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Four-way data analysis within the linear mixed modelling framework

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ABSTRACT: Cultivars have to be evaluated under different crop management systems across agro-ecosystems and years using multi-environment trials (MET) before releasing them to the market. Frequently, data collected in METs are arranged according to cultivar (G), management (M), location, (L) and year (Y) combinations in a four-way G x M x L x Y data table that is highly unbalanced for cultivars across locations and time. Therefore, we present the restricted maximum likelihood method (REML) for linear mixed models (LMM) with a factor analytic variance-covariance matrix for assessing cultivar adaptation to crop management systems and environments based on unbalanced datasets. Such a multi-environmental trial system has been in operation in Poland for winter wheat (*Triticum aestivum* L.) in the form of the Post-registration Variety Testing System (PVTS). This study aimed to illustrate the use of LMM in the analysis of unbalanced four-way G x M x L x Y data. LMM analysis provided adjusted means of grain yield for 51 winter wheat cultivars bred in different regions in Europe, tested across 18 trial locations and seven consecutive cropping seasons in two crop management intensities. The application of the four-way LMM with a factor analytic variance-covariance matrix is a complementary and effective tool for evaluating the unbalanced G x M x L x Y table. Cultivars tested had different adaptive responses to the Polish agro-ecosystems separately for each of the crop management intensities. Wide adaptation in both crop management systems was exhibited by cultivars Mulan and Jenga bred in Germany.

Keywords: crop management, restricted maximum likelihood methods, unbalanced data, winter wheat

Introduction

Multi-environment trials (MET) are conducted to investigate cultivar adaptation patterns of cultivars (Annicchiarico et al., 2010). To deliver essential information for flexible and cultivar-specific management and environment recommendations, released cultivars have to be evaluated under different crop management systems across locations and years (Loyce et al., 2012). A similar system has been operating in Poland, called the Post-registration Variety Testing System (PVTS). The raw plot data is collected and arranged according to cultivar (G), management (M), location (L), and year (Y) combinations in a complex four-way G x M x L x Y data table that is highly unbalanced for cultivars.

Frequently, comparisons among cultivars from unbalanced METs datasets are based on distinguished balanced data subsets (So and Edwards, 2009). Although this approach to cultivar evaluation enables the use of classic statistical methods, it results in a loss of useful information on cultivars. Therefore, linear mixed models (LMM) appear to better handle the unbalanced data. (Piepho, 1998; Smith et al., 2001, 2005).

Most previous studies on unbalanced MET data have been limited to two-way G x E data sets (Smith et al., 2001, 2005). and Piepho et al. (2014) analysed unbalanced four-way G x M x L x Y data for the first time. Their approach treated each of the crop managements separately. However, for agronomical purposes, this approach does not allow for an evaluation of the effects of crop management and their interactions with cultivars. There are no proposals of methodology, based on an LMM with more complex variance–covariance matrices for the statistical analysis of an unbalanced G x M x L x Y data table from METs.

This study aimed to illustrate the use of LMM with a complex variance-covariance matrix in the analysis of unbalanced four-way G x M x L x Y data on winter wheat yields from the PVTS. Such a procedure is necessary to properly and comprehensively evaluate adaptive responses of cultivars to both environments and crop management systems based on MET databases containing typically unbalanced, though very valuable, four-way data.

Materials and Methods

Trials and data description

Data on grain yield used in this study came from the PVTS. The entire dataset included up to 139 winter wheat (*Triticum aestivum* L.) cultivars evaluated in (at most) 18 Cultivar Testing Stations (trial locations) over seven growing seasons from 2004/2005 to 2010/2011. We excluded cultivars tested for time periods shorter than three years and those tested only in one location to provide a sufficiently representative sample of years as a random factor and a reasonable level of location as a fixed factor. As a result of this data preparation, we obtained a four-way G x M x L x Y dataset for the grain yield of 51 cultivars. Cultivars shown in Table 1 represent a genetic variation of agronomic attributes of an advanced winter wheat germplasm in Europe. The cultivars come from various breeding programs and breeding

Table 1 – Description of 51 winter wheat cultivars with the number of trial locations in Polish Post-Registration Variety Testing System across growing seasons (years of harvest) 2005 – 2011.

