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Response of Winter Wheat Cultivars to Crop Management and Environment in Post-registration Trials

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Abstract

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In order to deliver essential information related to flexible cultivar recommendations, the cultivars which have been released have to be evaluated under different crop management treatments across agro-ecosystems using two-factorial post-registration multi-environment trials. The objective of this study was to evaluate the yield adaptive patterns of 24 winter wheat cultivars tested across 20 trial locations and three consecutive cropping seasons. The evaluated winter wheat cultivars from many Western European countries and Poland showed different adaptive responses to the Polish agro-ecosystems under each of the crop management intensities. Under the high-input management, the cultivars Rapsodia, (UK) Bogatka and Nadobna (Poland) showed a wide adaptation. The cultivars Alcazar (France), Anthus (Germany), Batuta (Poland) and Boomer (UK) were the best adapted to lower-productive environments and poorly adapted to highly productive conditions under both management treatments.

Keywords: AMMI analysis; ANOVA mixed model; cluster analysis; cultivar adaptations; G × E interactions

In order to deliver essential information related to flexible cultivar recommendations, the cultivars which have been released have to be evaluated under different crop managements across agro-ecosystems using two-factorial post-registration multi-environment trials (Przystalski *et al*. 2008; Anderson *et al*. 2011). Such a multi-environment trial (MET) system is called in Poland the Post-registration Variety Testing System (PVTS). The primary aim of this MET system is to assess agronomic performance and management adaptation of cultivars in main field crops recently released in the Polish National List or in the Common Catalogue of Varieties of Agricultural Plant Species.

In agronomical studies the value of a crop cultivar for cultivation in a growing region under crop management is defined through its performance for yield relative to other (especially prominent commercial) cultivars tested across environments and the management systems of interest (Annicchiarico 2002; Gan *et al*. 2007; Loyce *et al*. 2008). This cultivar response for yield to environments or management practices is called the cultivar adaptive response to environments (Annicchiarico 2002) or to crop management (Gan *et al*. 2007), respectively.

The objective of this study was to evaluate yield adaptive patterns of 24 modern winter wheat cultivars tested across 20 trial locations and three consecutive cropping seasons. In this study complementary techniques were used including the combined analysis of variance (ANOVA) with additive main effects and multiplicative interaction (AMMI) analysis of the cultivar-location subdesigns within each of the crop management practices, and a clustering procedure of grouping cultivars similar for their environmental adaptation based on AMMI(1)-modelled responses of cultivars.

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MATERIAL AND METHODS

Trial data. The data comprises 24 modern cultivars developed by breeding companies in Poland and European countries. The cultivars were tested at two crop management intensities, including a moderate-input management treatment (M1) and a high-input management treatment (M2), as shown in Table 1.The 24 cultivars were tested across 20 trial locations (Figure 1) over the 2006/2007–2008/2009 growing seasons. The trials in each location were planned according to a two-factor strip-plot design, with two blocks as replicates.

Statistical data analysis. Analysing the data on grain yield in the balanced Genotype × Management × Location × Year (G × M × L × Y) table was performed using a two-stage approach in the linear standard mixed modelling framework. Two-stage analysis is usually done by weighting, but an unweighted analysis was used. The study of Möhring and Piepho (2009) provided evidence that the results of the weighted analysis of yields tend to be similar to those of the unweighted analysis. At the first stage of the analysis, for the plot data from each trial an ANOVA of a two-factor strip-plot design was employed (Gomez & Gomez 1984), considering cultivar and crop management as fixed factors and block as a random one (Möhring & Piepho 2009). At the first stage separately at each location and year, the ANOVA produced least squares means (LS means) of cultivar-management combinations, and mean squares of the three experimental errors adequate to the strip-plot experimental design. Pooled average error was calculated based on errors observed at the first stage of analysis (from the analysis of a single trial). Its pooled average errors were used for the tested main and interaction effects in 4-way ANOVA and they were also used for testing at the second stage of analysis. The within-environment LS means, combined in a balanced G × M × L × Y table (Table 2), were used at the second stage of the combined ANOVA. Due to significant (P < 0.01) G × M revealed by the combined ANOVA (Table 2), the assessment of the cultivar adaptation to crop management was performed by means of comparing cultivar yield means across years and locations, separately under each of the crop management systems. This approach involves the joint use of the combined ANOVA and AMMI analysis for the fixed G × L interaction effects (Table 3). The combined ANOVA together with AMMI analysis based on model (1) is presented in Table 3. It shows the methodology of testing important hypotheses including those about significance of the multiplicative terms by F_R test (Annicchiarico 2002).

