TWO EXPERIMENTS, AT AZUL, BUENOS AIRES, ARGENTINA."

		CDWb ($g\ m^{-2}$)		SF (grains g^{-1})		SDW ($g\ m^{-2}$)		SGR ($g\ m^{-2}\ d^{-1}$)		Part (%)		CGR ($g\ m^{-2}\ d^{-1}$)		RUE ($g\ MJ^{-1}$)		SGP (d)	
Cultivar		+P	-P	+P	-P	+P	-P	+P	-P	+P	-P	+P	-P	+P	-P	+P	-P
Bacanora	Expt1	1448	1080	104	100	227	209	7.9	7.6	27	28	29	28	2.5	2.8	27	26
Granero	Expt1	1380	1198	84	84	233	198	7.5	6.6	33	28	23	25	2.0	2.5	30	28
Ámbar	Expt1	1646	1352	59	65	275	250	8.1	7.2	27	28	31	26	2.3	2.1	33	33
Ombú	Expt1	1386	1254	75	82	215	200	7.2	6.7	29	34	26	22	2.2	2.1	28	28
Bacanora	Expt2	975	612	109	121	160	114	6.3	4.6	33	25	22	19	2.2	2.5	24	24
Granero	Expt2	939	700	102	104	159	133	5.8	4.8	27	28	22	18	2.2	2.0	26	26
Ámbar	Expt2	1233	796	45	76	260	156	9.5	6.4	37	42	26	17	2.2	1.6	26	23
Ombú	Expt2	1113	832	81	88	189	159	7.3	6.4	26	29	29	22	2.7	2.4	25	24
Mean	Bacanora	1212	846	107	111	194	162	7.1	6.1	30	27	26	24	2.4	2.7	26	25
Mean	Granero	1160	949	93	94	196	166	6.7	5.7	30	28	23	22	2.1	2.3	28	27
Mean	Ámbar	1440	1074	52	71	268	203	8.8	6.8	32	35	29	22	2.3	1.9	30	28
Mean	Ombú	1250	1043	78	85	202	180	7.3	6.6	28	32	28	22	2.5	2.3	27	26
Mean	Expt1	1465	1221	81	83	238	214	7.7	7.0	29	30	27	25	2.3	2.4	30	29
Mean	Expt2	1065	735	84	97	192	141	7.2	5.6	31	31	25	19	2.3	2.1	25	24
Mean	year	1343	900	82	91	226	166	7.4	6.4	29	31	26	22	2.3	2.2	29	25
S.E.M.[1]		19.6		2.4		6.7		0.1		-		1.6		-		0.4	
S.E.M.[2]		19.6		2.4		6.7		0.1		-		1.6		-		-	
S.E.M.[3]		55.1		5.7		12.8		0.5		-		-		-		0.6	
Y		*		*		*		*		ns		*		ns		*	
P		*		*		*		*		ns		*		ns		ns	
C		ns		*		*		*		ns		ns		ns		*	
Y x P		*		ns		ns		ns		ns		*		ns		ns	
Y x C		ns		ns		ns		*		ns		ns		ns		*	
P x C		ns		ns		ns		ns		ns		ns		ns		ns	
Y x C x P		ns		ns		ns		ns		ns		ns		ns		ns	

SEM: Standard error of mean differences of year. [2]SEM: Standard error of mean of P level. [3]SEM: Standard error of mean of cultivars. SEM only showed if means differences are significant. * P value from ANOVA F-test significant ($P \leq 0.05$) ns: ($P>0.05$) Y: year; P: Phosphorus; C: Cultivar.

TABLE 4

COMPARISON BETWEEN OBSERVED GRAIN NUMBER *(GNo)* OF LOW P TREATMENTS IN EXPERIMENTS 1 AND 2 AND ESTIMATED GRAIN NUMBER *(GNe)* FROM LINEAR REGRESSIONS BETWEEN GRAIN NUMBER m^{-2} AND SPIKE DRY WEIGHT (SDW) GENERATED WITH TREATMENTS WITHOUT P LIMITATIONS *(Lázaro&Abbate, 2012)* FOR FOUR WHEAT CULTIVARS (Bacanora, Granero INTA, Buck Ámbar and Buck Ombú). SE: STANDARD ERROR OF NGO; PROB.: PROBABILITY OF EQUAL BETWEEN *NGo* AND GNe.

