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FIELD-SCALE SPATIAL AUTOCORRELATION OF SOME SODIUM AND POTASSIUM FORMS IN A LUVISOL HUMIC HORIZON

Jacek Długosz[1], Mirosław Kobierski[1], Anna Piotrowska-Długosz[2], Dariusz Gozdowski[3]

[1]Chair of Soil Science and Soil Protection
[2]Departament of Biochemistry
University of Technology and Life Sciences in Bydgoszcz
[3]Chair of Experimental Design and Bioinformatics
Warsaw University of Life Sciences – SGGW

Abstract

Knowledge of the spatial variability of the content and transformations of soil nutrients is important for precision agriculture and environmental protection. Spatial patterns of exchangeable (Na-Exch, K-Exch) and water soluble (Na-WS, K-WS) forms of sodium and potassium were examined in Luvisol soil lying in the region of Cuiavia and Pomerania, northwest Poland, so as to identify their spatial distribution for the implementation of site-specific management. In April 2007, soil samples were collected in a system of 10 x 10 m grids (n = 50) from an area of 0.5 ha located in an intensively used arable field. Water soluble forms of Na and K were determined after extraction with distilled water in a 1:5 soil to water ratio, while the exchangeable forms of these elements were assayed in 0.1 M $BaCl_2$. The data were analyzed both statistically and geostatistically from semivariograms and their modelling. The spatial autocorrelation of a data set is described with the Moran's I correlograms, hence adequate correlograms were drawn. Among all the properties determined, it was only water soluble K that showed significant spatial autocorrelation. Other soil properties (Na-WS, Na-Exch, K-Exch) did not demonstrate any spatial autocorrelation (the Moran's I values were close to zero at $p < 0.05$), which indicated their random spatial variability. In order to assess the spatial variability of K-WS, a spherical model with the nugget effect was fitted into the calculated semivariogram. The results were assigned to the moderate variability class (the nugget effect 52%), and the range of the spatial impact stretched for 38 m.

Keywords: Luvisol, exchangeable and water soluble forms of K and Na, Moran's I, spatial variability, geostatistics.

prof. dr hab. inż. Jacek Długosz, Chair of Soil Science and Soil Protection, University of Technology and Life Sciences, Bernardyńska 6/8 St., 85-029 Bydgoszcz, Poland, e-mail: jacked@utp.edu.pl

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KORELACJA PRZESTRZENNA WYBRANYCH FORM SODU I POTASU W POZIOMIE ORNO-PRÓCHNICZNYM GLEBY PŁOWEJ W SKALI POLA UPRAWNEGO

Abstrakt

Znajomość zmienności przestrzennej zawartości i przemian składników odżywczych w glebie ważna jest zarówno z punktu widzenia rolnictwa precyzyjnego, jak i ochrony środowiska. Zmienność przestrzenną wymiennych (Na-Exch, K-Exch) oraz wodnorozpuszczalnych (Na-WS, K-WS) form sodu i potasu badano w glebie płowej regionu Pomorza i Kujaw (północno-wschodnia Polska). Próbki glebowe do badań pobierano w siatce kwadratów o boku 10 m (n = 50) w kwietniu 2007 r. z obszaru o powierzchni 0,5 ha znajdującego się w obrębie pola uprawnego. Formy wodno-rozpuszczalne Na i K oznaczono po ekstrakcji z wodą destylowaną w stosunku 1 : 5, natomiast formy wymienne analizowano wg metody z 0,1 M $BaCl_2$. Wyniki poddano analizie statystycznej i geostatystycznej opartej na wykreśleniu semiwariogramów i ich modelowaniu. W celu określenia korelacji przestrzennej wyliczono indeks Morana oraz wykreślono odpowiednie korelogramy. Spośród badanych zmiennych tylko zawartość K-WS wykazywała istotną autokorelację przestrzenną. Pozostałe badane zmienne (Na-WS, Na-Exch, K-Exch) nie wykazywały podobnej zmienności (wartości indeksu Morana I zbliżone były do zera i wartości p były większe od 0.05), co wskazuje na losowe rozmieszczenie ich wartości w przestrzeni. W celu scharakteryzowania zmienności przestrzennej wartości K-WS, do teoretycznego semiwariogramu dopasowano model sferyczny z efektem samorodka. Wartości badanej zmiennej mieściły się w umiarkowanej klasie zmienności, z efektem samorodka wynoszącym 52,0%, a zakres oddziaływania przestrzennego wynosił 38 m.

