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FRACTAL ANALYSIS TO EVALUATE THE PRODUCTIVITY ELEMENTS AT WHEAT SPIKE

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ABSTRACT
"Non-contact" imaging methods for plant analysis are increasingly promoted due to the benefits of rapidity and high precision. The present study has used fractal analysis to characterize the productivity elements of wheat spike in relation to nitrogen differentiated fertilization, in order to develop prediction models for these elements, based on fractal dimension. Geometry of wheat spikes, "Fanulus" variety, showed a specific variation with respect to the N doses in the range of 0-180 kg ha^{-1}, active substance (a.c). Fractional dimensions (D) and multifractal dimensions (Dmf) recorded specific values depending on the shape of wheat spikes, influenced directly by the N doses. The Kruskal-Wallis test revealed significant differences between fractal dimension (D, Dmf) and qualitative indicators on spike development (spike length - SL, number of spikelets - SpN, seeds number - SN, seeds weight - SW) with the different levels of fertilization. The fractal dimensions (D) correlated positively with the productivity elements of the spike, respectively: SL (R^2 = 0.925, $p<0.01$, F = 24.832), SpN (R^2 = 0.935, $p<0.01$, F = 28.84), SN (R^2 = 0.916, $p<0.01$, F = 21.54), and SW (R^2 = 0.936, $p<0.01$, F = 29.44). Multifractal dimension (Dmf), obtained by multifractal analysis, were also correlated with SL (R^2 = 0.928, $p<0.01$, F = 25.755), SpN (R^2 = 0.927, $p<0.01$, F = 25.71), SN (R^2 = 0.833, p = 0.014, F = 15.106), and SW (R^2 = 0.916, $p<0.01$, F = 21.95). By regression analysis it was possible to predict productivity elements based on fractal dimensions (D and Dmf), by means of polynomial functions of grade 2, under statistical safety.

KEY WORDS: *fractal dimension, fractal geometry, model, prediction, wheat*

INTRODUCTION

Plants with the specificity of the morpho-anatomical structure can be studied through fractal analysis both at the individual level (leaves, flowers, etc.) as well as in their entirety or at the level of vegetal associations. With the introduction of fractal geometry and fractality concepts (Mandelbrot, 1983), they have presented interest in many areas, and on their basis a number of applications have been developed to study and research some realities that until then could only be addressed by conventional methods, expensive as time, disadvantageous as precision and degree of comprehension and generalization.

Fractal analysis has already been successfully used to characterize plant anatomical particularities (Cope *et al*., 2012), and to identify different plant species based on fractal quantifiable elements of leafs (Bruno *et al*., 2008; Backes & Bruno, 2009; Bakes *et al*., 2009; Du *et al*., 2007, 2013). The description of the root system was performed by fractal analysis at maize (Eghball *et al*., 1993) and wheat (Jozefaciuk & Szatanik-Kloc, 2001; Manschadi *et al*., 2008) in relation to the influence of nutrients, stress factors or genetic variability. The temporal variability of some crops and production was studied by fractal analysis at corn, rice and wheat (Eghball *et al*. 1995; Eghball & Vaefel, 1997; Green *et al*., 2004; Eshani *et al*., 2008; Sala *et al*., 2014a). Characterization of some plant species was possible through fractal analysis in relation to the attack of some diseases (Gong & Zhang, 2002; Asfarian *et al*., 2013; Waghmare *et al*., 2016). Fractal analysis has also been used to analyze and characterize some natural or urban areas in the context of geological, geophysical, or biomonitoring studies (Turcotte 1992; Ianovici *et al*., 2015).

Wheat is a plant cultivated with many varieties, cultivars and hybrids whose morphological parameters vary according to genotype but also to the technological and environmental conditions (Iqtidar *et al*., 2006; Ugarte *et al*., 2007; Gutiérrez-Alamo *et al*., 2008; Carew *et al*., 2009). Fertilizers are factors that have a strong impact on plant development, nitrogen being an element of nutrition with a major role in growth processes. The influence of some nutrients on wheat plants has been described by: physiological indices (Rawashdeh and Sala, 2013, 2014a), productivity elements (Iqtidar *et al*., 2006; Alam & Jahan, 2013; Shafi *et al*., 2015; Rawashdeh & Sala, 2016), elements and models on yield and economic efficiency (Sala & Boldea, 2011; Rujescu *et al*., 2015; Sala *et al*., 2015, 2016). Among the cultivated gramineous grain species, fractal analysis was used in the study and characterization of panicle at rice in relation to the production (Gong *et al*., 2009), and to study of rice grains in relation to the stages of vegetation and formation and filling of grains (Espinosa-Mendoza *et al*., 2012).

