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Mazowsze Studia Regionalne 18, 181-196

2015

Artykuł został opracowany do udostępnienia w internecie przez Muzeum Historii Polski w ramach prac podejmowanych na rzecz zapewnienia otwartego, powszechnego i trwałego dostępu do polskiego dorobku naukowego i kulturalnego. Artykuł jest umieszczony w kolekcji cyfrowej bazhum.muzhp.pl, gromadzącej zawartość polskich czasopism humanistycznych i społecznych oraz w kolekcji mazowieckich czasopism regionalnych mazowsze.hist.pl.

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MUZEUM HISTORII POLSKI

DOI: 10.21858/msr.18.13

Response of Winter wheat cultivars to the environment and crop management in post-registration multi-environment trials (PDO)[1]

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ABSTRACT

In many works in the fields of agronomy, agriculture and biology, there is a need to study the impact of cultivar (genotype), agricultural technology (crop management intensity levels), and the locations (agro-ecostems or environment) on the yield of plants. PDO experiments allow such studies in Poland. In order to be properly carried out the analysis of this data must be based on statistical methods on the basis of the assumed purpose. Some studies examine the impact of the locations on crop varieties and then examine the effect of GL (GxL) interaction (genotype x location). In other studies, the researchers want to establish the impact of agricultural technology on crop varieties, e.g. in only one location. In this situation we have to deal with the classification of cultivar x crop management. There are also studies conducted to examine the impact of both the Agro-ecostyems and agricultural technology. Many authors have compared the yield of old and modern cultivars in various locations or in different crop management intensity levels (Broncourt-Hulmel et al. 2003, Derejko et al. 2011, Mądry et al. 2011, 2012).

In this case we are dealing with the classification of cultivar x crop management x location. An example of such statistical analysis adjusted for 3-way classification of data from the "Post-Registration Variety Testing System (*Porejestrowe Doświadczalnictwo Odmianowe i Rolnicze* – acronym: PDO)" experiments for grain yield of winter wheat have been presented in this study. However, this is not strictly statistical work. It is a study resulting from a series of field experiments in Poland, the benefits of these experiments and how useful it may be with appropriate modification of statistical methods for this data on grain yield of winter wheat (*Triticum aestivum L*).

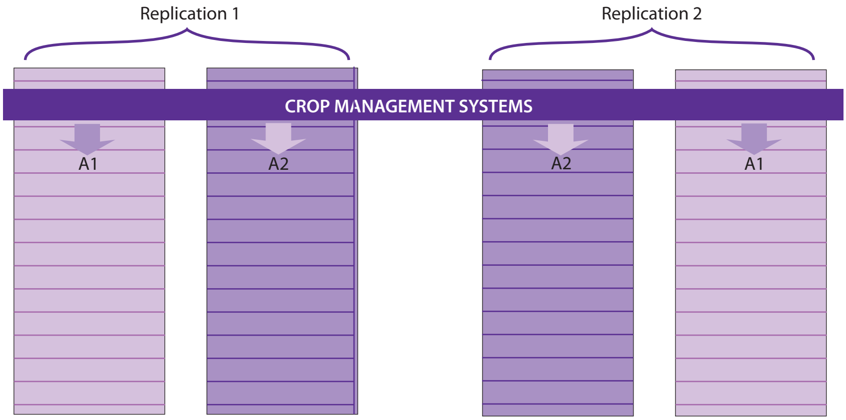
Little research has been carried out to date on the development and adaptation of the currently used methods or development of new methods mainly for more in-depth inference (Derejko et al. 2011). The problem is also insufficient knowledge and application, resulting in rather modest achievements by foreign scientists regarding the methodology discussed. In this paper we have data from a multi-factor series of experiments, planned in the *split–block* design and repeated both in one growing season and over time, (McIntosh 1983).

