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FRACTAL DIMENSION AND CAUSALITY RELATIONSHIPS WITH FOLIAR PARAMETERS: CASE STUDY AT *ALNUS GLUTINOSA* (L.) GAERTN.

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ABSTRACT

This paper purpose was to analyze leaves shape geometry through fractal dimension parameter for Alnus glutinosa (L.) Gaertn, a species that can be found generally in alluvial forests, situated below 1000 m, but growing sporadically up to 1800 m. This index, which can be determined quickly and cheaply, is appropriate in biomonitoring studies in urban or non-urban environments, because this species is also often found in parks, in towns and cities. Fractal dimension can be analyzed in relation with various morphometric parameters, as perimeter, scanned leaf area, leaf length and width. In this study, mathematical models between these indices and fractal dimension were developed, statistical safety being assured. Fractal dimension D can be a stable index for the leaves geometry characterization, having a low degree of variability when compared with L, W, Per or SLA, which presented a high degree of variability, noticed based on variation coefficient CV.

KEY WORDS: *Alnus glutinosa, fractal analysis, leaf parameters, isoquants, RMSE*

INTRODUCTION

Alnus glutinosa (L.) Gaertn., black alder, is a relatively small, broad-leaved tree, native to almost all Europe (Ellenberg, 2009), being one of the three Alnus species widespread in this region (Aniszewska *et al.*, 2019). It has simple, dark green leaves, which morphologically are obovate (Mitchell, 1974). This species grows below 1000m in elevation, although in the mountains of central Europe it can occasionally be found along watercourses up to 1800m (Houston Durrant *et al.*, 2016). Common alder establishes populations in various environments, due to the fact that is adapted to a wide range of temperatures and is quite frost-tolerant (Rutkowski *et al.*, 2019). Although black alder is not really common, it is an important component in open landscapes, especially along river banks and in marshy areas (Rutkowski et al., 2019). For this species, researches were realized regarding wood structure (Yaman, 2009; Han *et al.* 2015), growth patterns (Vacek *et al.*, 2016; Socha & Ochał, 2017), wood quality (Kaliniewicz *et al.*, 2018), weight, size, and storage of seeds (Gosling *et al.*, 2009; Kaliniewicz & Trojanowski, 2011)

Plant functional characteristics reflect plant adaptations to different environments and utilization of resources, and therefore provide important information for the analyses of community assembly (McGill *et al.,* 2006; Ackerly & Cornwell, 2007) and ecosystem functioning and services (Díaz *et al.*, 2007). Moreover, studies regarding the relation between leaves features (degree of lobing, leaf apex, size and outline shape, base morphology and presence or absence of marginal teeth) and climate (average annual temperature, precipitation) over the last decades has revealed that, for many plant species, physical characteristics vary predictably in response to local environmental variation (MacLeod & Steart, 2015).

Fractal dimension analysis for leaves was developed starting with 1977 by Mandelbrot (1977) and there are different types of methods generally used like box-counting method (Trictot, 1995; Buczkowski *et al.*, 1998) or, for multifractal dimension Minkoswki's method (Costa & Cesar, 2000).

The study purpose was the analyze and characterization of leaves geometry through fractal analysis and estimation of determination relations between foliar parameters and fractal dimensions (D) for *Alnus glutinosa* (L.) Gaertn.

MATERIAL AND METHOD

The study evaluated fractal geometry of black alder leaves and the causality relation between fractal dimension and foliar parameters.

The biological material was represented by *Alnus glutinosa* (L.) Gaertn samples. Leaf probes were randomized collected and contained the natural size variation of leaves. 100 leaves with variable sizes were investigated. The black alder leaves are ovate or roundish, with an obtuse apex, an acuminate base and margins coarsely and doubly serrate figure 1. Leaves images were obtained through 1:1 scanning. Some foliar parameters were studied: leaf length (L), leaf width (W), perimeter (Per), scanned leaf area (SLA) (Sala *et al.*, 2015).

FIGURE. 1. *Alnus glutinosa* (L.) Gaertn. leaf

For the fractal analysis, box-counting method was used (Voss, 1985). It was applied on binarized images (Rasband, 1997). Fractal dimensions, intermediary values, relation (1) and mean value, relation (3) were obtained in statistical safety conditions (R^2 for D had values from 0.997 to 0.998).

$$D = m\left[\frac{\ln(F)}{\ln \varepsilon}\right] \tag{1}$$

where: D – fractal dimension;
m – slope to regression line, from equation (2);
F – number of new part;
ε – scale applied to an object.

$$m = (n\sum SC - \sum S \sum C)/(n\sum S^2 - (\sum S)^2) \tag{2}$$

where: m – slope of the regression line;
S – log of scale or size;
C – log of count;
n – number of size;

$$Mean\, D = \sum (D) / GRIDS \tag{3}$$

For experimental data analysis, ANOVA single factor test was utilized for the variance evaluation and the safety of experimental data.

Causality relations between D and foliar parameters was studied through multiple and simple regression analysis and as statistical safety parameters regression coefficient (R^2), p parameter, RMSE, relation (4) and SEP relation (5) were used. For imagistic analysis of leaf probes and experimental data, ImageJ, EXCEL and PAST (Hammer *et al.*, 2001) were used.