The present study has used fractal analysis to characterize the shape of wheat spike and productivity elements, in relation to N doses in order to obtain prediction models of productivity elements based on fractal dimensions.

MATERIALS AND METHODS

The purpose of the study was to evaluate by fractal analysis the variation of the productivity elements in the wheat spike under the influence of nitrogen doses, in order to achieve models of prediction of the productivity elements according to the fractal dimensions.

Biological material. The biological material was represented by the "Fanulus" wheat variety (non-awned), representative images of the spikes in relation to N doses being presented in Figure 1. Experimental variants were performed by differentiated nitrogen fertilization in the range 0 - 180 kg a.s. ha-1, with the 30 units step of variation.

Capturing of digital images. Image capture was performed at physiological maturity of spikes under uniform laboratory conditions with a Nikon D300 camera, 12.3 MPx, focal length 50mm, F-stop f/8, Exposure time 1/60s, ISO 200, Resolution 300dpi, Bit dept 24. Subsequently, equal surfaces (1424x2848 pixels) were extracted from the digital images for uniformity in fractal analysis (Figure 1). Within each variant the images of 5 spikes were analyzed, in total 35 images.

Fractal analysis. The shape of the spike from the digital images was evaluated by fractal analysis (bynarized images) to obtain the fractal dimension D, and multifractal dimension Dmf (under threshold image 1.5%) with ImageJ software (Rasband, 1997). Fractal analysis was based on the Box-Counting method, considered to be an appropriate method (Buchníček *et al*., 2000; Roy *et al*., 2007).

