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COMMUNICATIONS IN BIOMETRY AND CROP SCIENCE
VOL. 10, NO. 1, 2015, PP. 27–40

INTERNATIONAL JOURNAL OF THE FACULTY OF AGRICULTURE AND BIOLOGY,
WARSAW UNIVERSITY OF LIFE SCIENCES – SGGW, POLAND

REGULAR ARTICLE

# Evaluation of yield response of second early edible potato cultivars to spatial environmental conditions

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CITATION: Rymuza K., Lenartowicz T., Radzka E., Bombik A. (2015). Evaluation of yield response of second early edible potato cultivars to spatial environmental conditions. *Communications in Biometry and Crop Science* 10, 27–40.

Received: 22 October 2014, Accepted: 21 April 2015, Published online: 13 May 2015


## ABSTRACT

Analyses were performed on a tuber yield dataset consisting of yield data for 14 second early edible potato cultivars, obtained from a series of multi-year (2010-2013), multi-location PDO (post-registration variety testing) experiments. The trials were conducted at 6 experimental stations at the Research Centre for Cultivar Testing (COBORU) in Słupia Wielka (Poland). The objective of this work was to evaluate the response of potato cultivars to diverse environmental conditions in Poland, taking into account total precipitation and mean air temperature during the growing season. The analyses demonstrated that there was a significant interaction between cultivars and years as well as between cultivars, years, and locations. On the contrary, the 'cultivar x location' interaction was not significant. The structures of both the significant interactions were analysed using mixed multidimensional and joint regression models. The cultivars Ametyst and Bogatka did not interact with the environment, but only the first cultivar was considered stable. All the remaining cultivars significantly interacted with the environment, in particular Finezja and Oberon, which responded significantly to environmental conditions during the growing season.

**Key Words**: *genotype-by-environment interaction; multi-environment experiments; yield stability; potato cultivar.*

## INTRODUCTION

Edible potato is a major crop worldwide due to its versatility and role in human nutrition (Cotes et al. 2002, Sadowska et al. 2004, Hassanpanah and Azimi 2010). Potato tubers may be consumed directly or after processing. Depending on how they are used, potato cultivars should possess certain qualitative characteristics and produce high and stable yields. Yield performance of a crop is affected by the cultivar (genotype) and environmental conditions, as well as by crop management systems (Cotes et al. 2002, Kołodziejczyk 2013).

Potato is mainly cultivated on light soils and, therefore, yield depends on an even rainfall distribution during the growing season. Furthermore, many authors stressed the importance of the combined effect of temperature and precipitation (Szutkowska and Lutomirska 2002, Chmura et al. 2009).

In general, farmers are interested in growing genotypes which produce high and stable yields under a wide range of soil and climatic conditions (Dopierała et al. 2003, Jeżowski et al. 2003, Scapim et al. 2010, Stefanova and Buirchell 2010). Yield instability relates to the presence of a significant genotype-by-environment interaction, which results either from dissimilar (non-parallel) response of genotype traits to environmental conditions (locations and/or years) or from dissimilar differences between means for genotypes in different environments (Annicchiarico 2002, Yan and Kang 2003, Annicchiarico et al. 2006a). When the genotype-by-environment interaction is found, high-yielding cultivars may perform poorly when growing conditions change (Cooper 1999, Tai and Coleman 1999, Cotes et al. 2002, Abalo et al. 2003).

Analysis of the genotype-by-environment interaction provides information on the average yield-forming ability of cultivars and on their adaptation to a range of environmental conditions (Mądry et al. 2003). Furthermore, such an analysis makes it possible to assess which cultivars produce the highest average yields and which perform well in all environments. Cultivars (genotypes) whose yields are only slightly affected by changes in environmental conditions are considered as stable (Kang 1988, Mądry and Iwańska 2011), while cultivars producing high and stable yields under a wide range of soil and climatic conditions in the whole target region are regarded as widely adapted (Cooper and DeLacy 1994, Basford and Cooper 1998, Annicchiarico and Piano 2005, Annicchiarico et al. 2006b). On the contrary, cultivars producing relatively high yields only in some selected environments (sub-regions) are regarded as narrowly (locally) adapted (Atlin et al. 2000 a, b, Yan et al. 2000, de la Vega and Chapman 2006).