Słowa kluczowe: Luvisol, wymienne i wodnoropuszczalne formy K i Na, indeks Morana, zmienność przestrzenna, geostatystyka.

INTRODUCTION

Spatial heterogeneity is one of the most serious obstacles to successful monitoring and modeling of nutrient transformations in soil, which is extremely important for good plant nutrition as well as environmental control and protection. Soil fertility management and adequate application of fertilizers and other chemicals must be based on our understanding of the distribution of exchangeable and water soluble forms of nutrients. Traditionally, soil management used to rely on the concept that fields were homogenous areas and all field operations should therefore be planned for a whole field (Patil et al. 2011). However, at least 70 years ago it was concluded that fields were not homogenous and specific sampling techniques were recommended to describe spatial variability (Flower et al. 2005, Santra et al. 2008). Recently, geostatical methods have been employed to testing the spatial variability of soil properties. Geostatistics, an increasingly popular solution in soil science, helps to predict the spatial distribution of spatially dependent soil properties in a field, according to several soil samples (McBratney, Webster 1983, Kerry, Oliver 2004, Aşkin, Kizilkaya 2006, Aşkin et al. 2012). Semivariograms and autocorrelograms are typically used to study the spatial structure of soil properties.

Like nitrogen and phosphorus, potassium is a basic element that determines the soil's production potential. In plants, potassium affects the water management and enzymatic activity (RANDAME-MALVI 2011). Potassium is considered to be a highly mobile element in soil, although it is easily absorbed as a cation (BURZYŃSKA, PIETRZAK 2010), leading to a potassium deficit and worse crop yields (RAGÁLY, KÁDÁR 2005). Although sodium is an antagonist of potassium, it may alleviate the effects of a minor deficit of potassium. Sodium may stimulate the sugar beet yield and the content of sucrose (PROŚBA-BIAŁCZYK, MYDLARSKI 2002, SZULC et al. 2008). However, a high sodium content can trigger a series of negative changes in soil properties, such as increased salinity, worse soil structure and impeded uptake of potassium by plants. The colloidal system of soil tends to disperse when the sodium content at exchangeable sites increases. Excessive amounts of salts cause high osmotic pressure, which adversely affects the water uptake by plants. In general, high soil pH values are associated with high sodium concentrations (ARDAHANLIOGLU et al. 2003). Therefore, it is very important, especially in precision agriculture, to monitor the content of available forms of Na and K (both water soluble and exchangeable forms) and to assess their spatial variability in cultivated soils (FRANZEN 2011).

The objective of the present study has been to assess the spatial autocorrelation and variability of soil water soluble and exchangeable forms of Na and K in a field-scale study using geostatistical techniques.

MATERIAL AND METHODS

Study site and soil sampling

In the present research, the spatial variability of soil exchangeable and water soluble forms of K and Na have been determined on an area of 0.5 ha of Luviosol soil, in a field located at the village of Orlinek near Mrocza, in the region of Cuiavia and Pomerania (53°15′31″N, 17°32′43″E), in northwest Poland. Soil samples were taken in April 2007, in a field cropped with winter wheat which followed winter oilseed rape. The apparently homogenous area of 0.5 ha was divided into 10 x 10 m grids for sampling. Samples were collected from the 0-20 cm top layer across the field. There were 50 sampling points. Each soil sample represented a mean value of 10 individual samples. The samples were air dried and ground to pass a 2 mm sieve for chemical analyses.

Soil analyses

Exchangeable K and Na (K-Exch, Na-Exch) were determined in 0.1 M $BaCl_2$ (according to ISO 11260), while the water-soluble forms of both elements (K-WS, Na-WS) were assayed after extraction in distilled water (1 : 5

soil to water ratio). The content of K^+ and Na^+ in the extracts was determined by atomic absorption spectroscopy (AAS) on a Philips PU 9100X spectrometer. Basic chemical parameters were determined as follows: pH in 1 M KCl by the potentiometric method (PN-ISO 1039) and organic carbon and total nitrogen content in a dry combustion CN analyzer (Vario Max CN). The verification of the results was done with the TILL 3 certificate.