N_0 N_{30} N_{60} N_{90} N_{120} N_{150} N_{180}

FIGURE 1. Images of wheat spikes in relation to nitrogen doses

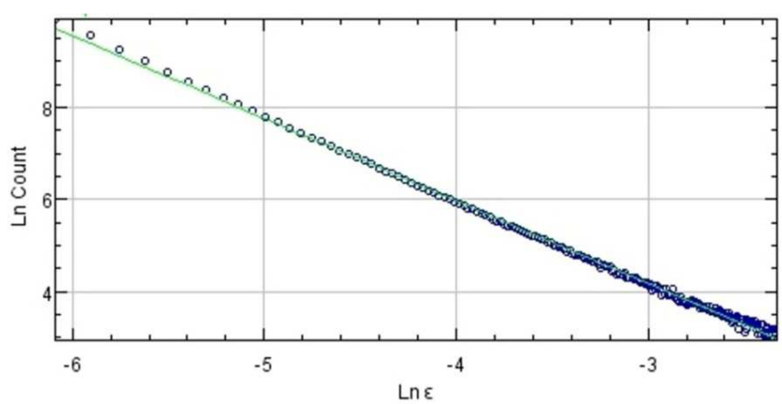

FIGURE 2. Regresion line for fractal dimension analysis

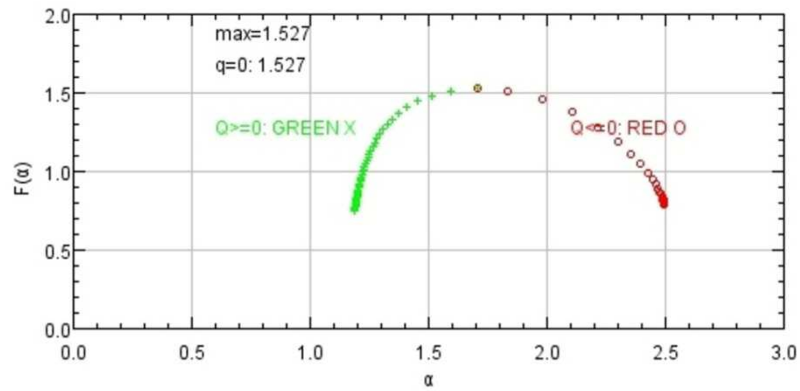

FIGURE 3. Multifractal distribution in multifractal analysis

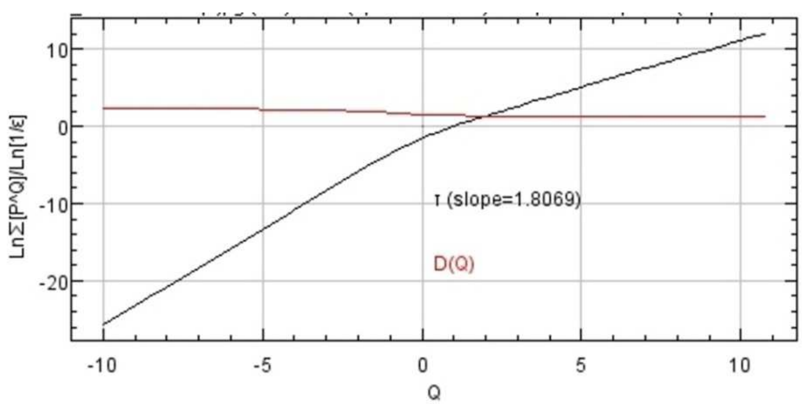

FIGURE 4. Slope for multifractal analysis

Differences between data groups were evaluated based on the Kruskal-Wallis test. For this purpose, SPSS was used with the Nonparametric Tests / K Independent Samples procedure. The predictive safety of the productivity elements based on fractal dimensions was evaluated based on RMSE (Root Mean Square Error), by equation (1).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2} \tag{1}$$

Determination of regression models, graphical representations and statistical analysis was made with the statistical module of EXCEL (Office 2007 package), with the statistical and mathematical module of PAST software (Hammer *et al*., 2001) and SPSS respectively.

RESULTS AND DISCUSSIONS

Providing variable nutrient conditions with nitrogen in the range of 0-180 kg ha-1, with the variation step of 30 units, determined the differential growth and development of wheat plants, the "Fanulus" variety. At the level of the spike were recorded changes in the dimensions (length, thickness, and width), fractal geometry of the spike, and the productivity elements (number of spikelets, number of grains in the spic and grains weight).

The characterization of the wheat spike geometry by fractal and multifractal analysis, has facilitated obtain the fractal dimensions (D and Dmf), whose distribution in relation to the nitrogen fertilizer doses is shown in Table 1.

From the overall analysis of the experimental data, the increasing variation in spike size was proportional to the increase in N doses. Associated with spike sizes, the other analyzed productivity elements (SpN, SN and SW) also had a similar variation.

As a result of the change of the shape of the spikes, its fractal geometry was surprised by the fractal values, which had an increasing variation in the fractal dimensions (D) and decreasing in the case of multifractal analysis (Dmf).

TABLE 1. Variation of productivity elements and fractal dimensions in the spikes under the influence of variation in nitrogen doses in wheat "Fanulus" variety

Variant	N	D	Dmf	SL	SpN	SN	SW
V_0 (Control)	0	1.697±0.061	1.597±0.31	5.76±0.10	11.2±0.37	21.8±0.58	0.828±0.04
V_1	30	1.757±0.065	1.566±0.33	6.68±0.18	13.4±0.51	27.8±1.06	1.123±0.04
V_2	60	1.772±0.075	1.570±0.33	7.40±0.13	15.0±0.32	33.2±1.35	1.363±0.03
V_3	90	1.804±0.051	1.556±0.32	7.64±0.08	15.8±0.37	35.6±1.91	1.477±0.07
V_4	120	1.833±0.046	1.535±0.31	8.78±0.10	17.8±0.37	45.0±2.06	2.087±0.18
V_5	150	1.842±0.041	1.539±0.31	9.62±0.06	19.6±0.40	57.2±1.56	2.495±0.10
V_6	180	1.844±0.045	1.523±0.29	10.30±0.12	21.0±0.32	60.2±0.86	2.662±0.12

N – nitrogen doses, a.s. kg ha^{-1}; D – fractal dimension; Dmf – multifractal dimension; SL – Spike length (cm); SpN – spikelets number; SN – Seeds number; SW – seeds weight (g).

The Kruskal-Wallis test revealed significant differences between indicator groups based on different levels of fertilization. Specifically, for both, the fractal dimension (D, Dmf) and the qualitative indicators on spike development (SL, SpN, SN, SW), different values were found for different fertilization levels ($p < 0.01$ for each of the groups tested). Moreover, following the mean rank values (Table 2), there was a tendency to decrease them in the case of Dmf, respectively to growth in all the other indicators analyzed.