Introduction

The purpose of this work is adaptation and an approach other than the statistical approach applied up to now, to data from a series of experiments in post-registration multi--environment trials (PDO), performance, the empirical illustration of use as well as the opinion of usefulness of the combined analysis of variance and Tukey's procedure and T-Student test for multiple means comparisons to draw inference about reaction of changes on conditions of the agro-ecosystems (environmental) in locations and two crop management intensi-

[1] Od redakcji: Artykuł pani Adriany Derejko zamieszczony został w części *Varia* ponieważ porusza zagadnienia odmienne problemowo w stosunku do pozostałych tekstów publikowanych w niniejszym tomie. Artykuł ma charakter naukowy i był poddany recenzji.

Figure 1. Experimental trial obtained in a split-block design (COBORU 2002).



ty levels (A1 and A2), with data from one year, multiple series of post-registration multi-environmental trials PDO, obtained in a *split-block* design (Fig. 1).

Empirical illustration of data analysis on winter wheat yield is distinguished in PDO experiments conducted in 2009. Many field experiments are conducted over two or more locations or years, but statistical references do not contain sufficient detail for a comprehensive analysis. The purpose of my study is to provide a reference for analysis of combined experiments. In the experiments presented in this study ANOVA tables include sources of variation, degrees of freedom, and F-statistic for one factor and *split-block* experiments combined over locations and/or years. The F-statistics are given for fixed, mixed and random models.

Proposed statistical methodology is effective to draw inference about reaction to changes in the winter wheat studied, both in environmental conditions and the crop management intensities. In environmental conditions the variable reaction of winter wheat was examined. The change in winter wheat varied in the level of intensity of cultivation and variable environmental conditions in Poland, and not in relation to cultivation of wheat to environmental conditions. Winter wheat crop was higher in all varieties with the use of higher crop management intensities, irrespective of locality. However, as the average crop management intensities in each Experimental Station for Cultivar Testing changes diminished, so did the intensity of productiveness of these environments.

What exactly is PDO ?

In 1998 in Poland a system of post-registered cultivar trials was conducted. Historically, PDO (*Porejestrowe Doświadczalnictwo Odmianowe*), and now PDOiR (*Porejestrowe Doświadczalnictwo Odmianowe i Rolnicze*), is the only such system of experimentation in the

European Union, which uses a synergistic organizational and economic effect and the outcome stemming from the cooperation between experimental research units in the country and central and local government. (COBORU 2011). Post-Registration Variety Testing System operates on the regional level to help Polish, but not only, farmers to select the most adapted cultivars for different agricultural conditions and for the processing industry. In this open and flexible system the cooperation of all parties interested in varietal selection and usage (e.g. Agricultural Chambers, Advisory Services, Cultivation Companies, Seed Producers, Producers' Unions, Processing Industry and other interested institutions) is a norm. Based on the results of copious research and experience a Polish National List of Varieties recommended for cultivation in the province (LZO – *Lista Zalecanych Odmian*) was compiled.

The scope of research and the state of PDO:

Within the post-registration agricultural experimental specific system multi-factor experiments are performed. Among these factors the most important are agricultural plant species varieties and crop management intensity levels. Data of agricultural products (mainly yield, but also other farm characteristics), obtained in the series of experiments form the basis of an empirical study of varied reactions of cultivars to the spatially variable environmental conditions in various systems of cultivation, and reaction of different varieties in two levels of intensity of cultivation under different environmental conditions. This way you can reliably assess the suitability of agricultural varieties currently available on the seed market in Poland, intensive or semi-intensive cultivation in different micro-regions or across the country. Therefore, the studies of PDO cultivars are the basis for micro-regions in the country and also allow them to detect the factors limiting crop varieties registered in certain parts of the country (Derejko et al. 2011). The scope of PDO research covers all major crop species, especially field, focused on the study of cereals, including winter wheat.