Statistical analysis

The intra-population variability was analyzed by classical statistics (mean, maximum, minimum, standard deviation, skewness and coefficient of variation). Normality of all the properties analyzed was tested by the Shapiro-Wilk test (*p*-value). The spatial autocorrelation of the sampling variables was measured with the Moran's *I* autocorrelation coefficient (Moran 1948). The Moran's *I* was determined using a 50-m active lag distance and a 10-m lag interval (ArcGIS 9.3). Properties with the highest Moran's *I* index were chosen to be modelled. Autocorrelograms and semivariograms were drawn with the Isatis software (Geovariance Co.) and the models were verified with the cross-validation method. Empirical correlograms and semivariograms were drawn at the difference lag intervals. The geostatistical techniques including the semivariogram analysis and kriging were used to model the spatial variability and interpolation of data values at unsampled locations, and for mapping in the district. Semivariance γ(h) is defined by the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \Sigma \left[Z(x_i) - Z(x_i + h) \right]^2 ,$$

where, N(h) is the number of sample pairs at each distance interval h, and Z (Xi,) and Z (Xi + h) are the values of a variable at any two places separated by the distance h. A semivariogram is drawn by plotting semivariance against the distance. Its shape indicates whether the variable is spatially dependent. The experimental semivariograms were fitted into theoretical models that had well-known parameters, such as the nugget (CO), sill (CO + C) and range (AO) of spatial dependence (Cambardella et al. 1994). A suitable model of variogram was based on the minimum residual sum of a square. The nugget semivariance is the variance at zero distance; the sill is the lag distance between measurements at which one value for a variable does not influence neighboring values; and the range is the distance at which values of one variable become spatially independent from values of other variables. In our analysis, two indices of spatial dependence were determined. One is the nugget variance, which was expressed as the percentage of total semivariance used to define spatial dependence of soil variables. In order to define different classes of spatial dependence for the soil variables, the ratio between the nugget semivariance and the total semivariance or the sill was used (Cambardella et al. 1994). If the ratio was ≤ 25%, the variable was considered to be strongly spatially dependent, or strongly distributed; if the ratio was between 26 and 75%, the soil variable was considered to be moderately spatially dependent; if the ratio was greater than 75%, the soil variable was considered to be weakly spatially dependent. The other index is the range, which indicates the limit of spatial dependence.

RESULTS AND DISCUSSION

The reaction of the analyzed soil samples ranged from acidic to neutral (pH from 4.8 to 6.8). The organic carbon content was 5.5 - 9.0 g kg^{-1} (on average 7.3 g kg^{-1}) and the total nitrogen content varied from 0.68 to 0.98 g kg^{-1} (on average 0.80 g kg^{-1}) More detailed data describing the basic physicochemical properties of the soil were presented earlier (Piotrowska, Długosz, 2012).

The content of K-Exch in the studied area was 3.2-6.2 mmol kg^{-1} (on average 4.3 mmol kg^{-1}) – Table 1. Its contribution to the CEC equalled 3.6-8.1% (on average 5.7%), which was slightly above the acceptable share of this ion in the CEC, such as 5%. The limit was exceeded in 76% of the soil samples. The content of Na-Exch ranged from 0.4 to 2.8 mmol kg^{-1} (on average 2 mmol kg^{-1}) – Table 1, and its contribution to the CEC was between 0.5 and 3.8% (on average 1.6%), i.e. below the limit value, which is set at 5%. The content of water soluble forms of the two nutrients was relatively low, especially that of Na-WS (Table 1). Less K-WS was determined in surface horizons of Luvisols in the Czech Republic (Škarpa, Hlušek 2012).