Cultivar	P	Expt	GNo	SE	GNe	SDW	Prob.
			(num m^{-2})			(g/ m^{-2})	
Bacanora	low	1	20688	530	20996	209	0.99
	low	2	13663	655	15450	114	0.98
Granero	low	1	15725	530	15769	198	0.99
	low	2	13752	655	13247	133	0.99
Ámbar	low	1	14920	530	13517	250	0.97
	low	2	11523	655	9493	156	0.96
Ombú	low	1	15699	530	15536	200	0.84
	low	2	12741	655	13074	159	0.68

TABLE 5

COMPARISONS OF LINEAR REGRESSIONS OF WHEAT CULTIVARS: BACANORA (BA), GRANERO INTA (GR), BUCK ÁMBAR (AM) AND BUCK OMBÚ (OM) BETWEEN (VARIABLE Y) YIELD, GRAIN NUMBER M^{-2} (GN), GRAIN WEIGHT (WG), SPIKE FERTILITY (SF), SPIKE DRY WEIGHT (SDW), SPIKE GROWTH RATE (SGR), AND PHOTOSYNTHETIC ACTIVE RADIATION INTERCEPTED (PARI) AND THEIR ENVIRONMENT INDEX (EI, VARIABLE X), THROUGH TREATMENTS WITH AND WITHOUT P FERTILIZATION IN TWO EXPERIMENTS, AT AZUL, BUENOS AIRES, ARGENTINA.

Variable Y	Probability of differences between cultivars for			Slope and r for cultivar individual regression[1]							
	Regression	Slope	Constant	Ba		Gr		Am		Om	
Yield (gm^{-2})	0.02	0.056	0.624	1.30	0.99	0.81	0.98	0.98	0.98	0.91	0.99
WG (mg)	0.001	0.145	0.001	0.94	0.96	0.73	0.98	1.23	0.98	1.10	0.99
GN (10^{3} m^{-2})	0.001	0.001	0.001	1.71	1.00	0.85	0.94	0.82	0.91	0.62	0.93
SF (grains g^{-1})	0.001	0.921	0.001	1.09	0.93	1.15	0.76	1.12	0.66	0.65	0.90
SDW (g m^{-2})	0.001	0.214	0.001	1.21	0.98	1.02	0.96	1.20	0.93	0.57	1.00
SGR (g m^{-2} d^{-1})	0.180	0.504	0.063	1.48	0.91	1.11	0.88	1.02	0.70	0.39	0.89
CGR (g m^{-2} d^{-1})	0.271	0.258	0.327	1.25	0.89	0.79	0.90	1.54	1.00	0.42	0.46
PARi(MJm^{-2}d^{-1})	0.001	0.039	0.001	1.41	0.99	0.97	0.98	0.81	0.98	0.81	0.99

[1]Slope of correlation (left) and coefficient of linear correlation (r) of each cultivar (right).

V. CONCLUSION

Phosphorus deficiencies operated in similar way on cultivars with different strategies to generate yield. Responses to P deficiencies are negative for PARi, CGR, SGR, SDW and GN, while the other components remained unchanged (RUE, partitioning, duration of SGP and grain weight) and even SF increased slightly. All variables analyzed (yield, weight per grain, GN and components) are very stable among cultivars under contrasting P availability, since the interactions cultivar x P were not significant, moreover none of the interactions involving P was important. Only interaction cultivar x year was significant in some few cases (GN, SGP, PARi) and stability between cultivars was different because they responded differently to year effects but not to P effects. The results support the idea that breeding programs in high or low P availability can be developed, and that any ecophysiological component can be improved under any condition since cultivar x P interactions were low in all components.

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