Table 1. Characteristics of two crop management intensities – A1 and A2, examined in the post-registration multi-environmental trials (PDOiR)

Agronomic treatments	crop management intensity levels	
	A1	A2
Nitrogen application level	+	N level for A1+40
Fungicide use: the first treatment (protection of stalk and leaves)		+
Fungicide use: the second treatment (protection of leaves and spike)		+
Retardant use		+
Foliar compound fertilization use		+

Figure 2. Locations of the Experimental Stations for Cultivar Testing in Poland within the network of COBORU stations where post-registration trials (PDOiR trials) were conducked – www.coboru.pl, (COBORU 2002)

The main aim of this system is evaluation of selected cultivars of main crops. One of the crops included in this system is winter wheat. The most common experimental design used in this PDO system is the *split-block* design. It is a two-factorial design which, apart from the main factor i.e. cultivar, examines a second factor i.e. management level (A1 – crop management of lower intensity and A2 – crop management of higher intensity) – Table 1.

Such experiments are conducted in several locations across Poland. They assists evaluation of the stability of grain yield in different environmental conditions. PDO systems are conducted in many places in Poland (Fig. 2) with many different plants. However, 50% of all experiments within this system involve cereals, 17% winter wheat (COBORU 2002, 2010).

All experiments under the PDO coordinated in terms of methodology and content are conducted in the Experimental Centre for Cultivar Testing (COBORU – *Centralny Ośrodek Badania Odmian Roślin Uprawnych*). It is a state institution, whose main task is to survey and register crop varieties, legal protection of plant varieties, information about the varieties listed in the National Register of Varieties and their botanical descriptions in drawing up lists of cultivars of agricultural, vegetable and fruit varieties listed in the register, and preparation of descriptive lists of cultivars, along with information on yield, quality features and functional cultivars, cooperation with foreign entities involved in the registration and legal protection of varieties and the International Union for the Protection of New Varieties of Plants (UPOV), the European Commission and the Community Plant Variety Office (CPVO) and the implementation of tasks in the post-registration and experimental specific information about its results (Journal of Laws No. 239/2010, 1591).

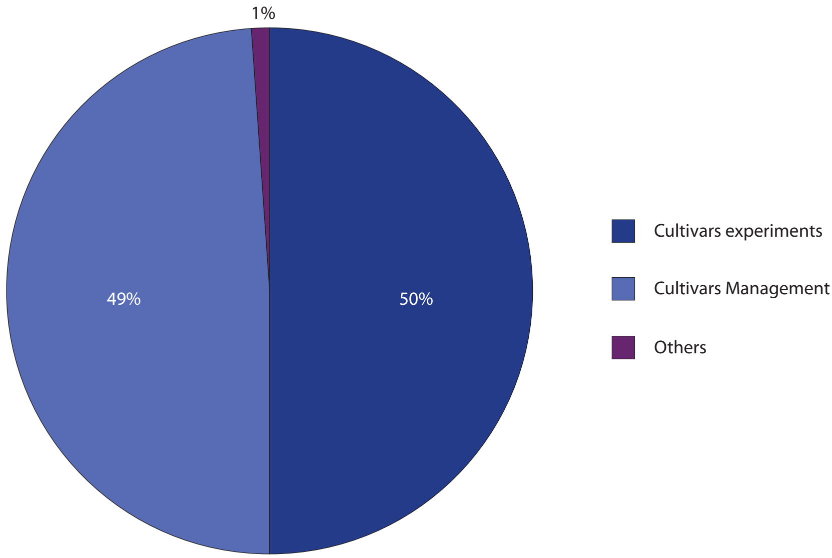
An impediment in the methodology of the PDO are reflections on the impact of the number of locations, on the scale of the interaction with the environment, varieties and their interaction in each locality, which cultivars have of each locality in the creation of this interaction. The considerations are carried out using the results of a one-year series of experiments with varieties of a given species carried out in the locations.

The percentage structure of PDO experiments conducted in terms of their types and the structure of these experiments in terms of agricultural plant species tested, is illustrated in Figure 3. Among all the PDO experiences, about half are a specific experience and the same, a variety-agro experience. Most studies of this type involve cereals. The realization of a series of PDO experiments conducted throughout the country (in experimental stations and experimental plants) represent the spatial variability of agro-ecosystems for the major plant species cultivated in Poland (Derejko et al. 2011, Weber et al. 2011, www.coboru.pl).