Culivars	Year of registration	Country of origin	Breeding Company	Number of locations by year						
				2005	2006	2007	2008	2009	2010	2011
Bogatka	2004	PL	DANKO Hodowla Roślin sp. z o.o.	18	18	18	18	18	18	18
Finezja	2002	PL	DANKO Hodowla Roślin sp. z o.o.	18	18	18	18	18	18	18
Nutka	2001	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	18	18	18
Rapsodia	2003	UK	RAGT Seeds Ltd.	18	18	18	18	18	18	18
Smuga	2004	PL	DANKO Hodowla Roślin sp. z o.o.	18	18	18	18	18	18	18
Tonacja	2001	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	18	18	18
Fregata	2004	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	3	2	2
Nadobna	2003	PL	Poznańska Hodowla Roślin sp. z o.o.	18	18	18	18	18	18	X
Satyna	2004	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	18	18	18	18	18	18	X
Trend	2003	DE	KWS Lochow GmbH	18	18	18	18	18	18	X
Dorota	2004	FR	RAGT 2n	18	18	18	18	18	X	X
Flair	2001	DK	Syngenta Seeds B.V.	18	18	18	18	18	X	X
Kobiera	2003	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	18	18	18	18	18	X	X
Kris	2000	FR	RAGT 2n	18	18	18	18	18	X	X
Mewa	1998	PL	DANKO Hodowla Roślin sp. z o.o.	18	18	18	18	18	X	X
Rywalka	2003	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	18	X	X
Sukces	2001	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	18	X	X
Turnia	2001	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	18	18	18	18	18	X	X
Zyta	1999	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	18	18	X	X
Muza	2004	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	18	18	18	18	X	X	X
Zawisza	2004	PL	Hodowla Roślin Smolice sp. z o.o. Grupa IHAR	18	18	18	18	X	X	X
Kobra Plus	1992	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	18	18	18	2	X	X	X
Aristos	2004	FR	Limagrain Verneuil Holding	18	18	18	X	X	X	X
Kaja	1997	PL	Poznańska Hodowla Roślin sp. z o.o.	18	18	18	X	X	X	X
Olivin	2004	FR	RAGT 2n	18	18	18	X	X	X	X
Pegassos	2001	DE	ILVO Plant Toegepaste Genetica en Veredeling	18	18	18	X	X	X	X
Rubens	2000	DE	KWS Lochow GmbH	18	18	18	X	X	X	X
Sława	2001	PL	Poznańska Hodowla Roślin sp. z o.o.	18	18	18	X	X	X	X
Soraja	2000	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	X	X	X	X
Symfonia	1999	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	18	18	18	X	X	X	X
Sakwa	1996	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	17	18	18	18	X	X	X
Legenda	2005	PL	Poznańska Hodowla Roślin sp. z o.o.	X	18	18	18	18	18	18
Wydma	2005	PL	Hodowla Roślin Smolice sp. z o.o. Grupa IHAR	X	18	18	18	18	18	18
Alcazar	2006	FR	Secobra Recherches	X	X	18	18	18	18	18
Batuta	2006	PL	DANKO Hodowla Roślin sp. z o.o.	X	X	18	18	18	18	18
Boomer	2006	FR	RAGT 2n	X	X	18	18	18	18	18
Ludwig	2006	AT	Saatzucht Donau Ges.m.b.H. & CoKG	X	X	18	18	18	18	18
Naridana	2006	PL	Poznańska Hodowla Roślin sp. z o.o.	X	X	18	18	18	18	18
Turkis	2006	DE	Lantmännen SW Seed Hadmersleben GmbH	X	X	18	18	18	18	18
Anthus	2006	DE	KWS Lochow GmbH	X	X	18	18	18	18	X
Akteur	2007	DE	Deutsche Saatveredelung AG	X	X	X	18	18	18	18
Figura	2007	PL	DANKO Hodowla Roślin sp. z o.o.	X	X	X	18	18	18	18
Garantus	2007	FR	RAGT 2n	X	X	X	18	18	18	18
Markiza	2007	PL	Hodowla Roślin Strzelce sp. z o.o. Grupa IHAR	X	X	X	18	18	18	18
Meteor	2007	DE	Lantmännen SW Seed Hadmersleben GmbH	X	X	X	18	18	18	18
Nateja	2007	PL	DANKO Hodowla Roślin sp. z o.o.	X	X	X	18	18	18	18
Jenga	2008	DE	Nordsaat Saatzucht GmbH Saatzucht Langenstein	X	X	X	X	18	18	18
Kohelia	2008	PL	Małopolska Hodowla Roślin-HBP sp. z o.o.	X	X	X	X	18	18	18
Mulan	2008	DE	Nordsaat Saatzucht GmbH Saatzucht Langenstein	X	X	X	X	18	18	18
Muszelka	2008	PL	DANKO Hodowla Roślin sp. z o.o.	X	X	X	X	18	18	18
Ostroga	2008	PL	DANKO Hodowla Roślin sp. z o.o.	X	X	X	X	18	18	18

X denotes lack of evaluating the cultivar in a given growing season.

companies. A geographical distribution of the 18 Cultivar Testing Stations is presented in Figure 1. These locations were chosen to represent agro-ecological conditions for winter wheat across all regions of Poland.

Winter wheat cultivars were evaluated at two levels of crop management intensity, a moderate-input (MIM) and conventional management (HIM) (Table 2). MIM did not include plant protection treatments and standard fertilization was applied according to the soil needs of a given location. HIM was a high-input treatment designed to maximize yield. It included high nitrogen fertilization combined with frequent fungicide use, foliar fertilization and the application of a growth regulator (trinexapac-ethyl). This crop management corresponds to the crop management system commonly used in commercial winter wheat production in Poland.