Mean and median values served as primary estimates of the central tendency, while standard deviation (SD), coefficient of variation (CV), skewness and kurtosis were used as estimates of variability (Table 1). The mean and median values of the soil properties were similar, indicating that the outliers did not dominate the measure of the central tendency and could be used for exploratory data analysis. The coefficients of variation (CV%) of the

Table 1

Statistics of soil properties (n = 50)

Property	Min	Max	Mean	Geometric mean	Median	SD	Skewness	Kurtosis	CV
	(mg kg^{-1})								(%)
K-WS	40.7	118.4	65.3	62.6	59.5	19.9	1.05	0.25	30.6
Na-WS	4.1	11.8	7.4	7.3	7.1	1.4	0.68	1.31	19.2
	(mmol kg^{-1})								(%)
K-Exch	3.2	6.2	4.3	4.3	4.2	0.64	0.87	1.30	14.9
Na-Exch	0.4	2.8	1.2	1.1	1.2	0.6	0.96	0.72	46.0

CV – coefficient of variation, SD – standard deviation soil properties were divisible into three classes: the least (<15%), moderately (15% - 35%), and the most (>35%) variable ones (WILDING 1986). The results shown in Table 1 prove that only one of the four measured properties, namely K-Exch, belonged to the least variable class (coefficient of variation less than 15%), whereas Na-WS and K-WS were moderately variable (CV > 15 ≤ 35%), and Na-Exch was highly variable (CV > 35%).

Skewness and kurtosis coefficients have been used to verify the statistical distribution of parameters (CERRI et al. 2004). It is known that if skewness is close to zero the parameters it describes represent the classical, normal distribution, but positive skewness is the sing of a long tail of high values (to the right) in the data distribution, making the median less than the mean (LI et al., 2012). In this study, all variables presented positive skewness values ranging from 0.68 to 1.05. Kurtosis is a parameter that describes the shape of a random variable probability density function. Kurtosis greater than one shows that a given random variable is leptokurtic but kurtosis less than one indicates a variable that is platykurtic. The kurtosis of the studied variables fluctuated between 0.25 and 1.31.

Spatial autocorrelation can be used to describe and compare the spatial structure of data. Significant spatial autocorrelation (<0.05) was found only for K-WS (Table 2). The autocorrelogram (Figure 1a) for K-WS was characterized by a positive MC (Moran's coefficient) for separation distances generally < 20 m and a negative MC at > 20 m. The highest K-WS spatial autocorrelation was at 10 m, decreasing gradually at further distances and approaching zero at a 23 m separation distance. Over that distance, the spatial autocorrelation of this property continued to decrease, falling down to negative values and finally approaching zero again (at a distance of 57 m).

Table 2

Moran's *I* for soil properties

Parameter	K		Na	
	Exch	WS	Exch	WS
Moran's index	-0.0322	0.1100	0.0250	0.0010
Z Score	-0.2470	2.7157	0.9499	0.4503
p-value	0.8049	0.0066	0.3421	0.6525

Other soil properties (Na-WS, Na-Exch, K-Exch) did not show spatial autocorrelation, which was confirmed by the Moran's *I* values close to zero and the *p* values higher than 0.05 (Table 1). This indicated the random spatial variability of these properties, which was confirmed by the impossibility of drawing up empirical semivariograms and adjusting relevant models, despite using different lag intervals. The models achieved did not satisfy the requirements of well-fitted models (high values of thee standard error variance). Additionally, the verification of a pure nugget model in the semivariogram of K-Exch did not confirm its presence (Figure 2a).