Countries around the world attach increasing importance to the experience regarding variety – agronomic crops, as evidenced by the growing number of scientific articles in the press on this subject. Ratings of the adaptive response of varieties of agricultural plant species which are important in cultivation studies are reviewed on the basis of a series of field experiments conducted, specific agronomic or variety – called Multi-Triassic environment METs (Hayward 1994, Sivapalan et al. 2000; Annicchiarico 2002, Paderewski et al. 2011).

A specific series of experiments to evaluate the adaptive response to environmental conditions of varieties in terms of yield and/or other characteristics, such as agricultural nitrogen fertilization, resistance to diseases or paralysis (Ma et al. 2004, Souza et al. 2004). Grain yield is, of all the features of agriculture, the easiest parameter to measure because of the quantitative nature of this trait (Mądry 2003, Mądry and Iwańska 2011. A series of variety – agronomic tests is not performed as often as the above-mentioned specific experiment. With data from these experiments it is possible to study the type of adaptation to environmental variations, the intensity level of agricultural technology and the interaction of these factors (Ayoub et al. 1994, Ma et al. 2004, Souza et al. 2004). In Poland such experiments are carried

Figure 3. Types of experiments conducted in PDOiR (www.coboru.pl)



out under the PDO. Here methodology used was developed by the Experimental Centre for Cultivar Testing, which provides guidance necessary to carry out each stage of the experiment, the stages of planning, observation, measurement and the documentation of results (COBORU 2002).

Multi-location testing remains the main tool for understanding cultivar responses to agro-ecosystems, but the process is both time-consuming and expensive. The efficiency of this analytical process can be enhanced by using recently developed statistical methods. This publication aims to assist plant cultivators and farmers by examining the opportunities offered by such methods. FAO hopes that this publication will be useful to a wide variety of persons interested in efficient, sustainable use of plant genetic resources, especially those focusing on the improvement of agriculture in the food-deficit of developing countries (Annicchiarico 2002).

Plant cultivation can be expected to assume a pivotal role in increasing the availability and stability of agricultural production in the future, particularly insofar as increased attention will be paid to: the sustainability of agricultural systems; and the development of farming systems in less favourable areas.

PDO programs aim to make correct decisions on a number of issues comprising cultivation strategy. Decisions may relate to, in particular:

- adaptation strategies, yield stability and other (e.g. crop quality) targets;

- genetic resources forming the genetic base (indigenous or exotic, from traditional or improved varieties);
- techniques for the recombination and useful genetic variation;
- cultivation plan and selection procedures (selection environments, indirect selection criteria, presence and extent of participatory cultivation, experimental designs etc.) – (Annicchiarico 2002);
- the systematic provision of reliable information on the usefulness of economic varieties for different regions in the country and different levels of agricultural technology;
- facilitating farmers accurate selection of the most valuable varieties for cultivation adapted to local economic conditions and growing technology – www.coboru.pl (COBORU 2002, 2010).

Implementation of the specific post-registration and Agricultural Experiments every year brings tangible benefits, because it uses biological progress in agriculture more efficiently. Through this program, the farmer regularly receives reliable information about the value of varieties of traded seed in diverse growing conditions in different parts of the country. PDO makes it easier for farmers to select the most valuable crop cultivars adapted to local environmental conditions.

GxL, GxMxL Interaction in PDO experiments – why is it so important?