Analysis of genotype stability makes use of data from a series of multi-location cultivar experiments within a given area, which may be performed within a single year or across several years. In the former case, genotype stability in the area may be assessed, while in the latter case genotype stability and adaptation to the area can be determined together with the repeatability of performances across years (Léon and Becker 1988). The process of data analysis is based on studying how the actual shape of genotypic responses to the environment differs from the average yield response of all the tested cultivars. Many parametric and non-parametric methods have been used to achieve this aim (Scapim et al. 2000, Sabaghnia et al. 2006, Mohammadi et al. 2010), though, according to Mądry et al. (2006), Iwańska et al. (2008) as well as Paderewski et al. (2011), the best methods should combine the evaluation of genotype yield means and their across environments variances.

The mixed Shukla model, either in its basic version or in the modified version known as mixed joint regression Eberhart-Russell-Shukla (E-R-S) model (Eberhart and Russel 1966, Shukla 1972), has been used frequently to analyze the stability and adaptation of genotypes (Caliński 1966, Shukla 1972). In Poland, the mixed Sheffe-Caliński model has been often applied as an alternative to the Shukla model. This model has been implemented both in its basic version and in its joint regression version (Caliński et al. 1997, Mądry and Rajfura 2003), within the computer package SERGEN 4. The program can analyze balanced multi-environment experiments and can manage two types of incomplete data: incomplete multiple series of experiments (where the experiments were not carried out in all combinations of environmental classifications) or a series of experiments with different genotype sets. Only when the genotype-by-environment system is cohesive and repeatable, one can assign a value to a genotype that has not been examined in a given environment (Caliński et al. 2003). Moreover, SERGEN 4 permits the analysis of genotype means and makes it possible to extend the analysis of variance for a series of experiments by including a regression analysis on environmental covariates. In all, this program makes it possible to analyse the results of several types of agricultural experiments repeated in time and space, which is the basis of agricultural research.

As literature is limited on the stability of edible potato cultivars grown in Poland, we attempted to analyse the yields of 14 second early edible potato cultivars grown at 6 locations in Poland. The objective of this work was to assess the response of cultivars to rainfall and average air temperature during the growing season.

## MATERIALS AND METHODS

The dataset was composed of yield performance results for 14 second early edible potato cultivars. Cultivars were collected from a series of multi-year (2010-2013) post-registration trials (PDO) carried out at 6 experimental stations (SDOO) of The Research Centre for Cultivar Testing (COBORU) in Słupia Wielka (Poland). The test cultivars had already been registered and accepted for post-registration testing.

Field trials were arranged as randomized complete block designs with three replicates and were established at the following six locations: Karżniczka, Naroczyce, Słupia, Sulejów, Uhnin and Węgrzce, which are characterised by different soil and weather conditions. All cultivars (listed later on) were cultivated at each station during the 2010-2013 growing seasons, except Bogatka, Malaga and Otolia, which were introduced in 2011. Table 1 presents geographical coordinates of the localities and Table 2 contains soil conditions as well as precipitation and thermal conditions during the growing season. Table 2 shows that the lowest rainfall level was recorded in Sulejów in 2012 (287 mm) and the highest in Węgrzce in 2010 (804 mm). The average air temperature during the growing season was the lowest in Karżniczka in 2010 (13.6°C) and the highest in Węgrzce in 2012 (16.2°C).

To be included in the analysis a cultivar was tested at each location for at least three years during the study period. The results obtained for individual years and locations were analysed statistically using the mixed multidimensional Scheffé-Caliński model and the Caliński-Kaczmarek joint regression model using SERGEN 4 (Caliński et al. 1997, Caliński et al. 2003, Mądry and Rajfura 2003, Mądry and Kang 2005).

Data were analyzed in two steps. The first step was a classical one-way ANOVA for yield to determine differences among cultivars in each of the 24 field experiments (6 locations (L) × 4 years (Y)). Second, average yields for cultivars, mean squares for errors and degrees of freedom for error were obtained for individual (24) experiments and analysed using SERGEN. The combined analysis of variance evaluated the influence of cultivar (G), environment (E) and GE effects on potato yield. Each environment was a year× location combination.

Table 1. Geographic coordinates of Research Centre for Cultivar Testing (COBORU) stations

| Station | Geographic coordinates | | $H_s$ m above sea level |
|---|---|---|---|
| | φ° | λ° | |
| Węgrzce | 50° 07′ | 19° 59′ | 285 |
| Karżniczka | 54° 29′ | 17° 14′ | 80 |
| Naroczyce | 51° 31′ | 16° 26′ | 110 |
| Uhnin | 51° 34′ | 23° 02′ | 157 |
| Słupia | 50° 38′ | 19° 58′ | 290 |
| Sulejów | 52° 12′ | 19° 08′ | 132 |

Explanations: φ – geographic latitude, λ – geographic longitude, $H_s$ – elevation above sea level.