Figure 1. Geographical distribution of 20 winter wheat test locations within the Post-registration Variety Testing System (PVTS)

Table 1. Characteristics of two crop management intensities

Crop management treatments	Timing (developmental stages) of the treatments	Crop management intensity	
		M1	M2
Nitrogen fertilization rate	tillering[1] heading[2]	+[y]	N rate for M1 + 40 kg N/ha
Fungicide use: the first treatment	stem elongation	–	+
Fungicide use: the second treatment	heading	–	+
Growth regulator	stem elongation	–	+
Foliar compound fertilization	heading	–	+

M1 – moderate-input management; M2 – high-input management; [y]N rate was fit to the general nutrient status of the field at a given location; [1]the first part of the N rate; [2]the second part of the N rate

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This procedure is based on the following three-way ANOVA mixed model for the G × L × Y data table, with multiplicative terms for the fixed G × L interaction effects (Anicchiarico *et al*. 2010; Gauch 2013):

$$X_{ijk(l)} = m_l + Y_{i(l)} + L_{j(l)} + YL_{ij(l)} + G_{k(l)} + GY_{ik(l)} + \sum_{t=1}^{T} u'_{tk(l)} v'_{tj(l)} + GLY_{ijk(l)} + e_{1ijk(l)} \quad (1)$$

where:

$X_{ijk(l)}$ – LS mean for yield in the i^{th} year, the j^{th} location and the k^{th} cultivar at the l^{th} management treatment (for simplicity, the symbol l is omitted in the next parameter description)

m_l – general mean

$Y_{i(l)}$ – random main effect of the i^{th} year

$L_{j(l)}$ – fixed main effect of the j^{th} location

$G_{k(l)}$ – fixed main effect of the k^{th} cultivar

$YL_{ij(l)}$ – random interaction effect of the i^{th} year and the j^{th} location

$GY_{ik(l)}$ – random interaction effect of the k^{th} cultivar and the i^{th} year

$\sum_{t=1}^{T} u'_{tk(l)} v'_{tj(l)} = GL_{jk(l)}$ – sum of the $T = \min\{(J–1),(K–1)\}$ multiplicative terms for the $GL_{jk(l)}$ interaction effect of the k^{th} cultivar and the j^{th} location, in which $u'_{tk(l)}$ and $v'_{tj(l)}$ are the symmetrically scaled eigenvector values for the k^{th} cultivar (genotypic interaction principal component score for the k^{th} cultivar, called GIPC$t_{(l)}$ score) and the j^{th} location (environmental interaction principal component score for the j^{th} location, called EIPC$t_{(l)}$ score), regarding the t^{th} interaction principal component (IPC$t_{(l)}$) (Annicchiarico 2002; Ebdon & Gauch 2002)

$GLY_{ijk(l)}$ – random interaction effect of the k^{th} cultivar, the i^{th} year and the j^{th} location

$e_{1ijk(l)}$ – average (mean across replicates) error 1 within-strip-plot design (the first step of analysis)

Model (1) can be used effectively to study cultivar adaptive responses to the environments at each of the l^{th} management treatments using a nominal yield equation (Gauch & Zobel 1997; Annicchiarico 2002). The nominal yield equation for the k^{th} cultivar under the l^{th} management was used for the expression of cultivar nominal yields (i.e. expected responses from which the main effect of location, which has no influence on genotype ranking, has been removed