Almost all the important agronomic traits are subject to the phenomenon of genotype-environment interaction (G × E Interaction). This interaction consists of a diverse response of the characteristics of the tested varieties to changing environmental conditions in different localities, systems, crops and years (Mądry and Iwańska 2011, Caliński et al. 1980, Basford et and Cooper 1998, Annicchiarico 2002). When examining the interaction so far proposed, different procedures of GEI (gemotype × Environment interaction) analysis were used, such as a regression coefficient (Finlay and Wilkinson, 1963), the sum of squares of deviations in analyzing regression (Eberhart and Russell, 1966), the coefficient of variation (Francis and Kanneberg, 1978), AMMI analysis (Gauch and Zobel, 1988, Annicchiarico, 1997), analysis of GGE (Yan et al. 2000). GEI interaction is described in more detail in section 3.2. In practice, the cultivator, determines the existence of that interaction on his own system genotype × location. The definition of a strategy with respect to GL (genotype × location) interactions or three factors – GML (genotype × crop management intensities × location) interactions may require decisions on most of these elements, namely: adaptation strategy and stability targets, genetic resources, variety type, cultivating plan and selection procedures. Initial decisions may change with time as a consequence of new opportunities offered by scientific progress, experimental evidence, available funding, food security policies, changes in national seed systems, international cooperation etc. But they should remain consistent with the cultivation objective. For example, the inconsistency between targeting unsuitable areas also and adopting genetic resources and selection of procedures producing material specifically adapted to favourable environments has contributed to the partial failure of a number of cultivation programs carried out in the Green Revolution context. Cultivation for wide adaptation and for high yield stability and reliability has sometimes been considered as one and the same, insofar as the latter is concerned, two terms indicate a consistently good yield response across environments. Some authors, however, have applied the yield stability concept to consistency in the time of genotype performance, using the adaptation concept in relation to consistency in many locations. It has also been widely acknowledged (Annicchiarico 1997, 2002) that only genotype × location (GL) interaction, rather than all kinds of GE interaction, is useful for depicting adaptation patterns, as only this interaction can be exploited by selection for specific adaptation or by growing specifically adapted genotypes. For example, the knowledge of specific adaptation in past years, as shown by positive genotype × year (GY) interaction effects, cannot be used in future years, since the climatic conditions that generate year-to-year environmental variation are not known in advance. This view implies that analysis of adaptation – and its implications for the definition of adaptation strategies for cultivation programs and domains of cultivar recommended for extended varieties, may concern only responses to locations, geographic areas, farming practices or other factors that can be controlled or predicted prior to sowing. In particular, the analysis of multi-environmental yield trials should focus primarily on GL interaction, with the characteristics of the locations depending on climatic, soil, biotic (pests and diseases) and crop management factors. The remaining interactions of genotype with the time factor (year for annual crop, crop cycle for perennials) should be dealt with in terms of yield stability. In some cases, the concept and the analysis of adaptation may concern the genotype responses to a set of management practices that have a crucial impact on GE effects, rather than the responses to locations (e.g. Annicchiarico and Piano, 1995, Annicchiarico et al. 2010).

Both the effect of the interaction of double and triple grain yield is related to the statistical methodology used and the target set by the researchers. It is always a difficult methodological and substantive task. In this paper, for example, inference from data for grain yield of winter wheat was presented in a PDO in simple statistical methodology based on the classical method of three way ANOVA and multiple comparison procedures. This is not the only approach to the analysis of such data. However, the usefulness of applying such methods has been confirmed in the work Derejko et al. (2011) and in the works cited therein (Brancourt-Hulmel et al. 2003, Ma et al. 2004, Souza et al. 2004).

The aim of this survey is to present possibilities of inference based on data collected from such PDO trials with winter wheat.

Example of PDOiR empirical experiments

Material and methods

Each year a series of experiments in PDO/PDOiR systems are conducted with a different set of cultivars. Every year some of the older cultivars are removed and new registered cultivars are included in trials. Such series of experiments are referred to as: series L. In our study we consider 8 locations across Poland (Fig. 2) and 28 of wheat cultivars.

Figure 4. Locations in which PDOiR field trials with winter wheat were conducted

The second factor was crop management intensity. Two levels of crop management (A1 and A2) – Table 1, were examined. The main differences between these management levels are: higher nitrogen fertilization for A2 (+40 kg N/ha) and lack of fungicide protection in A1 – Table 1. A *Split-block* design was conducted in each location in two blocks. The classical approach was used for statistical analyses with three-way ANOVA (fixed factors: locations, cultivars and management levels) and Tukey's post-hoc procedures (McIntosh 1983). The analyses were conducted in SAS 9.1 using the GLM procedure.