Table 2. Soil, precipitation and thermal conditions of Research Centre for Cultivar Testing (COBORU)stations

| Station | Total rainfall (Apr-Sept) | | | |
|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 |
| Węgrzce | 804 | 416 | 311 | 458 |
| Karżniczka | 581 | 470 | 550 | 445 |
| Naroczyce | 489 | 429 | 462 | 510 |
| Uhnin | 455 | 425 | 326 | 443 |
| Słupia | 745 | 352 | 349 | 465 |
| Sulejów | 491 | 401 | 287 | 451 |
| | Mean air temperature (Apr-Sept) | | | |
| Węgrzce | 15.4 | 16.0 | 16.2 | 15.2 |
| Karżniczka | 13.6 | 14.6 | 14.2 | 14.0 |
| Naroczyce | 14.9 | 15.9 | 15.4 | 15.1 |
| Uhnin | 16.1 | 15.5 | 16.1 | 15.4 |
| Słupia | 14.6 | 15.4 | 15.7 | 14.8 |
| Sulejów | 14.7 | 15.3 | 15.6 | 14.7 |
| | Soil | | | |
| | Complexes of agricultural soil suitability | | Soil quality classes | |
| Węgrzce | very good wheat, good wheat, | | I-IIIb | |
| Karżniczka | very good wheat, good wheat, imperfect wheat, | | I-IIIa | |
| Naroczyce | very good rye, good rye, | | II-VI | |
| Uhnin | very good rye, good rye, poor rye, rye-lupine | | IVa-VI | |
| Słupia | very good wheat, good wheat, imperfect wheat, | | IIIa-VI | |
| Sulejów | very good rye, good rye, poor rye, rye-lupine | | IVa-VI | |

The mixed Scheffé-Caliński model assumes that genotypes are a fixed factor, whereas environments are a random factor, which generates a population of locations within the target region during one year (if the environments are locations in a selected year) or a population of locations and years (if the environments are a combination of locations and years). The following works confirm that it is justified to treat environments as a random factor in a series of cultivar experiments (Denis et al. 1997, Basford and Cooper 1998, Nabugoomu et al. 1999).

The Caliński-Kaczmarek model for the genotypes x environments classification is as follows:

$$y_{ij.} = \mu + g_i + e_j + ge_{ij} + \varepsilon_{ij.} \quad (1)$$

where $y_{ij.}$ is an observed yield for the genotype $i$, μ is the overall mean, $g_i$ is the main effect of $i$-th genotype, $e_j$ is the random main effect of $j$-th environment, $ge_{ij}$ is the effect of an interaction of $i$-th genotype and $j$-th environment, $\varepsilon_{ij.}$ is the experimental error.

It is assumed that the random component for the $j$-th environment and the interaction effect for the $i$-th genotype and $j$-th environment $ge_{ij}$ may be related. Such correlation takes the form of a linear regression of the environmental main effect and may be used to assess the trend of genotype response to varying environmental conditions. In this model, environmental means are used as indicators of environment quality (Mądry and Rajfura 2003).

Interaction effects $ge_{ij}$ expressed as a regression function on environment means $y_{.j.}$ result in the following joint regression analysis model (Caliński-Kaczmarek model):

$$y_{ij.} = \mu + g_i + (y_{.j.} - \mu) + \beta_i( y_{.j.} - \mu) + d_{ij} + \varepsilon_{ij.} \quad (2)$$

where $\beta_i$ is a linear regression coefficient (slope) for *i*-th genotype, $y_{.j.}$, is the average yield for environment *j*, $d_{ij} = ge_{ij} - \beta_i(y_{.j.} - \mu)$ is a regression residual (deviation from regression) for the *i*-th genotype in *j*-th environment.

The regression coefficient $\beta_i$, also known as a sensitivity parameter of a genotype, describes the environmental trend of yield for *i*-th genotype, which characterises its response to environment quality. When $\beta_i$ is high in absolute value the *i*-th genotype appears to respond to environmental quality, in contrast to a stable genotype, which shows a very small $\beta_i$ value (Mądry and Rajfura 2003).

The first stage of calculations involved variance analysis conducted separately for each year and locality according to the model of a one-factor experiment arranged as randomised blocks design:

$$y_{ij} = m + a_i + r_j + \varepsilon_{ik} \qquad (3)$$

where $y_{ij}$ is the observed yield for genotype *j* in block *i*, *m* is the population mean, $a_i$ is the effect of *i*-th genotype, $r_j$ is the effect of *j*-th complete block and $\varepsilon_{ij}$ is the random error.