The four-way G x M x L x Y dataset (51 cultivars, 2 managements, 18 locations and 7 years) was unbalanced (Table 1). Only seven cultivars were tested during the entire trial period (Table 1). The rest of the cultivars were tested for shorter durations, but the durations were longer than three growing seasons (Piepho et al., 2014). This outcome was the result of favouring popular cultivars over poorly performing ones. Cultivars included in our dataset were usually assessed at all of the 18 trial locations for a given year. Only a few cultivars (Fregata, Kobra Plus and Sakwa) were not tested in all locations. In the G x M x L x Y data, 8400 combinations (cells) were filled, representing 65 % of all the combinations possible in the balanced classification.

Figure 1 – Trial locations of the PVTS used in seven growing seasons from 2004/2005 to 2010/2011 for winter wheat cultivars.

In each location and year, individual trials were established as a two-factor strip-plot (split-block) design with two replications (Mintenko et al., 2002). Within the blocks, the cultivars were arranged in sub-blocks, and the two crop managements in the other sub-blocks were arranged perpendicularly to the sub-blocks with the cultivars. The plot size (planted) was 16.5 m^2 (11 m × 1.5 m) and the plot size harvested was 15 m^2 (10 m × 1.5 m).

Statistical methods

For the statistical analysis of the unbalanced grain yield derived from raw G x M x L x Y data, we used a two-stage combined analysis, commonly recommended and practiced in METs (Smith et al., 2005; Möhring and Piepho, 2009). During the first stage, we analysed the data per trial (location-year combination) using a mixed-model ANOVA approach for a strip-plot design, modelling cultivar and management effects as fixed and block and error effects as random (Möhring and Piepho, 2009). The least squares (LS) means for cultivar and management combinations were estimated in the routine analyses conducted by the Polish Research Centre for Cultivar Testing (COBORU). Then, the LS means were combined across trials and years to obtain an unbalanced G x M x L x Y mean data table.

In the second stage of the combined analysis of the G x M x L x Y data, we used two models utilized for various purposes (Burgueño et al., 2011; Liu et al., 2013). First, the analysis of the LS means was conducted to test the significance of the effects of G, M, L, Y and their interactions. Then, an analysis was performed based on LMM as shown below:

$$X_{ijkl} = m + Y_i + L_j + YL_{ij} + G_k + GY_{ik} + GL_{jk} + GLY_{ijk} + M_l + MY_{il} + ML_{il} + MLY_{ijl} + GM_{kl} + GMY_{ikl} + GML_{ljk} + GMLY_{ijkl} \quad (1)$$

Table 2 – Characteristics of two crop management intensities, MIM and HIM, included in the winter wheat PVTS.

Crop managements treatments	Crop management intensity	
	MIM	HIM
Nitrogen fertilization rate (kg N ha^{-1})	+ [x]	N rate for MIM + 40 kg N ha^{-1}
Fungicide use: the first treatment (protection against stalk and leaves diseases)	-	+
Fungicide use: the second treatment (protection against leaves and spike diseases)	-	+
Growth regulator	-	+
Foliar compound fertilization	-	+

- denotes crop management treatment was not used; + denotes crop management treatment was used; [x]N fertilization rate was fitted to productivity potential of the environment in a trial location; MIM = moderate-input management; HIM = high-input management.

In which: X_{ijkl} is the LS mean of yield for the 4-factorial combination of the i-th year, the j-th ($j = 1,2, \ldots, J$) location, the k-th cultivar and the l-th crop management intensity; m is the general mean; Y_i is the random main effect of the i-th year; L_j is the fixed main effect of the j-th location; G_k is the random main effect of the k-th cultivar; M_l is the fixed main effect of the l-th crop management intensity; YL_{ij} is the random interaction effect of the i-th year and the j-th location; GY_{ki} is the random interaction effect of the k-th cultivar and the i-th year; GL_{kj} is the random interaction effect of the k-th cultivar and the j-th location; MY_{li} is the random interaction effect of the l-th crop management intensity and the i-th year; ML_{lj} is the fixed interaction effect of the l-th crop management intensity and the j-th location; GM_{kl} is the random interaction effect of the k-th cultivar and the l-th crop management intensity; GLY_{kji} is the random interaction effect of the k-th cultivar, the j-th location and the i-th year; GMY_{kli} is the random interaction effect of the k-th cultivar, the l-th crop management intensity and the i-th year; GML_{klj} is the random interaction effect of the k-th cultivar, the l-th crop management intensity and the j-th location; MLY_{lji} is the random interaction effect of the l-th crop management intensity, the j-th location and the i-th year; and $GMLY_{klji}$ is a random residual comprising both the interaction effect of the k-th cultivar, the l-th crop management intensity, the j-th location, the i-th year, and the error term associated with a mean X_{ijkl}.