Agricultural techniques, following an assessment of their economic performance in regional yield trials, can be recommended: either widely over the target region or specifically for one sub-region (Annicchiarico 2002). For specific recommendation, the recommendation

Table 2. Joint analysis of variance for grain yield of winter wheat based on fixed model

Sources of variability		df	SS*	MS**	F***	p-value
L	location	7	10444575	1492082	306.99	<.0001
block/L	block (location)	8	394695	49337		
A	management	1	1877311	1877311	163.27	<.0001
AxL	management*location	7	375691	53670	4.67	0.0229
AxBlok/L (Error I)	block*management (location)	8	91983	11498		
B	cultivar	27	503471	18647	4.15	<.0001
BxL	cultivar*location	189	1307860	6920	1.54	0.0011
BxBlok/L (Error II)	block*cultivar (location)	216	970121	4491		
AxB	management*cultivar	27	161590	5985	1.23	0.2081
AxBxL	management*cultivar* location	189	894343	4732	0.97	0.574
AxBxBlok/L (Error III)	residual	216	1049823	4860		

* Sum of squares; ** Mean of squares; *** F-Statistic

domain of a given technique may be defined on the basis of geography alone, or also on the basis of farming practices (e.g. irrigated or rainfall cropping) or socio-economic constraints. In all cases, the information obtained from previous testing is used to predict yield responses in the coming years and, most frequently, in new locations.

Results

The results based on a three-way analysis of variance (procedure GLM in SAS, 2004) and the procedure of multiple comparisons are presented in Table 2.

On the basis of the results in Table 2 we can prove a significant effect of management level (factor A) and significant effect of cultivar (Fig. 5) to compare winter wheat grain mean yields calculated across 28 cultivars and 8 locations for two crop management intensities using the T-Student test. Mean grain yield for tested cultivars was presented in Figure 6. The grain yields were very high for all cultivars and homogenous groups are not seperable.

Figure 7 presents interaction between management levels and locations. In almost all locations there was a significant difference between mean grain yields except for two locations with lower yields i.e. Marianowo and Głębokie where differences were not significant in this comparison between two crop management intensity levels using the T-Student test.

Figure 5. Comparison of winter wheat grain yield means calculated across 28 cultivars and 8 locations for two crop management intensities ($LSD_{\alpha=0,05}$=16.5)

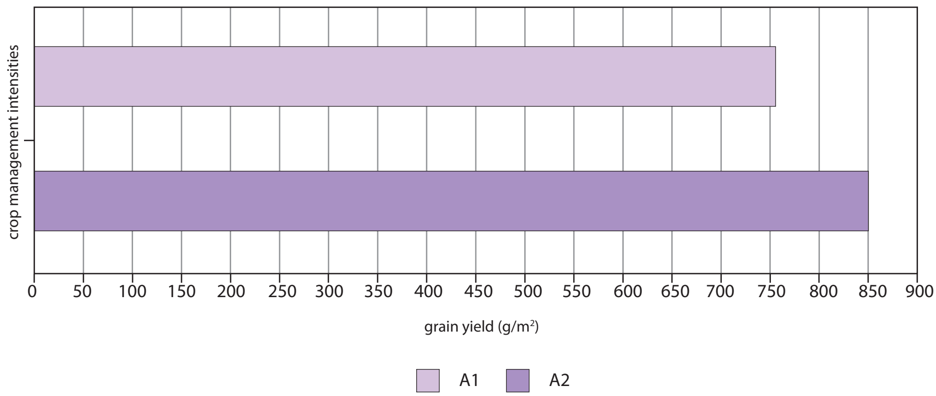


Figure 8 presents interaction between cultivar and locations (GL interaction). We observed a difference in reaction in 5 out of 28 cultivars in 8 locations. Unequal reaction of varieties is a statistically significant interaction between cultivars and locations. These varieties responded with unequal yield increase in various Agro-ecosystems. Significant interaction of factor A and B with locations (A × L and B × L) was observed. This means that yielding of

Figure 6. Comparison of winter wheat cultivar means for grain yield calculated across 2 crop management intensities and 8 locations and mean homogenous groups established using Tukey's procedure ($HSDTukey_{\alpha=0,05}$=63.1)