The above analyses produced average yields for each cultivar in individual locations and years, mean square errors and their degrees of freedom for individual experiments. The values were entered into a SERGEN 4 spreadsheet. Additionally, the following two explanatory variables were included in the multiple combined analysis: mean air temperature during the growing season and total precipitation during the growing season, as these variables may strongly impact potato yield (Kołodziejczyk 2013).

In order to explore the structure of the genotype x year and genotype x location interactions, canonical variate analyses were performed on the matrices of residuals from the additivity (matrix of interaction effects), both for the genotype x year and for the genotype x location interaction. Scores for genotypes and environments (either years or locations) were displayed on a series of plots to depict the relationships among genotypes, years/locations.

Statistical methods used in SERGEN 4, based on the aforementioned models, made it possible to:

- assess genotype main effects as well as interaction effects of individual genotypes in various environments;
- conduct complete statistical analysis of data series after missing observations have been supplemented;
- analyse comparisons (contrasts) between genotypes in terms of their main effects and interactions with the environments;
- apply methods of linear regression and explain the genotype-by-environment interaction;
- conduct linear regression analyses of individual genotypes on explanatory variables describing experimental conditions;
- examine the structure of genotype-by-environment interaction by determining the share of individual genotypes in their interaction with the environments using some methods of multidimensional statistical analysis (canonical variate analysis);
- graphically present GE interaction in terms of the environments and genotypes including determination of the shortest dendrite (graph). The dendrite illustrates distances between genotypes, years, locations, for all the GE interaction components.

## RESULTS

Mean squares of variation obtained in the combined analysis of variance for tuber yield are presented in Table 3. Based on the analysis of variance (Table 3), significant effects of location, environment, genotype, and genotype x year and genotype-by-environment interactions were observed. The analysis of variance partitioned the sum of squares for the genotype-by-environment interaction into two components: regression on the explanatory variables and deviation from regression. It was possible to test the hypothesis of no significant genotype-by-environment interaction after removal of the regression on the explanatory variables. The hypothesis was rejected.

Thus, mean yields of cultivars were different as was their response to diverse environmental conditions.

Table 3. Mean squares in the analysis of variance for tuber yield

| Source of variation | Degrees of freedom | Mean squares | F value |
|---|---|---|---|
| Year | 3 | 1131.48 | 0.90 (p=0.445) |
| Location | 5 | 4512.67 | 3.59 (p=0.003) |
| Year x location | 15 | 1258.16 | 188.31 (p<0.001) |
| Genotype | 13 | 388.72 | 38.89 (p<0.001) |
| Genotype x year interaction | 39 | 60.80 | 8.63 (p=0.049) |
| Genotype x location interaction | 65 | 24.01 | 3.21 (p=0.266) |
| Genotype x year x location interaction | 195 | 22.37 | 3.35 (p<0.001) |
| Regression on environment | 26 | 26.75 | |
| Regression deviation | 169 | 21.70 | 3.25 (p<0.001) |

Table 4. Tests for main effect and interaction with the environment for individual genotypes

| Genotype | Estimation of main effect | F value for main effect | F value for interaction of genotype and: location | year | environment |
|---|---|---|---|---|---|
| Ametyst | 7.418 | 172.52 (p<0.001) | 4.95 (p<0.001) | 9.95 (p=0.001) | 1.23 (p=0.247) |
| Bogatka | -1.835 | 9.39 (p=0.008) | 1.27 (p=0.277) | 3.25 (p=0.052) | 1.39 (p=0.155) |
| Cekin | -1.993 | 3.10 (p=0.098) | 0.35 (p=0.562) | 1.41 (p=0.320) | 4.96 (p<0.001) |
| Finezja | -1.613 | 1.88 (p=0.190) | 0.26 (p=0.617) | 1.46 (p=0.302) | 5.36 (p<0.001) |
| Gawin | -4.274 | 17.86 (p<0.001) | 0.95 (p=0.345) | 0.79 (p=0.656) | 3.96 (p<0.001) |
| Jurek | 2.388 | 5.43 (p=0.034) | 1.80 (p=0.391) | 1.33 (p=0.351) | 4.06 (p<0.001) |
| Legenda | -8.838 | 126.41 (p<0.001) | 2.19 (p=0.110) | 4.49 (p=0.020) | 2.39 (p=0.003) |
| Malaga | -1.019 | 1.06 (p=0.319) | 0.40 (p=0.910) | 0.99 (p=0.523) | 3.77 (p<0.001) |
| Oberon | 0.341 | 0.19 (p=0.669) | 0.20 (p=0.988) | 2.45 (p=0.105) | 2.38 (p=0.003) |
| Otolia | -1.267 | 2.25 (p=0.154) | 0.50 (p=0.846) | 1.90 (p=0.178) | 2.75 (p<0.001) |
| Satina | 3.722 | 10.76 (p=0.005) | 0.56 (p=0.803) | 2.02 (p=0.162) | 4.98 (p<0.001) |
| Stasia | -0.295 | 0.09 (p=0.768) | 1.48 (p=0.266) | 10.60(p=0.001) | 3.73 (p<0.001) |
| Tajfun | 3.175 | 14.29 (p=0.001) | 1.70 (p=0.200) | 3.32 (p=0.048) | 2.73 (p<0.001) |
| Tetyda | 4.090 | 20.37 (p<0.001) | 2.10 (p=0.167) | 0.94 (p=0.554) | 3.18 (p<0.001) |