In this stage of the analysis, the cultivar effects were considered to be random because the cultivars evaluated were considered to be a representative sample of the wide range of genetic and phenotypic diversity in cultivars (germplasm population) released recently in Poland and other European countries (Smith et al., 2005; Curti et al., 2014). The locations were assumed to be fixed because they are not truly random samples from a target region and they have a repeatable nature (Virk et al., 2009). The significance of fixed effects in equation (1) was tested with the Wald F test (Anderson et al., 2011). The variance components for random effects were estimated using the restricted maximum likelihood (REML) method (Patterson and Thompson, 1971). The likelihood ratio test was used to evaluate the significance of the random effects in equation (1).

Secondly, an analysis of the LS means in the G x M x L x Y table was also conducted to assess cultivar adaptation to environment and crop management (estimates of adjusted means for the considered combinations), based on an LMM with some nested effects as follows:

$$X_{ijkl} = m + Y_i + L_j + YL_{ij} + G(L)_{kj} + G(L)Y_{kji} + M_l + MY_{il} + ML_{il} + MLY_{ijl} + G(L)M_{kjl} + G(L)MY_{ijkl} \quad (2)$$

In which $G(L)_{ki}$ is the random effect of the k-th cultivar at (within) the j-th location, $G(L)Y_{kji}$ is the random effect of interaction between the k-th cultivar at the j-th location and the i-th year; $G(L)M_{kjl}$ is the random effect of the interaction between the k-th cultivar at the j-th location and the l-th crop management intensity and the k-th cultivar at the j-th environment; $G(L)MY_{ijkl}$ is the random effect of the residual, comprising both the interaction between the i-th year l-th crop management intensity and effect of the k-th cultivar at the j-th environment location, the l-th crop management intensity and the i-th year as well as the error term associated with a mean X_{ijkl}; other abbreviations were compatible with equation (1).

For the random effects of cultivars at locations $G(L)_{ki}$ in equation (2), we assumed a factor analytic (FA) structure of the genetic variance-covariance matrix (Smith et al., 2001; Kelly et al., 2007). This variance-covariance structure is a parsimonious form of the fully unstructured variance-covariance matrix (Kelly et al., 2007). It is as flexible as the unstructured matrix, but with a smaller number of parameters. The FA models have been considered as giving the best fit for many different datasets, and superior in terms of selection of the best adapted cultivars (Kelly et al., 2007; Burgueño et al., 2011). The factor analytic structure is a decomposition of the unstructured variance-covariance matrix, based on a factor analysis with Cholesky factorization (So and Edwards, 2009). For equation (2), we used a factor analytic structure with six components. Piepho (1998) and Kelly et al. (2007) suggested using two components for the FA model, but their studies were based on GxE datasets with fewer trail locations than in our data.

The best linear unbiased estimators (BLUEs) for the fixed effects of equation (2) and the best linear unbiased predictors (BLUPs) of the random effects in the model were calculated using the REML procedure. These estimates were used to calculate the adjusted means for the considered combinations of factors, using the algorithm described by Welham et al. (2004). Traditional methods of pairwise comparisons of means in unbalanced data and a large number of levels of factors are not useful. Decision, where adjusted means differed, was based on confidence intervals, calculated as two times the standard error of the means (Piepho, 2000).

Due to the number of cultivars evaluated in the PVTS, as in other METs, it is difficult to effectively interpret and distinguish various adaptive response patterns of these entries. Therefore, the cultivars tested in this study were classified based on their yield response to environments (adjusted means for the G x L combinations). The 51 cultivars were grouped based on adjusted means for grain yield at each location separately for the two crop management intensities (Curti et al., 2014). Cultivars with similar patterns of response to location were included in the same group. The Ward's cluster analysis method with the squared Euclidean distance was used for grouping cultivar response to environments (Ward, 1963). The dendrogram was cut when the fusion of groups explained at least 0.8 of the total sum of squares.

For equations (1) and (2), in the second stage of the combined analysis, we assumed homogeneous residual error variances across locations and years. These assumptions are rather restrictive and may be unrealistic in many MET datasets (Möhring and Piepho, 2009; Hu et al., 2013). However, these assumptions simplify the LMMs and allow an unweighted two-stage analysis of the considered data. Two-stage analyses without weighting produced acceptable results in comparison to weighted ones, and, in most cases, performed better (Möhring and Piepho, 2009). Caliński et al. (2005) also advocate using an unweighted approach, based on the randomization theory for analysing METs data. Although the unweighted two-stage analysis will be approximated and can decrease the predictive accuracy in cultivar evaluation (Möhring and Piepho, 2009; Hu et al., 2013), it is very practical for large sets of four-way data within the mixed modelling framework. Therefore, this analysis can deliver information that is sufficiently accurate for making recommendations on released cultivars across agro-ecosystems and crop managements.

The use of LMM for large and unbalanced METs data can be challenging to compute. Equations (1) and (2) were fit using ASReml 3.0, implemented in the R package (ASReml-R). The cluster analysis was performed using the CLUSTER procedure in SAS (Statistical Analysis System, version 9.4).