Interest in the study of wheat spikes by non-destructive, imagistic methods was also present in other researches. Cointault and Gouton (2007), and Cointault *et al*., (2008) studied the feasibility of using color and texture imaging analysis methods for detecting wheat densities with good results. The advantage of these methods can be found in reducing the workload associated with the manual determination of the density of the spikes, and increasing the working speed, in safety and precision conditions.

Nitrogen fertilizer doses determined the variation in the size and shape of wheat spikes in the studied "Fanulus" variety. Fractal and multifractal analysis was used to evaluate the fractal geometry of the wheat spike. The fractal dimensions obtained, D and Dmf, presented in Table 1, were analyzed in relation to the doses of nitrogen fertilizer applied. Between the fractal dimensions (D, Dmf) and the fertilizer doses (Table 1), close relationships of interdependence have been identified (Table 2). Thus, the fractal dimensions, D and Dmf of the spike shape, had a strong correlation with the nitrogen doses, Figure 2.

TABLE 2. Mean rank for different levels of fertilization

Parameter	N	Mean Rank	Parameter	N	Mean Rank	Parameter	N	Mean Rank
	0	31.70		0	3.20		0	3.00
	30	23.30		30	8.00		30	8.50
	60	23.10		60	13.90		60	14.20
Dmf	90	18.50	SL	90	16.90	SpN	90	16.90
	120	10.80		120	23.00		120	22.50
	150	11.60		150	28.00		150	29.20
	180	7.00		180	33.00		180	31.70
	0	3.40		0	3.20		0	3.00
	30	10.30		30	8.60		30	8.40
	60	11.20		60	13.60		60	13.80
D	90	17.30	SN	90	16.80	SW	90	16.80
	120	26.40		120	23.10		120	24.80
	150	28.70		150	28.30		150	28.60
	180	28.70		180	32.40		180	30.60

TABLE 2. Relationships between fractal dimensions (D, Dmf) and fertilizer doses

Dependent	R^2	F	Sigf	*b0	b1	b2
D	0.971	49.82	0.005	1.7151	0.0013	-3E-06
Dmf	0.891	12.20	0.036	1.5764	-0.0002	-6E-07

D – Values resulting from fractal analysis; Dmf – Values resulting from multifractal analysis.

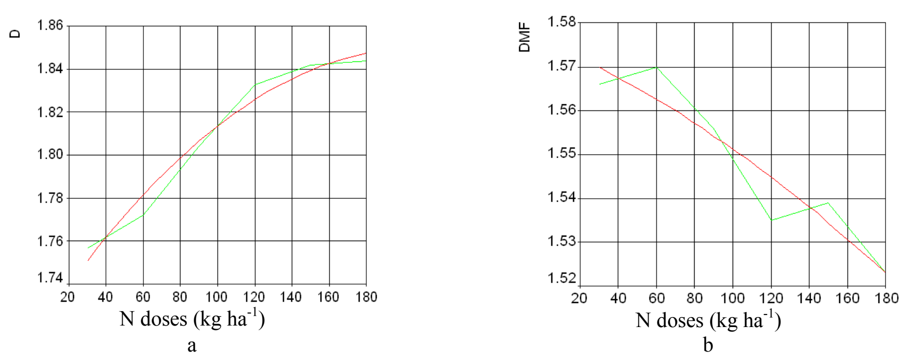

FIGURE 2. The particular distribution of the fractal dimensions (D and Dmf) of the wheat spike, the "Fanulus" variety, depending on the nitrogen doses

The productivity elements of the wheat spike, such as spike length (SL), number of spikelets (SpN), number of grains (SN) and grain weight (SW), are specific to each genotype.

At the same time, they are influenced by environmental and technological factors, among which fertilizers are a determining factor (Sinclair & Jamieson, 2006; Ugarte *et al*., 2007; Sala *et al*., 2014b; Rawashdeh & Sala, 2014b, 2016).

The variation of the productivity factors in the wheat spike, the "Fanulus" variety, was analyzed in relation to the applied nitrogen doses, and the interdependence relationships (Table 3) described by the general relationship (2), were identified between the two categories of variables.

$$y = b_0 + b_1 x + b_2 x^2 \qquad (2)$$

where: y – the parameter studied; x –nitrogen doses; b_0, b_1 and b_2 – coefficients.