Table 2. The four-way mixed model-based combined ANOVA for the balanced G × M × L × Y data of winter wheat grain yield (t/ha) obtained from the trials conducted during the three growing seasons 2006/2007–2008/2009 in the national Post-registration Variety Testing System (PVTS)

Sources of variation	df	SS	MS	*F*-ratio	%TSS
Year	2	1054.69	527.34	10546.80**	13.6
Location	19	2774.91	146.05	3.47**	35.7
Year × location	38	1601.12	42.13	842.60**	20.6
Cultivar	23	141.73	6.16	2.36**	1.8
Cultivar × year	46	120.09	2.61	52.20**	1.5
Cultivar × location	437	284.37	0.65	1.33**	3.7
Cultivar × year × location	874	435.14	0.49	9.80**	5.6
Pooled average error 1	709		0.05		
Management	1	975.40	975.40	194.70**	12.6
Management × year	2	10.02	5.01	22.77**	0.1
Management × location	19	133.93	7.05	2.71**	1.7
Management × year × location	38	98.88	2.60	11.82**	1.3
Pooled average error 2	129		0.22		
Cultivar × management	23	15.17	0.66	6.00**	0.2
Cultivar × management × year	46	5.14	0.11	1.57*	0.1
Cultivar × management × location	437	46.17	0.11	1.38**	0.6
Cultivar × management × year × location	874	70.05	0.08	1.14ns	0.9
Pooled average error 3	708		0.07		

df – degrees of freedom; SS – sum of squares; MS – mean squares; %TSS – explained percent of the total sum of squares equal to 776621.0; *,** significant at $P < 0.05$, 0.01, respectively; ns not significant ($P > 0.05$)

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in order to linearize the adaptive responses) as a function of the scaled location $EIPC1_{(l)}$ score. Then, this equation is a result of the transformation in multiplicative model (1) and is as follows (Annicchiarico 2002). Then, the evaluated cultivars were clustered into groups by cultivar nominal yields in the trial locations for each of the crop management treatments. Cluster analysis by Ward's hierarchical agglomerative procedure using the squared Euclidean distance as a dissimilarity measure was used. The whole statistical analysis was carried out with the R software system.

RESULTS AND DISCUSSION

The results of the 4-way combined ANOVA (Table 2) of a large balanced winter wheat grain yield data subset from the national PVTS dataset revealed significant main effects of cultivar, management, year and location, and all possible interactions between them except for the 4-order G × M × L × Y interaction. Variation of yield was affected predominantly by environmental effects which explained about 70% of the TSS (total sum of squares) (Table 2). Relative magnitudes of the main G effects and G × L interaction effects were much smaller compared to environmental effects, explaining 1.8 and 3.7% of TSS, respectively.

Due to significant ($P < 0.01$) G × M revealed by the combined ANOVA (Table 2), the assessment of the cultivar adaptation to crop management was performed by means of comparing cultivar yield means across years and locations, separately under each of the crop management systems. The differences in the means for the cultivars were approximately 0.9 t/ha under the M1 and M2 systems, but they were not proved significant ($P > 0.05$). This clearly illustrates the consequences of a small, though significant, variation in G × M interaction effects, explaining only 0.2% of TSS, and the similarity for yielding of the elite cultivar set in the studies. The main cultivar effects and G × L interaction effects were significant for both management treatments and explained approximately 5% of the total treatment sum of squares (Table 3). This finding clearly justifies using the AMMI analysis to assess cultivar adaptive responses under both management treatments. According to the F_R test only the IPC1 was found to be significant. The G × L sum of squares was explained by the IPC1 and IPC2 in decreasing order of magnitude of 31.5 and 14.5% of the G × L-SS for M1 and 26.8 and 16.8% of the G × L-SS for M2 (Table 3). This finding indicates that only approximately one third of the variations in the G × L interaction effects contributed to the pattern of cultivar environmental adaptations.