Results and Discussion

The Wald F test for the fixed effects in equation (1) indicated a statistically significant main effect of crop management (Table 3). Mean yields of genotypes for the two crop management intensities, MIM and HIM, were different ($p < 0.01$) and varied from 7.65 t ha^{-1} and 8.72 t ha^{-1}, respectively. The HIM resulted in an average increase in grain yield of 1.07 t ha^{-1}. This result contrasts to previous studies where no significant yield response to crop management was detected (Liu et al., 2013).

Table 3 – F ratio for fixed effect and variance components with percentage of total variation for random effects in the linear mixed model (1) from PVTS data set.

Source	F ratio	Variance Components	Percent of total variance
Year (Y)		58.22**	32.24
Location (L)	130.15**		
Year x Location (Y x L)		83.99**	46.52
Cultivars (G)		4.68*	2.59
Cultivars x Year (G x Y)		3.17*	1.76
Cultivars x Location (G x L)		2.03*	1.12
Cultivars x Location x Year (G x L x Y)		14.15**	7.84
Management (M)	226.14**		
Management x Year (M x Y)		0.16	0.09
Management x Location (M x L)	85.47**		
Management x Location x Year (M x L x Y)		13.13**	7.27
Cultivars x Management (G x M)		0.39*	0.22
Cultivars x Management x Year (G x M x Y)		0.23*	0.13
Cultivars x Management x Location (G x M x L)		0.40*	0.22
Cultivars x Management x Location x Year (G x M x L x Y)		0.01	0.01

*, ** = significant at $p \leq 0.05$ or 0.01.

The variance components of the yield for the year and the interaction between year and location were different ($p < 0.01$) from zero and accounted for 79 % of the total yield variation. Similar results were obtained in the study by Anderson et al. (2011) and De Vita et al. (2010). We identified a location effect ($p < 0.01$) and large variance components for the year and interaction between year and location, suggesting that the agro-ecological conditions in the trials were extremely varied and accounted for most of the yield variation. In our study, similar to Shrestha et al. (2012), grain yield was mainly influenced by the environment. The yield of 51 winter wheat cultivars was highly influenced by environmental factors (location, year and location × year interaction). Burgueño et al. (2011) and Tapley et al. (2013) also observed a much higher value for variance components for environmental effects than for genotypes in their wheat METs. This could be because the environmental effects (location and year) dominated the expression of the interactions between cultivars and management, and the cultivar effects (Anderson et al., 2011).

The interaction between location and crop management was significant ($p < 0.01$), and this result indicates a variable response of cultivar yield to the increased intensity of crop management across the test locations. This interaction for winter wheat was also observed by Annicchiarico et al. (2010). Figure 2 presents mean yields for the combinations of crop managements and locations and illustrates the yield-enhancing effects of increased crop management intensity. Response of cultivars to crop management was significant at 18 locations (significant G x M interaction - Table 3). However, the yield response was not always the same. In most locations, we observed an increase in mean yield when using HIM. At Głębokie, Marianowo, Masłowice, Nowa Wieś Ujska, Pałowice, Świebodzin and Tomaszów, the locations with the lowest mean yield and the one with highest mean yield - Węgrzce, there was no difference ($p > 0.05$) in yield between the MIM and the HIM crop management intensities. The highest increase in yield was observed for Głupczyce, where the difference between MIM and the HIM was equal to 2.38 t ha^{-1}.

The genotypic differences for grain yield explained only 3 % of the total variation (Table 3). The low variation in cultivar effects may be explained by the fact that the cultivars evaluated in this study are elite and top-yielding genotypes. De Vita et al. (2010) showed that the main genotype effects in a set of durum wheat landraces and advanced breeding lines explained 14 % of the total variation in grain yield. The comparison of grain yield means across years, locations and managements for 51 wheat genotypes is presented in Figure 3. These cultivar means varied from 7.81 t ha^{-1} for the Fregata cultivar, bred in Poland, to 8.69 t ha^{-1} for the Mulan cultivar, bred in Germany (an approximately 0.9 t ha^{-1} difference). The cultivars Jenga and Mulan (marked in dark grey in Figure 3) had higher mean yields ($p < 0.05$) compared to Fregata, Kobra Plus, Muza, and Olivin cultivars (marked in white in Figure 3). The cultivars marked in grey did not differ from one another.

The fraction of G x M interaction in the total variation was similar to that of the G x M x Y. Figure 4 shows the positive association between cultivars and crop management intensities. We found significant G x M interactions ($p < 0.05$), which is consistent with the finding of Tapley et al. (2013). A small percentage of the total variation for G x M and G x M x Y interactions were detected (Table 3). Thus, this interaction effect was the least important for explaining grain yield variation. The G x M interaction indicates that all examined winter wheat cultivars were characterized by higher mean yields under the more intensive crop management. The differences in mean grain yield among cultivars was 0.76 t ha^{-1} (from 7.29 to 8.05 t ha^{-1}) for the MIM level and approximately 0.8 t ha^{-1} (from 8.33 to 9.13 t ha^{-1}) for the HIM level. Fan et al. (2007) also observed a positive response of grain yield in each of the cultivars tested to increased intensity of management.