Table 4 shows that of the 14 cultivars subjected to analysis, Ametyst, Bogatka, Gawin, Jurek, Legenda, Satina, Tajfun and Tetyda had significant main effects, the effects being positive for Ametyst, Jurek Satina, Tajfun and Tetyda, which indicates that they produced higher yields than the environment mean. Bogatka, Legenda and Gawin had negative effects as their yields were lower than the environment mean. Ametyst and Bogatka did not interact with the environment but only Ametyst can be considered stable because of its high positive yield-forming effects. Yields produced by Bogatka were the same in all locations and study years (although they were lower than the mean). The remaining cultivars can be considered unstable due to their significant interaction with environment.

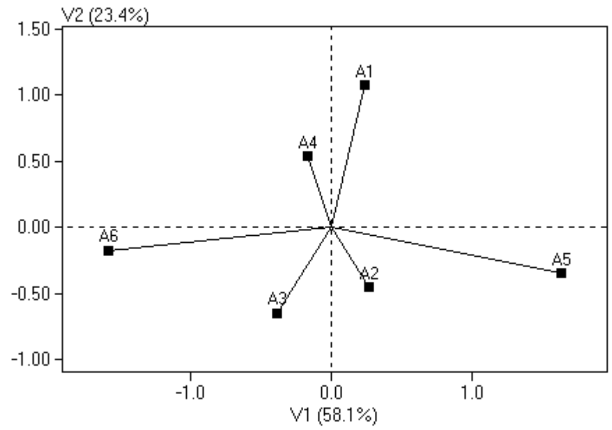
Table 5 summarizes the results of regressing the 'environment x genotype' interaction effects for each individual cultivar against the two environmental variables included in the analysis. Coefficients of determination and F values for regression and deviation from regression demonstrate that conditions during the growing season accounted for around 40% of the genotype-by-environment interaction for Frezja and Oberon. The interaction of Frezja with the environment was affected more by the total precipitation during the growing season than by the mean temperature. In the case of Oberon, F values for precipitation and temperature were similar but insignificant.

Table 5. Multiple regression and partial correlation between and explanatory variables (total precipitation and mean air temperature)

| Genotype | Regression of genotypes on explanatory variables | | | Partial correlation of interaction with: | | | |
|---|---|---|---|---|---|---|---|
| | Coefficient of determination | F value for regression | F value for deviations | total precipitation Correlation coefficient | F value | mean air temperature Correlation coefficient | F value |
| Ametyst | 2.57 | 0.17 (p=0.680) | 1.39 (p=0.152) | 0.102 | 0.14 (p=0.714) | 0.081 | 0.09 (p=0.768) |
| Bogatka | 6.39 | 0.44 (p=0.507) | 1.50 (p=0.106) | 0.187 | 0.47 (p=0.505) | 0.229 | 0.72 (p=0.411) |
| Cekin | 20.42 | 1.67 (p=0.198) | 4.56 (p<0.001) | 0.139 | 0.25 (p=0.625) | 0.375 | 2.13 (p=0.168) |
| Finezja | 40.95 | 4.51 (p=0.035) | 3.65 (p<0.001) | 0.608 | 7.62 (p=0.016) | 0.032 | 0.01 (p=0.921) |
| Gawin | 23.89 | 2.04 (p=0.155) | 3.48 (p<0.001) | 0.263 | 0.97 (p=0.342) | 0.338 | 1.68 (p=0.688) |
| Jurek | 11.15 | 0.82 (p=0.366) | 4.16 (p<0.001) | 0.323 | 1.52 (p=0.239) | 0.035 | 0.02 (p=0.889) |
| Legenda | 2.69 | 0.18 (p=0.672) | 2.68 (p<0.001) | 0.114 | 0.17 (p=0.686) | 0.152 | 0.31 (p=0.587) |
| Malaga | 21.34 | 1.76 (p=0.186) | 3.42 (p<0.001) | 0.273 | 1.04 (p=0.326) | 0.293 | 1.22 (p=0.289) |
| Oberon | 37.91 | 3.97 (p=0.047) | 1.70 (p=0.047) | 0.420 | 2.79 (p=0.118) | 0.389 | 2.32 (p=0.151) |
| Otolia | 0.43 | 0.03 (p=0.862) | 3.16 (p<0.001) | 0.049 | 0.03 (p=0.865) | 0.058 | 0.04 (p=0.844) |
| Satina | 0.90 | 0.06 (p=0.807) | 5.69 (p<0.001) | 0.095 | 0.12 (p=0.734) | 0.037 | 0.02 (p=0.889) |
| Stasia | 19.39 | 1.56 (p=0.213) | 3.47 (p<0.001) | 0.209 | 0.60 (p=0.452) | 0.318 | 1.46 (p=0.248) |
| Tajfun | 3.63 | 0.25 (p=0.617) | 3.04 (p<0.001) | 0.111 | 0.16 (p=0.6950 | 0.107 | 0.15 (p=0.705) |
| Tetyda | 3.01 | 0.20 (p=0.655) | 3.56 (p<0.001) | 0.033 | 0.01 (p=0.921) | 0.148 | 0.29 (p=0.599) |