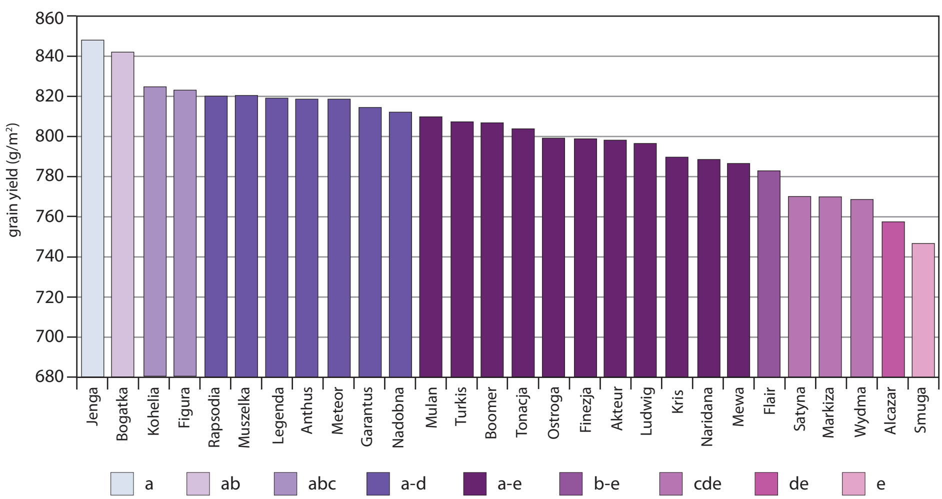
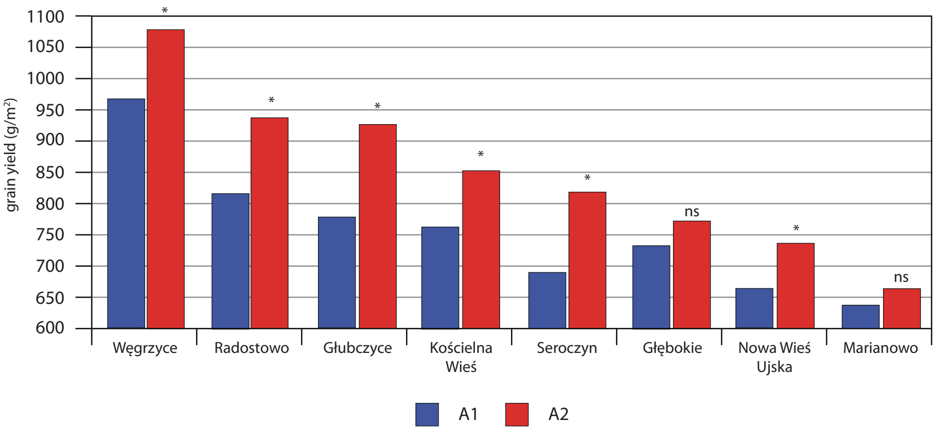


Figure 7. Response of grain yield of winter wheat to two crop management intensities A1 and A2, as averaged across 28 examined cultivars, to the test locations ($LSD_{\alpha=0,05}$=46,7 for comparisons of means at A1 and A2, respectively, to each of the test locations)



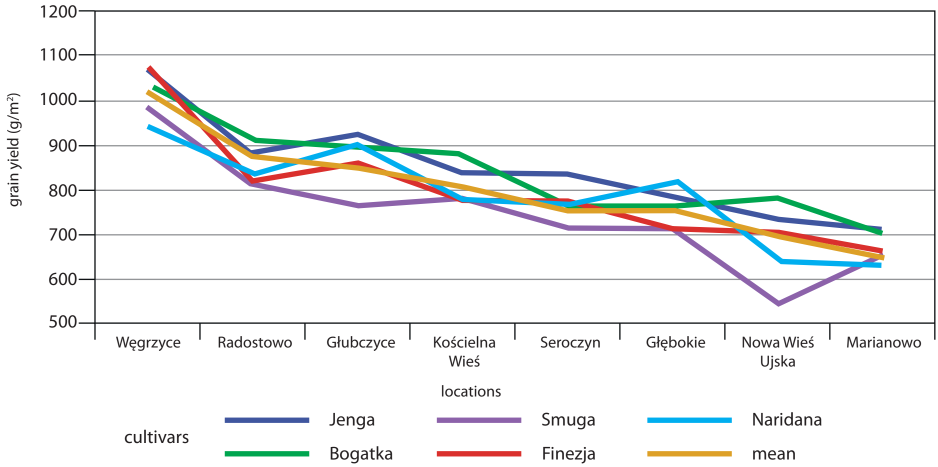
cultivars was modified by environmental conditions according to location. This interaction is presented in Figure 8. Figure 8 presents five out of 28 cultivars. The most visible interaction in this figure is for the Naridana cultivar.