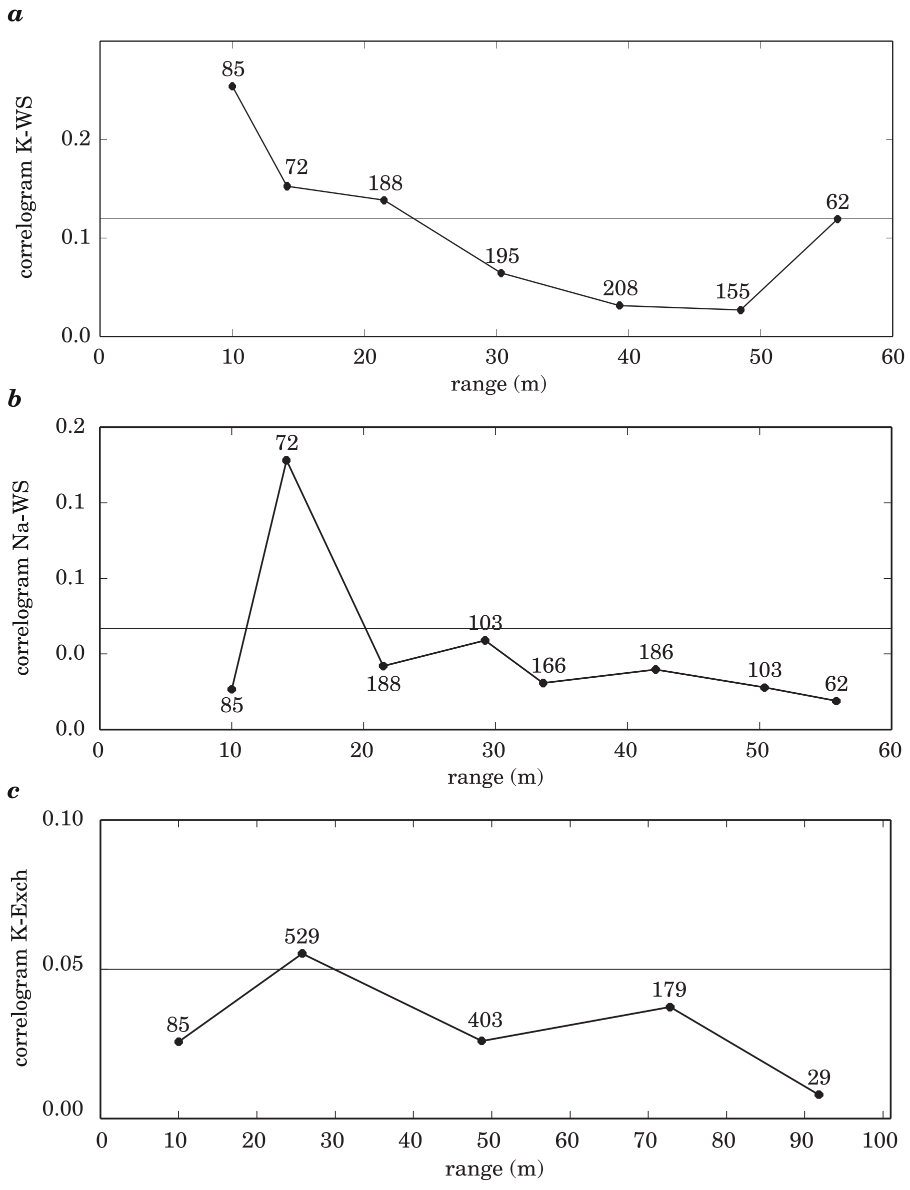

Fig. 1. Correlograms of (*a*) K-WS, (*b*) Na-WS, (*c*) K-Exch

In order to characterize the spatial variability of the K-WS spherical model with the nugget effect were fitted to calculated semivariogram (Figure 2b). The same model was adjusted to describe the spatial variability of the water soluble Mg form in the same research area (KOBIERSKI et al. 2011). The parameters of this model were as follows: the nugget (Co) 0.143, the sill (Co + C) 0.253, and the nugget effect 52.0%, which indicated that the data