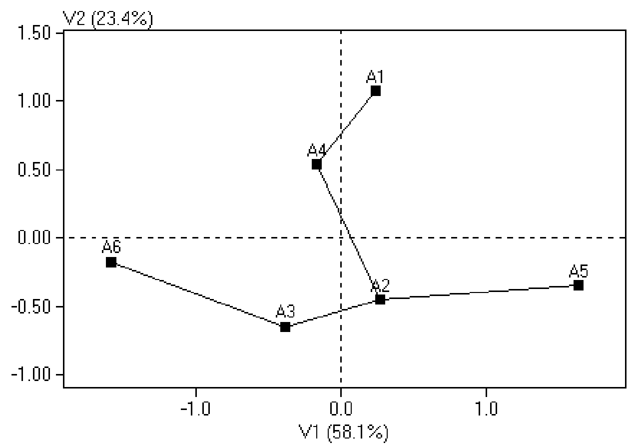
Figure 1 displays the configuration and vector view of locations in the plane spanned by the first two canonical variates for the genotype x location interaction: the distance of the points (representing the locations) from the origin indicates that the cultivars were most responsive to the conditions at the Uhnin and Węgrzce stations. The distances between locations were used to determine the shortest dendrite, which indicates that Karżniczka and Sulejów as well as Naroczyce and Słupia were the most similar in terms of yield-forming conditions. Also the cultivars could be displayed in the plane spanned by the first two canonical variates (Figure 3): it is shown that the cultivars formed three groups when their interaction with locations was considered. However, as the cultivar x location interaction was not significant, further analyses of the structure of this interaction were not undertaken.

The structure of genotype x year interaction was also examined by using canonical variate analyses. The first two canonical axes represented respectively 71% and 27% of the discriminating ability of the original variables. The placement of years in the plane spanned by the two canonical axes is shown in Figure 4. Points representing the years were used to locate a dendrite (Figure 5) and the years 2012 and 2013 were found to have the greatest effect on the performance of cultivars.




A1 – Karżniczka, A2 – Naroczyce, A3 – Słupia, A4 – Sulejów, A5 – Uhnin, A6 – Węgrzce

Figure 1. Canonical variate analysis for the residuals from the additivity (matrix of effects for the genotype x location interaction) for 14 genotypes in 6 locations. Vectors represent the scores for locations.




A1-A6. – see Figure 1.

Figure 2. The shortest dendrite stretched on points which represent locations in a system of canonical variates, based on the analyses in Figure 1.

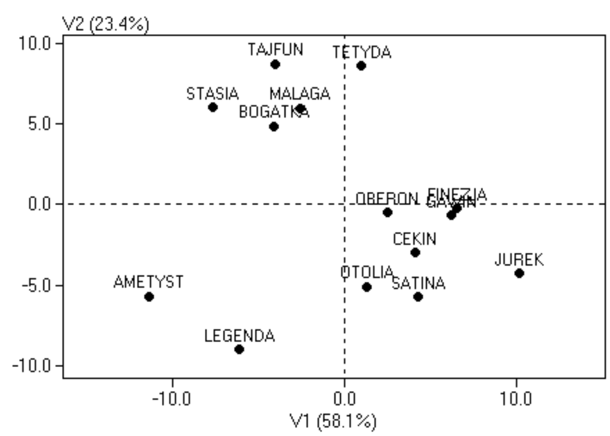



Figure 3. Canonical variate analysis for the residuals from additivity (matrix of effects for the genotype x location interaction) for 14 genotypes in 6 locations. Symbols represent the scores for genotypes.