In the graphs of the AMMI1 nominal yield for the cultivars under both M1 and M2 (Figure 2a, c), the abscissa represents the scaled EIPC1 score for locations, and the ordinate represents the nominal yield for cultivars. To assess the environmental causes of

Table 3. ANOVA and AMMI analyses for the fixed G × L interaction effects for winter wheat grain yield in a G × L × Y data table from the national Post-registration Variety Testing System (PVTS) conducted over the three seasons, separately for each of the two management intensities

Sources of variation	df	SS		*F*-ratios		%TSS		%G×L-SS	
		M1	M2	M1	M2	M1	M2	M1	M2
Year	2	602.60	462.10	6026.00**	4621.00**	18.75	12.92		
Location	19	1258.59	1650.26	3.06**	3.76**	39.17	46.13		
Location × year	38	822.23	877.77	432.80**	462.00**	25.59	24.54		
Genotype	23	79.31	77.59	2.56**	2.44**	2.47	2.17		
Genotype × year	46	61.96	63.27	27.00**	27.60**	1.93	1.77		
Genotype × location	437	155.08	174.86	1.30**	1.29**	4.83	4.89		
$IPC1_{(l)}$	41	48.88	46.85	1.30** (F_R)	1.29** (F_R)			31.52	26.79
$IPC2_{(l)}$	39	22.50	29.42	0.99^{ns} (F_R)	1.04^{ns} (F_R)			14.51	16.82
Genotype × location × year	874	233.47	271.72	5.40**	6.20**	7.27	7.59		
Pooled average error 1	709								

df – degrees of freedom; SS – sum of squares; %TSS – explained percent of the total sum of squares; %G×L-SS – explained percent of the G × L interaction sum of squares; M1 – moderate-input management; M2 – high-input management; ** significant at $P < 0.01$; ^{ns}not significant; F_R – *F*-statistic for F_R test;

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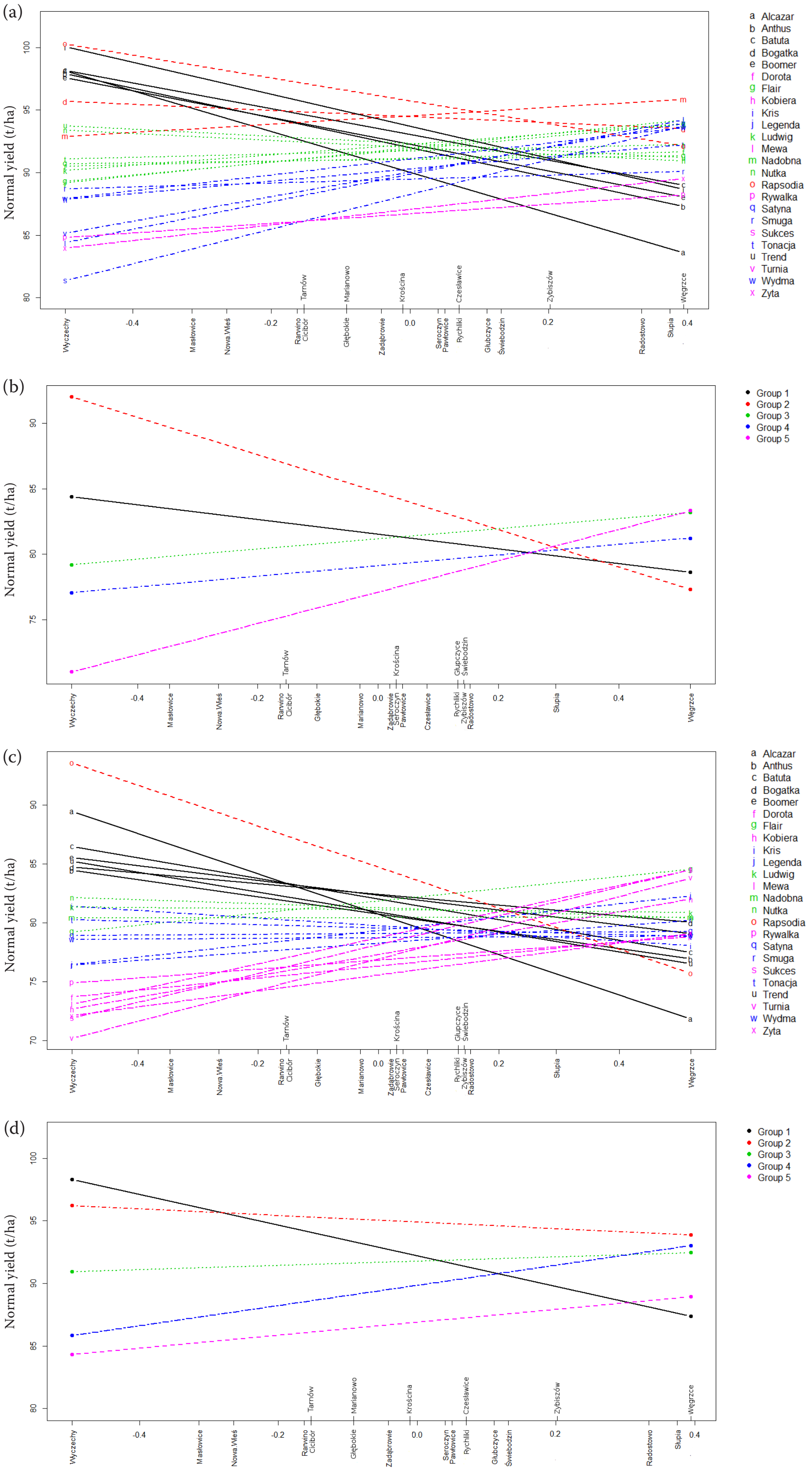