The relation between the length of the spike (SL) and the nitrogen doses described by equation (3) was identified at a high correlation level with statistical safety (R^2 = 0.986, p<0.01, F = 104.7). The length of the spike is also the anatomic and productivity element on which other elements have developed: the number of spikelets (SpN), the number of seeds (SN) and the weight of the seeds (SW).

The number of spikelets (SpN) also had a positive correlation with the variation in nitrogen doses, relationship (4), under statistical safety (R^2 = 0.993, p<0.01, F = 219.18). The dependence between the number of seeds in the wheat spike (SN) and the nitrogen doses, described by relation (5) (R^2 = 0.968; p <0.01; F = 45.8), respectively the dependence between the seeds weight (SW) and nitrogen doses, described by relation (6) (R^2 = 0.966, p <0.01, F = 42.73), also showed statistical safety. The graphical distribution of the particular values of the productivity elements in relation to the nitrogen doses is shown in Figure 3.

TABLE 3. Relationships of interdependence between the wheat spike productivity elements and nitrogen

Dependent	R^2	F	Sigf	b_0	b_1	b_2
SL	0.986	104.70	0.002	6.1800	0.0155	4.4E-05
SN	0.968	45.80	0.006	23.3600	0.1185	0.0005
SpN	0.993	219.18	0.001	12.2200	0.0387	6.0E-05
SW	0.966	42.73	0.006	0.8250	0.0079	1.5E-05

$$SL = 6.18 + 0.0155x + 4.4E - 05x^2 \qquad (3)$$

$$SN = 23.36 + 0.1185x + 0.0005x^2 \qquad (4)$$

$$SpN = 12.22 + 0.0387x + 6.0E - 05x^2 \qquad (5)$$

$$SW = 0.83 + 0.0079x + 1.5E - 05x^2 \qquad (6)$$

where: SL – spike length; SpN – spikelet number; SN – seed number; SW – seed weight; x – nitrogen doses.

The analysis of the relation between the fractal dimensions of the spice shape and the productivity elements in the wheat, "Fanulus" variety, revealed interdependence in conditions of statistical safety, between the two categories of variables.

The fractal dimensions (D) have closely correlated with the productivity elements of the spike, the correlations being described by the relation (7) for the length of the spike (R^2 = 0.925, p<0.01, F = 24.832), relation (8) for the number of spikelets (R^2 = 0.935, p<0.01, F = 28.84), relation (9) for number of seed (R^2 = 0.916, p<0.01, F = 21.54), and relation (10) for seed weight (R^2 = 0.936, p<0.01, F = 29.44).

$$SL = 186.4x^2 - 633.8x + 544.6 \quad (7)$$

$$SpN = 331.3x^2 - 1115x + 948.9 \quad (8)$$

$$SN = 2219x^2 - 7641x + 6600 \quad (9)$$

$$SW = 107.2x^2 - 369.1x + 318.5 \quad (10)$$

where: x = fractal dimension (D).