Conclusions

1. Multi-location post-registered trials (PDO) with winter wheat cultivars are a very important source of information on the yielding of the most important cultivars in the Polish recommendation list.
2. Analyses of data from such trials carried out using a statistical method (three-way ANOVA, and multiple mean comparisons) allows us effective assessment of the main effects of cultivars on grain yield and interaction of cultivars with environmental conditions (locations) and crop management intensity levels.
3. Inference based on such results can be used for more targeted recommendations of cultivars in farming.

Multi-location of post-registered PDO trials with wheat cultivars are a very important source of information about yielding of most important cultivars in the Polish register. Data from such experiments analyzed using the classical method (ANOVA and multiple comparisons) evaluate the effects of cultivars and their interaction with environmental conditions as well as with the management level. Inference based on such results can be used for recommendations for farmers. In testing interaction between environments, crop management

Figure 8. Different responses of 5 chosen winter wheat cultivars for mean grain yield to varied environments in test locations



intensity levels and cultivars we are faced with challenges and opportunities for plant cultivation and cultivar recommendations.

The applied methodology proved to be an effective tool to draw conclusions about the reaction of 28 winter wheat cultivars in 8 locations using two intensities of agricultural technology in one year – 2009. Much more reliable information could be obtained from this data and these experiments were repeated in several growing seasons. However, the classification of cultivar × crop managements × locations × years is a serious challenge for statisticians. The inference from such data classification is very complicated and requires a lot of knowledge in the field of statistics, biometrics and agronomy. However, this poses a challenge for young researchers in this direction, because the usefulness of statistical methods for inference of data from field experiments is used and appreciated worldwide. Results of the evaluation of yield and adaptability of the cultivars of winter wheat studied which are common in various agro-ecosystems in Poland and intensity of agricultural technology, obtained using the proposed statistical methods, can be an important source of reliable evidence on which to base recommendations for cultivation of this species of plant in the country, which is the result of conducting the PDO.

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Reakcja odmian pszenicy ozimej na środowisko i technologię uprawy na przykładzie Porejestrowego Doświadczalnictwa Odmianowego (PDO).

STRESZCZENIE

Praca ma charakter informacyjny, dotyczący prowadzonej działalności, doświadczeń oraz wpływu na rozwój polskiego rolnictwa Porejestrowego Doświadczalnictwa Odmianowego (PDO). System ten pod względem metodycznym oraz merytorycznym koordynowany jest przez Centralny Ośrodek Badań Roślin Uprawnych (COBORU), z siedzibą w Słupii Wielkiej. W pracy przedstawione zostały główne zadania PDO oraz na czym polegają doświadczenia polowe prowadzone w ramach tego systemu. W celu zobrazowania metodyki statystycznej, wykorzystywanej do analizy danych z PDO, został przedstawiony przykład doświadczenia z 28 odmianami pszenicy ozimej z serii L, realizowanych w 8 stacjach badawczych (miejscowościach testowych), przy dwóch intensywnościach technologii uprawy. Analiza statystyczna obejmuje trójczynnikową analizę wariancji wykonaną w celu wykrycia wpływu efektów głównych i interakcyjnych na plon pszenicy ozimej. Dodatkowo została zastosowana wizualizacja graficzna w celu prostszej i efektywniejszej analizy otrzymanych wyników.

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