Figure 2. Graph of the AMMI1 nominal three-year mean grain yield of 24 winter wheat cultivars and the cultivar group means (the ordinate) under M1 (a, b) and M2 (c, d) management

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the winter wheat cultivar adaptive response for grain yield and to make the agronomic interpretation of nominal yield-based cultivar adaptive responses (Figure 2a, c) as clear as possible, a correlation analysis was performed between the scores of the EIPC1 for grain yield and location grain yield means across the testing years and the environmental variables recorded at the locations (Annicchiarico *et al.* 2010). The EIPC1 scores were strongly and positively correlated with the location mean yield at M1 ($r = 0.92$) and M2 ($r = 0.93$), but the scores showed no significant correlation at $P < 0.05$ with total rainfall during the growing seasons and soil pH. No relationship was observed between the EIPC1 scores and the geographical proximity (Figure 1), but a relationship was observed between the EIPC1 scores and soil fertility. Thus, the order of the trial locations along the EIPC1 axis at M1 and M2 (Figure 2) is consistent with the increasing soil fertility (productivity of agro-ecosystem) and then location mean grain yield. To further simplify the nominal yield interpretation, the trial locations can be divided into three sectors according to the EIPC1 scores: the most negative scores, moderate scores near zero and the most positive values of these scores; these categories also exhibit the lowest, medium and highest soil fertility categories and mean yields, respectively (Figure 2). Clustering the cultivars for the nominal yields in locations was performed. The numbers of cultivar groups were determined using the SS retained in the G × L nominal yield matrix. The cultivars were classified into five groups (Table 4), which retained 80.2 and 81.1% of the SS of G × L nominal yield matrix for M1 and M2, respectively.

The lines in Figure 2a, c with the same colour denote the nominal yield of cultivars that belong to the same group and indicate substantial similarities between entries in the groups for adaptive response patterns under both M1 and M2. The cultivar group-mean nominal yields for each of the five groups under the M1 and M2 systems describe the patterns of cultivar mean-group adaptive responses (Figure 2b, d). Nominal yields for each of two groups of cultivars distinguished under M1 and M2 systems showing a similar adaptive response relative to other cultivar groups within a management treatment, although they do not include all of the same genotypes, are denoted by the same number and colour on the lines in Figure 2.The cultivar group nominal yields illustrate that the AMMI1 model of adaptive responses revealed the occurrence of some crossover interactions under both M1 and M2 and shows how they led to the different rankings of the cultivars across the environments.