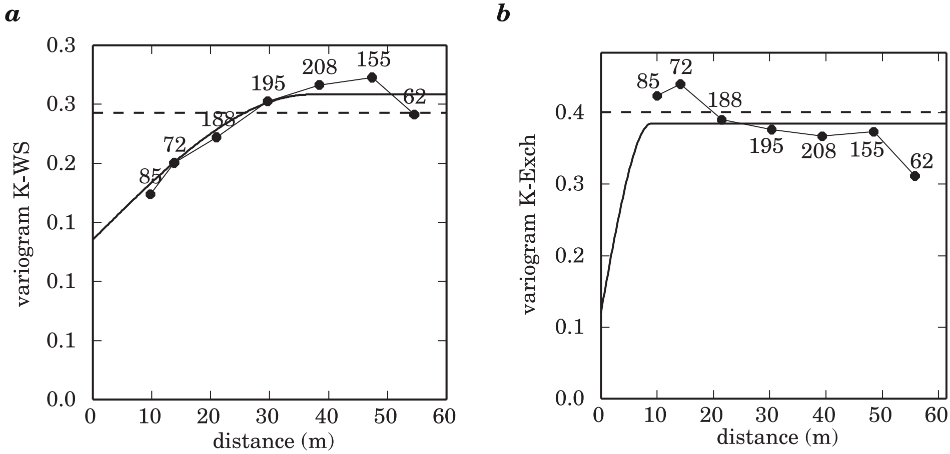

Fig. 2. Experimental semivariograms of (a) K-Exch, and (b) K-WS

were moderately spatially dependent; the range was 38 m and the standard error equaled -0.0127. The adjustment of the model to the empirical variogram was confirmed by the value of the standard error variance: 1.0008. The spatial variability of K-WS based on the percentage of total variance (*sill*) presented as random variance [(Co/Co+C),%] was considered to be moderately spatially dependent (52%). It has been found that the nugget effect reflects the variability unexplained in terms of distance for a sample used, such as local variations, errors in analysis, sampling and others. Since it is impossible to quantify the individual contribution to these errors, the nugget effect is expressed as a percentage of the level, thus facilitating the comparison of the extent to which analyzed variables are spatially dependent (VIEIRA 2000). Moderate spatial dependence has been attributed to both intrinsic (texture and mineralogy) and extrinsic variation (soil management, e.g. fertilizer application, tillage and land use) (CAMBARDELLA et al. 1994). The results indicated that 52% of the total variance of an analyzed property was due to random variability. That observation suggested that extrinsic factors such as fertilization, plowing and other soil management practices weakened their spatial correlation after a long history of cultivation. Other properties did not show a regular spatial structure, which was confirmed by the lack of autocorrelation. Similarly, a weak spatial structure for the K and Na forms was noted by YANAI et al. (2003), who reported a nugget/sill ratio of 95% for exchangeable K and 78% for exchangeable N, while moderate spatial dependence was found for exchangeable K by TOBI and OGUNKUNLE (2007) in the 0-15 cm soil horizon of Alfisols and by AISHAH et al. (2010) for paddy soil, where a nugget/sill ratio equalled 70% for K and 50% for N.

The spatial autocorrelation of the K-WS results is confirmed by the range of influence reaching 38 m. Since the range is the maximum distance over which the results are correlated (BERGSTROM et al. 1998), the sampling scheme for the analyzed properties (10 m ×10 m rgids) was suitable only for water soluble K. Other properties did not show the ranges of autocorrelation, which indicated that a lag distance should be less than 10 m, and that 50 samples were an insufficient number to describe their true characteristics in the analyzed area.

The main application of geostatistics to soil science is to estimate and map soil properties in unsampled areas. Since spatial autocorrelation is a necessary condition for the spatial prediction of soil properties, only one krigged map of spatial variability was presented for K-WS (Figure 3). An area with the highest values of the property occurred in the south-western triangle of the field (at 0-20 m of the length and 0-20 m of the width), running vertically from the centre to the south-eastern part of the area.

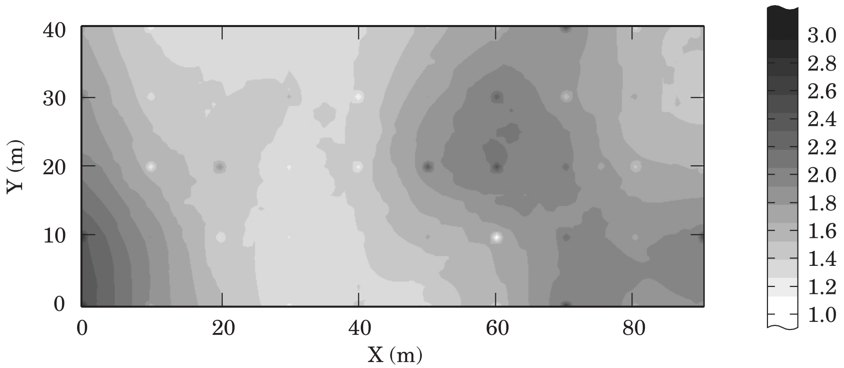

Fig. 3. Spatial distribution of K-WS

CONCLUSIONS

1. Significant positive spatial autocorrelation, indicating similar values of a given property in nearby places, was found only for water soluble K, suggesting that observations made at different locations were dependent on each other across the determined space and that they showed spatial dependence.

2. The spatial range values indicated that the sampling interval established in the study (10 m) was proper only for water soluble K. For the other properties, more samples should be collected over the analyzed area in the future, and the sampling should be done at different lag intervals to obtain the spatial autocorrelation of the data.

3. The nugget-to-sill ratios calculated to determine the level of spatial dependence of all the analyzed properties showed a moderate contribution of random variance to the total variability only in the case of K-WS.

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