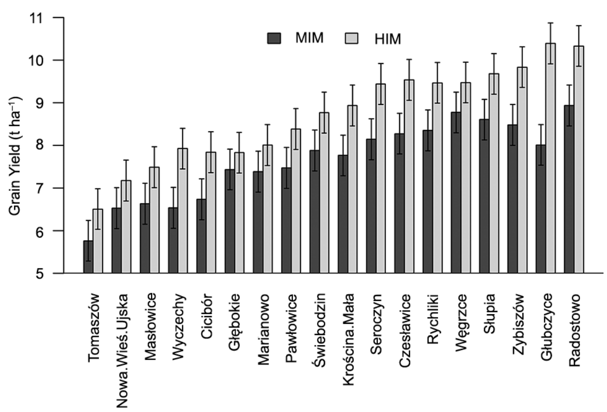

Figure 2 – Response of winter wheat grain yield to two crop management intensities (MIM and HIM) in specific environments (bars show the confidence interval of adjusted means).

The variance component for the cultivar × location interaction, which is the variation in cultivar yield response to the locations tested, was significantly different from zero. This interaction explained 1 % of the grain yield variation for winter wheat cultivars. Because of the significant variance components for the G x M and G x M x L interactions (Table 3), the adaptive responses of the 51 cultivars to agro-ecosystems are presented separately for both levels of crop management intensity. These interactions led to different rankings of cultivars across the environments between cultivars grown under MIM and HIM. To interpret the adaptive responses within the 51 cultivars and to distinguish them based on yield in each location tested, clustering was performed (Loyce et al., 2012). For clustering based on cultivar yield across all locations, we used Ward's criterion (Ward, 1963). The number (six) of cultivar groups was decided based on the sum of squares (SS) obtained from the G x L adjusted yield mean matrix.

The division of cultivars for both levels of management intensity is shown in Table 4 and dendrograms are presented in Figures 5A and 5B. The six group yields and their adjusted means across 18 locations for the two levels of management intensity are presented in Figures 6A and 6B. Each group presents similar yield responses across all agricultural environments tested. Overall, there were no apparent indications that environment was strongly associated with the significance of interactions between cultivars and crop management. The six groups earmarked for MIM explained 83 % of the total sum of squares for the yield response of cultivars (Figure 5A). Jenga and Mulan from group 1 had the highest yields in all tested environments for the MIM level. These cultivars were identified as being well adapted to lower, medium and higher yielding locations. These adaptations were consistent under both crop management intensities.

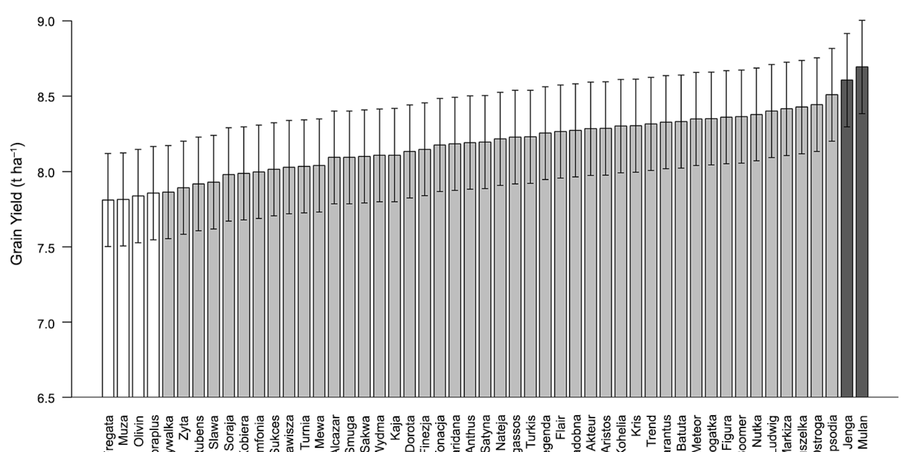

Figure 3 – Grain yield of winter wheat cultivars averaged across two levels of crop management intensity, 18 locations and seven growing seasons (bars show the confidence interval of adjusted means).

Cultivars included in group 2 were the second highest yielding for the MIM level. Group 3 included 16 cultivars and their yields were nearly the same as the environmental means and were stable in different environments. Group 4 contained 12 cultivars from various countries and breeding companies. Their yields were lower than the environmental means in most of the agro-ecosystems tested. Seven cultivars belonging to group 5 showed a stable performance of yield in different agro-ecosystems and lack of adaptation for all of them. Their yields were the lowest in 10 of the 18 locations. The two wheat cultivars from group 6 (Fregata bred in Poland and Olivin bred in France) exhibited a lack of adaptation for all locations and an unstable yield in different agricultural environments of Poland.