Under the moderate-input management treatment, the nominal yield line for the Rapsodia cultivar revealed a sharp slope and exhibited the highest nominal yield in most environments, i.e. in low to medium-productive environments, and the lowest nominal yield in the highest-productive environments. The group 2 cultivars showed a gradual slope in the nominal yield line and exhibited approximately average nominal yields across all the environments. Cultivars that belonged to groups 3, 4 and 5 showed the opposite behaviour relative to groups 1 and 2 cultivars in the test environments: they performed substantially worse than did the group 1 and 2 genotypes across lower- and moderate-productive environment and exhibited the best adaptation within the germplasm tested in the highest-productive environments. The nominal yield line patterns for the cultivar groups identified under the high-input management were relatively similar to each other compared with those observed under the moderate-input management and are denoted with the same number. Under M2 management, Rapsodia, Bogatka and Nadobna showed a gentle slope, exhibited the highest nominal yields in all of the environments and showed wide adaptation in a range of agro-ecosystems

Table 4. Winter wheat cultivar membership in homogeneous groups with respect to nominal yield under M1 and M2 crop management

Cultivar group No.	Cultivar membership
1	M1: Alcazar, Anthus, Batuta, Bogatka, Boomer, Trend M2: Alcazar, Anthus, Batuta, Boomer, Kris
2	M1: Rapsodia M2: Bogatka, Nadobna, Rapsodia
3	M1: Flair, Ludwig, Nadobna, Nutka M2: Dorota, Flair, Legenda, Ludwig, Nutka, Satyna, Tonacja, Trend
4	M1: Kris, Legenda, Satyna, Smuga, Tonacja, Wydma M2: Mewa, Kobiera, Smuga, Sukces, Turnia, Wydma
5	M1: Dorota, Kobiera, Mewa, Rywalka, Sukces, Turnia, Zyta M2: Rywalka, Zyta

M1 – moderate-input management; M2 – high-input management

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across Poland's winter wheat-growing area. Group 1 cultivars (Alcazar, Anthus, Batuta, Boomer and Kris) registered a sharp slope on the nominal yield line and presented an equally high adaptation as the group 2 cultivars did to the lowest-yielding agro-ecosystems but a poor adaptation to high-yielding environments (Figure 2d). This result means that Alcazar, Anthus, Batuta and Boomer (group 1) were the best adapted to lower-productive conditions and poorly adapted to high-productive conditions under both management treatments. Cultivars belonging to groups 3, 4 and 5 under M1 management had an opposite behaviour compared with group 1 and 2 cultivars in the test environments under M2 management in that they performed worse than the group 1 and 2 entries across lower- and moderate-productive environments and performed poorly in the highest-productive environments.

CONCLUSIONS

On average over random test cropping seasons the evaluated winter wheat cultivars from many Western European countries and Poland showed different adaptive responses to the Polish agro-ecosystems under each of the crop management intensities, which were also dependent on the management treatments. The cultivar Sukces (Poland) showed a specific adaptation to lower-input management. Under the moderate-input management, no cultivar exhibited a clearly wide adaptation across Poland's winter wheat-growing area; however, the cultivar Rapsodia (UK) was identified as the best adapted to lower and medium-productive environments and was poorly adapted to highly productive environments. This was clearly due to the greater resource use efficiency and ability of these cultivars to tolerate more stressful environmental conditions compared with the other cultivars tested. Under the high-input management, the cultivars Rapsodia, Bogatka and Nadobna (Poland) showed a wide adaptation. The cultivars Alcazar (France), Anthus (Germany), Batuta (Poland) and Boomer (UK) were the best adapted to lower-productive environments and poorly adapted to highly productive conditions under both management treatments.

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