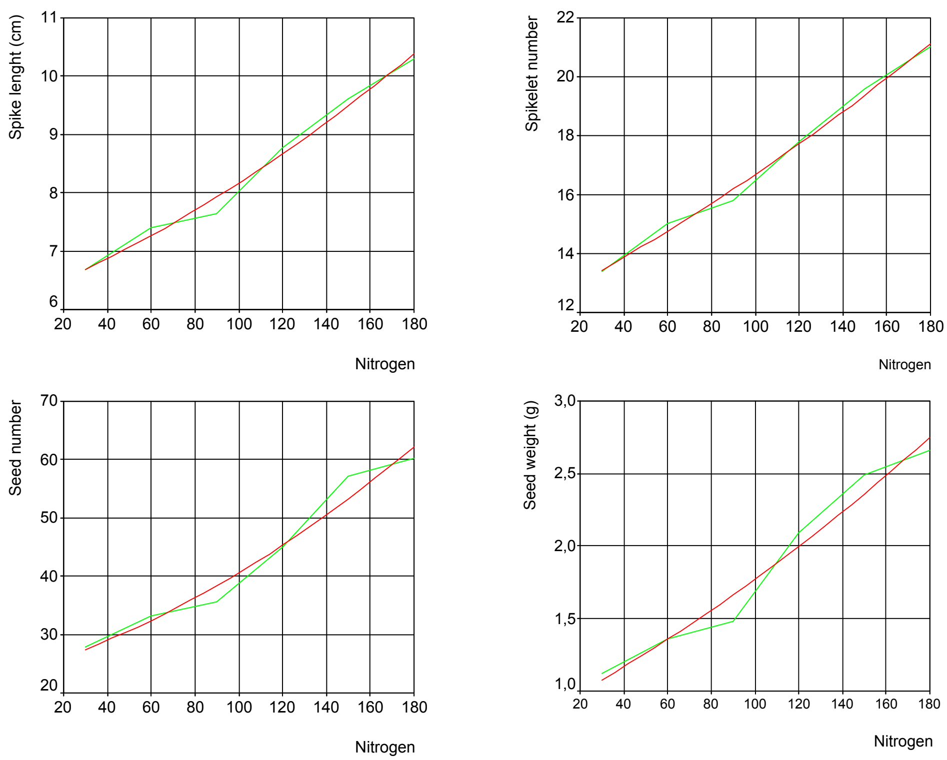

FIGURE 3. The graphical distribution of the values of the determined productivity elements, compared to the theoretical model, according to the rate of nitrogen.

Relationships of interdependence have also been identified between the Dmf values, obtained by multifractal analysis, and the spike productivity elements described by the relation (11) for the length of the spice (R^2 = 0.928, p<0.01, F = 25.755), relation (12) for the spikelets number (R^2 = 0.927, p<0.01, F = 25.71), relation (13) for number of seed (R^2 = 0.833, p = 0.014, F = 15.106), and relation (14) seed weight (R^2 = 0.916, p<0.01, F = 21.95).

$$SL = 376x^2 - 1234x + 1018 \quad (11)$$

$$SpN = 559.5x^2 - 1877x + 1581 \quad (12)$$

$$SN = 4463x^2 - 1.445E04x + 1.172E04 \quad (13)$$

$$SW = 219.9x^2 - 712.2x + 577.2 \quad (14)$$

where: SL – spike length; SpN – spikelet number; SN – seed number; SW – seed weight; x – multifractal dimension (Dmf).

Fractal analysis has been successfully used in the characterization of rice panicle by Gong *et al*. (2009), who found relationships of linear interdependence between fractal dimensions and production. Due to the fact that parameters characterizing wheat spikes are very important for the breeding process, Bi *et al*. (2011) proposed a mathematical method based on morphological elements of the spice to achieve - without contact - measurements of these parameters, with high accuracy. Studying the dimensional parameters of the spike in 6 wheat varieties, they obtained results with high precision, the errors being between 2 - 6.2%. Espinosa-Mendoza *et al*. (2012) used fractal analysis to characterize the morphostructure of rice grains during the formation and filling period, with statistical safety (p≤0.05).

Based on the interdependence relationships identified between fertilizers, fractal dimensions and productivity elements of wheat spikes, and in the context of the interest presented for indirect methods of studying the productivity elements highlighted by the literature, the hypothesis of the prediction of the productivity elements based on the fractal dimensions was formulated.

Through regression analysis, the prediction of the values of productivity elements of wheat spike, "Fanulus" variety, was made, on the basis of the fractal dimension (D and Dmf). Predictive safety was assessed on the basis of the RMSE parameter, the results being shown in Table 4.

TABLE 4. Safety of prediction of productivity elements of wheat spikes, "Fanulus" variety, based on nitrogen doses and fractal dimensions

Elements and parameters	Productivity element											
	SL			SpN			SN			SW		
The element used in prediction	N	D	Dmf	N	D	Dmf	N	D	Dmf	N	D	Dmf
RMSE	0.16	0.53	0.45	0.27	1.02	0.91	2.43	5.72	5.22	0.11	0.25	0.22

CONCLUSIONS

The variation of N doses in the studied range significantly influenced the elements of productivity, shape and geometry of wheat spikes.

Fractal analysis has facilitated the description of the variation of the wheat spike geometry based on fractal dimensions, in relation to differentiated nutrition status assured by the variation of the N doses.

By regression analysis it was possible to obtain polynomial functions in order to predict the productivity elements at the level of wheat spikes on the basis of fractal dimensions D and Dmf, under statistical safety conditions.

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