There were also six groups of cultivars distinguished for the higher intensity of agricultural management. The cultivar groups accounted for 81 % of the SS of the GxL adjusted mean yield matrix (Figure 5B). The content of almost all groups was similar to that corresponding to the MIM level. Group 1 included two cultivars that had yields which were stable and widely adapted to Polish agro-ecosystems. Their yields were the highest at all locations stud-

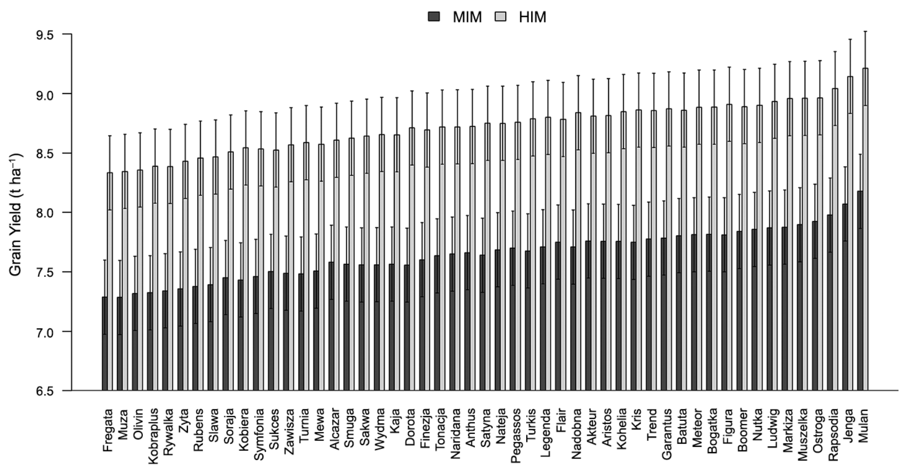

Figure 4 – Yield response of 51 winter wheat cultivars to two crop management intensities averaged across 18 environments and seven growing seasons (bars show the confidence interval of adjusted means).

Table 4 – Groups of winter wheat cultivars with a similar grain yield response across 18 environments in Poland for MIM and HIM crop management intensities.

Group 1		Group 2		Group 3		Group 4		Group 5		Group 6	
MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM	MIM	HIM
Jenga	Jenga	Batuta	Alcazar	Akteur	Akteur	Dorota	Dorota	Kobiera	Batuta	Fregata	Fregata
Mulan	Mulan	Bogatka	Anthus	Alcazar	Aristos	Finezja	Kaja	Kobraplus	Bogatka	Olivin	Kobiera
		Boomer	Finezja	Anthus	Figura	Kaja	Mewa	Muza	Boomer		Kobraplus
		Garantus	Legenda	Aristos	Flair	Mewa	Sakwa	Rubens	Garantus		Muza
		Ludwig	Naridana	Figura	Kris	Sakwa	Soraja	Rywalka	Kohelia		Olivin
		Markiza	Nateja	Flair	Meteor	Smuga	Sukces	Slawa	Ludwig		Rubens
		Meteor	Pegassos	Kohelia	Ostroga	Soraja	Symfonia	Zyta	Markiza		Rywalka
		Muszelka	Satyna	Kris		Sukces	Turnia		Muszelka		Slawa
		Nutka	Smuga	Legenda		Symfonia	Wydma		Nadobna		Zyta
		Ostroga	Tonacja	Nadobna		Turnia	Zawisza		Nutka		
		Rapsodia	Turkis	Naridana		Wydma			Rapsodia		
		Trend		Nateja		Zawisza			Trend		
				Pegassos							
				Satyna							
				Tonacja							
				Turkis							

MIM = moderate-input management; HIM = high-input management.

ied. This group's content was the same as in the case of group 1 for MIM management. Cultivars Mulan and Jenga, bred in Germany and Poland, exhibited a wide adaptation to Polish agro-ecosystems under both crop managements.

Unstable yields were demonstrated by group 2, which contained 11 winter wheat cultivars. Cultivars included in this group had the second highest yields in almost all tested environments, but had relatively yields in Nowa Wieś Ujska and Wyczechy (lower yielding environments). The seven cultivars from group 3 were characterized by unstable yield performance. Five cultivars were the same in group 3 for both MIM and HIM levels. Group 3, for the MIM level, contained cultivars with very stable grain yields, in contrast to those for the HIM level. Group 4 contained 10 winter wheat cultivars and the group yield was the same as the average yield in all environments studied. Cultivars included in group 4 for MIM and HIM levels were almost identical, but their adaptive response was different.