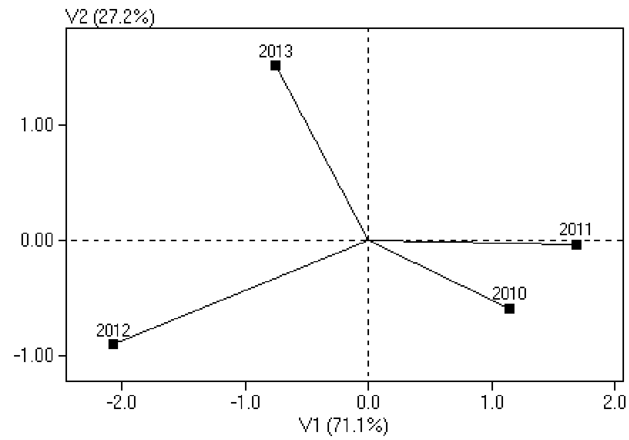



Figure 4. Canonical variate analysis for the residuals from additivity (matrix of effects for the genotype x year interaction) for 14 genotypes in 4 years. Symbols represent the scores for years.

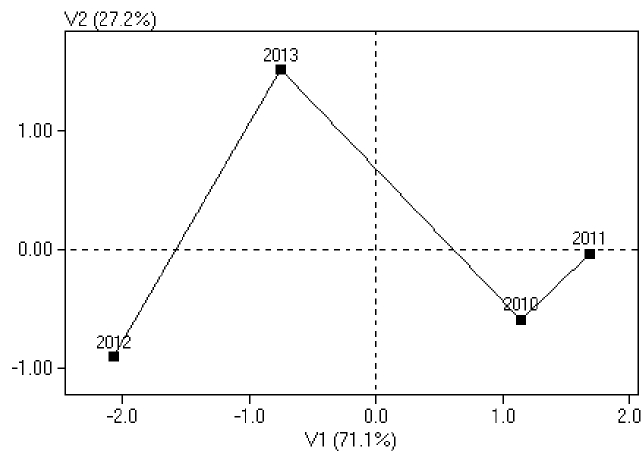



Figure 5. The shortest dendrite stretched on points representing the study years in a system of canonical variates, based on the analysis in Figure 4.

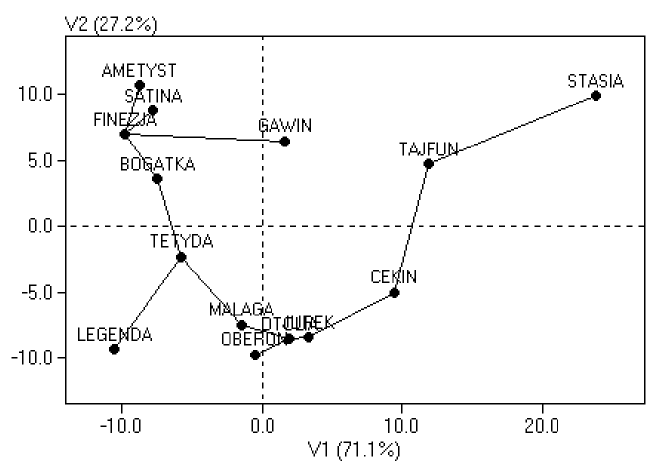



Figure 6. The shortest dendrite stretched on points representing cultivars in a system of canonical variates based on canonical variate analysis on the matrix of residuals from additivity (matrix of effects for the genotype x year interaction) for 14 genotypes in 4 years.

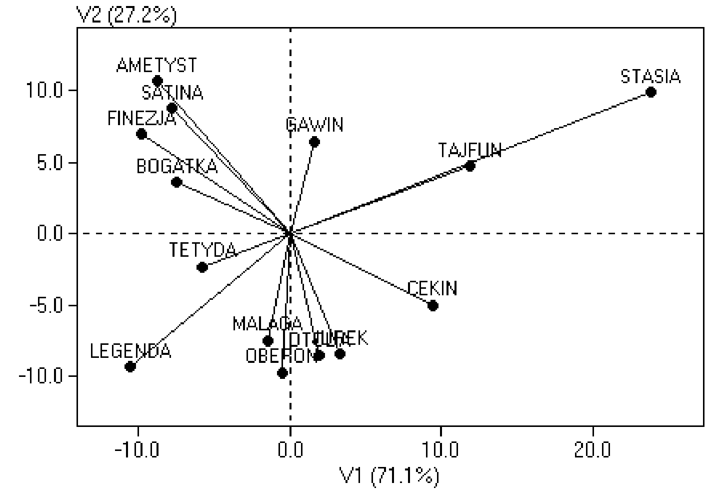



Figure 7. A genotype vector view in a system of canonical variates, based on the analysis in Figure 6.