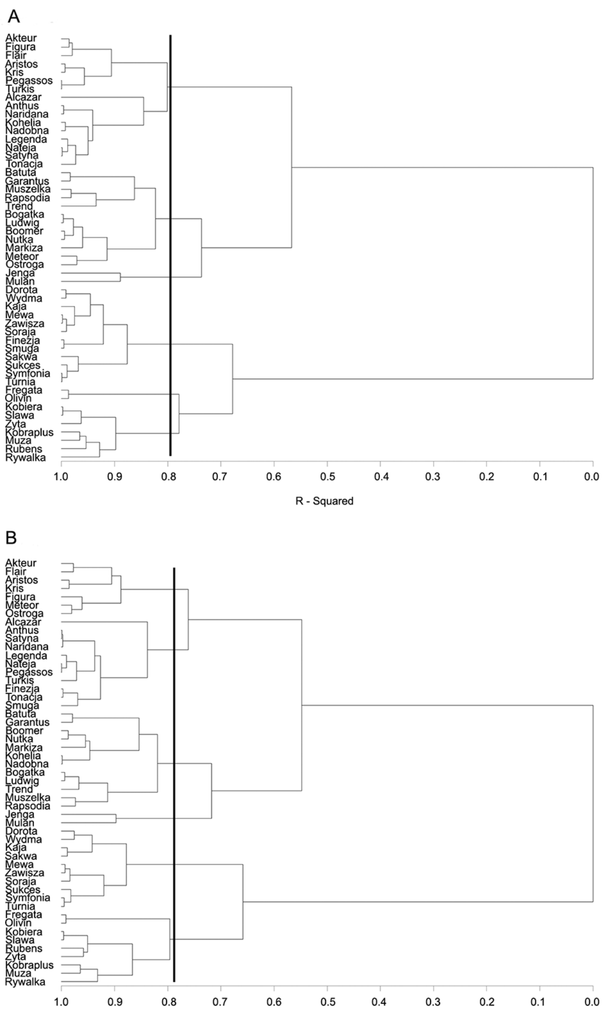

Figure 5 – Dendrogram based on the yield response of 51 winter wheat cultivars to 18 environments for A) MIM crop management intensity, and B) HIM crop management intensity.

Group 5, containing 12 cultivars, showed a lack of adaptation to agricultural environments of Poland. This group had the second lowest yield in comparison with other groups. Nine cultivars included in group 6 had an unstable performance for yield and a lack of adaptation for each tested Polish agro-ecosystem. This group had lower grain yields than any other group. Two of the cultivars from group 6 for the HIM level belonged to group 6 for the MIM level, and the rest to 5. A comparison of the mean-group yield (Figure 6A and 6B) between the two crop management intensities suggested that there can be a selection of cultivar lines with broad adaptation to both management intensities (Cooper et al., 2001). Based on G x M and G x M x L interactions, there was a different ranking of the cultivars belonging to group 1 than those belonging to the other groups.

The application of the four-way LMM with a factor analytic variance-covariance matrix, methods of pairwise comparisons and cluster analysis are complementary and effective tools for evaluating an unbalanced G x M x L x Y table. The analysis of experiments designed to examine combinations of Y, L, G and M can also provide evidence of the relative importance of each of these factors for grain yield. ASReml 3.0 proved to be an effective tool for computing the LMM with a factor analytic variance-covariance matrix for an unbalanced G x M x L x Y dataset.

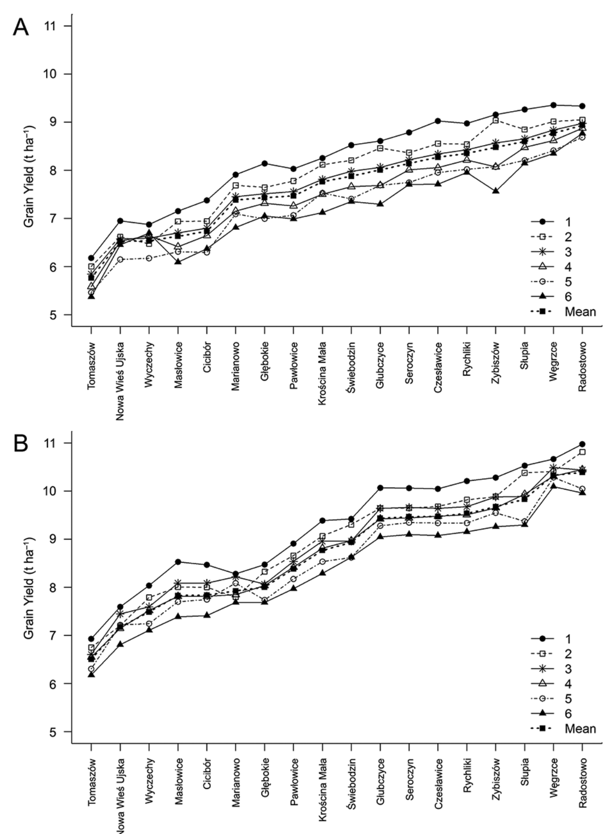

Figure 6 – Patterns of mean-group yield response across 18 agricultural environments for A) MIM crop management intensity, and B) HIM crop management intensity.

The winter wheat cultivars evaluated from the PVTS dataset yielded similar results for both crop managements. The range of the cultivar grain yield means varied from 8.37 to 9.13 t ha^{-1}. During the growing seasons studied, the 51 wheat cultivar yields tested responded differently to different agro-ecosystems in Poland. Their adaptive responses depended on the crop management intensity. Wide adaptation for both crop management systems was exhibited by Mulan and Jenga in all environments; they had the highest yield.

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