Further analyses of the interaction structure by using the graphic method revealed that Stasia, Tajfun and Legenda were most responsive to year, as they show the highest distance from the origin of axes (Figure 6, 7). Three groups of genotypes with similar responses to years were determined, based on the graph of the shortest dendrite. The first group included Stasia, Tajfun and Cekin, the second group included Legenda, Tetyda, Malaga, Oberon and Jurek, and the last group included Bogatka, Gawin, Finezja, Satina and Ametyst.

## Discussion

Post-registration variety testing (PDO) is a system which examines the value of cultivars to help farmers make an appropriate choice (Gacek and Behenke 2006). Knowledge of response of cultivars to diverse environmental conditions makes it possible to choose the cultivar which is best adapted to the soil and weather conditions of a farm (Bujak and Trawal 2011). To achieve this objective, it is necessary to analyse the experimental results collected from as many locations as possible for a period of several years. Analysis of such results provides information on how genotypes perform at these locations, how they respond to diverse soil and weather conditions and what their response is when growing conditions improve or get worse.

Analysis of tuber yield performance of edible potato cultivars in 15 environments, including the meteorological conditions during the growing season, revealed that observed yield levels were strongly dependent on environmental conditions. The existence of genotype-by-environment interaction has been confirmed for various plant species worldwide (Affleck et al. 2008, Scapim et al. 2010, Bujak et al. 2012). Analysis of genotype-by-environment interaction made it possible to determine which edible potato cultivars were stable and which were unstable in terms of yield performances.

The study reported here demonstrated that one cultivar (Ametyst) out of the 14 genotypes under investigation was stable in terms of yield. Yields produced by Ametyst were higher than the mean and the cultivar did not interact with the environment. Instability of so many cultivars indicates that potato is a crop whose yields are highly affected by environmental conditions. Similar inferences were reported by Bombik et al. (2007) as well as by Rymuza and Bombik (2010), who demonstrated that that genotype-by-environment interaction may contribute to 20-40% of yield variability. Also Flis et al. (2014) found that many genotypes were unstable. In their study, the authors examined the stability of yield performance (and other traits) of 21 potato cultivars in a 2-year cycle in three countries:

Poland, Spain and Hungary. They found only one stable cultivar: Frezja. In the present study, Finezja interacted with the environment and analysis based on explanatory variables demonstrated that around 40% of the interaction effects depended on the conditions during the growing season, in particular on total rainfall. Drzazga and Krajewski (2001) as well as Kołodziejczyk (2013) demonstrated that the nature of genotype-by-environment interaction was more affected by weather conditions during the growing season than by the experimental sites. As a result, the determination of the components of phenotypic variation for potato traits requires experiments to be conducted for at least three years in one location or for one or two years in several locations (Keller and Baumgartner 1982, Yildrim and Caliscan 1985). Weather is more variable than edaphic conditions over both the short and the long period, because edaphic conditions are predominantly stable in character (Kołodziejczyk 2013).

Analysis of yielding of cultivars in a series of multi-environment experiments can make it easier to select the best adapted cultivars to the environmental conditions in a given region. Such cultivars are dynamically stable and respond to a change in environment by making a corresponding change in yield (Annicchiarico 2002, Kang 1998, Mądry and Kang 2005, Affleck et al. 2008).

## CONCLUSIONS

1. Analysis of genotypes demonstrated that Ametyst, Satina, Tajfun and Tetyda produced higher yields than the environmental mean. However, only Ametyst was considered stable (no interaction with environment was observed). Yielding of Bogatka, Gawin and Legenda was lower than the environmental mean, and Bogatka yielded similarly in all environments, years and locations.
2. The remaining cultivars, that is Cekin, Finezja, Malaga, Oberon, Otolia and Stasia, yielded within the range of the environmental mean and were not stable. Total precipitation during the growing season accounted for 40% of the genotype-by-environment interaction for Frezja.
3. The most significant differences in yields of the analysed cultivars were observed in the years 2012 and 2013. During those years only Ametyst, Otolia and Bogatka demonstrated similar yield.

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