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(y_j - \hat{y}_j)^2} \tag{4}$$

$$\mathrm{SEP} = \sqrt{\mathrm{p}(1-\mathrm{p})\left(\frac{1}{\mathrm{n}_1} + \frac{1}{\mathrm{n}_2}\right)} \tag{5}$$

RESULTS AND DISCUSSIONS

The determinations and measurements of black alder leaves conducted to data obtained regarding leaves lengths (L) and widths (W). On the scanned images in a 1:1 ratio, scanned leaf area, (SLA) and perimeter (P) were determined. Considering leaves dimensions, 7 size groups were obtained, and the studied parameters varied: L=4.10±0.08 cm (G1) to L=10.15±0.13 cm (G7); W=3.57±0.12 cm (G1) to W=9.37±0.26 cm (G7), SLA=10.98±0.64 cm^2 (G1) to SLA=69.01±2.99cm^2 (G7), Per=134.72±3.79 mm (G1) to Per=340.58±7.35 mm (G7).

Fractal analysis, box-counting, conducted to D values with a high statistical safety (R^2=0.997 to R^2=0.998), with a variation between D=1.737±0.003 (G1) and D=1.811±0.004 (G7). Foliar parameters and fractal dimensions (D) are presented in table 1.

The analysis of the values for the determined biometric parameters (L, w, Per, SLA) and fractal values (D) conducted to a differentiated variability of common alder leaves, mathematic instrument being coefficient of variation (CV). Thus, the coefficient of variation had the value CV_L=28.8263 for leaves length, CV_W=30.3299 for leaves width, CV_{Per}=29.1355 for leaves perimeter, CV_{SLA}=59.0168 for scanned leaf area SLA. These values presented a high degree of variability for leaves depending on the dimensional parameters.

TABLE 1. Foliar parameters and fractal dimension (D) data for black alder *Alnus glutinosa* (L) Gaertn leaves (mean values depending on size groups)

Sample	L	W	Per	SLA	D	R^2 for D
G1	4.10±0.08	3.57±0.12	134.72±3.79	10.98±0.64	1.737±0.003	0.997
G2	5.06±0.11	4.61±0.05	171.10±2.44	17.34±0.49	1.746±0.002	0.997
G3	5.97±0.10	5.37±0.08	195.90±1.88	22.82±0.28	1.757±0.003	0.997
G4	6.43±0.14	5.85±0.09	210.61±1.30	26.69±0.32	1.761±0.001	0.997
G5	6.79±0.11	6.17±0.11	231.95±1.50	32.27±0.52	1.768±0.003	0.997
G6	8.22±0.15	7.29±0.15	270.36±5.26	42.95±1.49	1.771±0.003	0.998
G7	10.15±0.13	9.37±0.26	340.58±7.35	69.01±2.99	1.811±0.004	0.998

L – leaf length; W – leaf width; Per – leaf perimeter; SLA – scanned leaf area; D – fractal dimension

TABLE 2. ANOVA single factor

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3784941	4	946235.2	1040.329	1.7E-246	4.690517
Within Groups	472967.8	520	909.5534			
Total	4257908	524				

Alpha = 0.001

Regarding fractal dimensions (D), a low variability was noticed (CV_D = 1.4254) when compared with the other studied parameters. This fact shows that the stability of fractal dimensions in leaves typology expression for the studied species, similar results being communicated also in other studies (Sala et al., 2017).

Also, a high independence degree of D values when describing a plant species was noticed, the specific patterns of leaves shapes varying in a short range in relation with them size. This shows fractal analysis capacity to describe and characterize shapes fractal geometry, in this case, for black alder leaves shape.

Fractal analysis comprised the typology or the specific of fractal geometry of leaves shapes, generating D values with a high degree of stability. The highest variability in black alder leaves characterization was for SLA (CV_{SLA}=59.0168) and the highest stability was obtained for fractal dimensions (D), the value of variation coefficient being CV_D=1.4254. Correlation analysis conducted to the data presented in table 3. After the completion of the analysis of the obtained values, very high and high positive correlations were noticed between the studied foliar parameters, SLA and the values of fractal dimensions D.

Regression analysis evaluated the contribution of foliar parameters (L, W, Per, SLA), as parameters which define black alder leaves geometry for obtaining fractal dimensions (D).

The D variation in relation with the studied parameters was described by relation (6), with R^2=0.835, p<<0.001, and equations terms of the relation (6). After analyzing the coefficients values of relation (6), a differentiated contribution of leaf parameters, which defines in general, the fractal geometry of the leaves on the formation of fractal dimensions (D), was observed.

TABLE 3. Matrix table with correlations

	L	w	SLA	Per	D
L		3.26E-67	8.35E-61	2.01E-72	1.12E-33
w	0.973		5.79E-73	3.17E-82	1.20E-35
SLA	0.964	0.979		5.03E-79	1.35E-41
Per	0.978	0.986	0.984		2.24E-36
D	0.872	0.883	0.912	0.887	

$$D = 1.73756 + 0.001117 \cdot L - 0.00158 \cdot W - 0.00012 \cdot Per + 0.001677 \cdot SLA \quad (6)$$

By multiple regression analysis, equations were obtained that described the variation of the fractal dimension D according to L and W, equation (7), respectively according to W and Per, equation (8), under high statistical safety conditions. The values of the statistical safety coefficients for equations (7) and (8) are shown in table 4.

Based on the two equations (7) and (8), 3D graphical distributions were obtained, which express the fractal dimension (D) variation in relation to considered parameters of the leaves. Also, graphical representations were obtained in the form of isoquants, which express graphically the optimal range of x and y variation for optimal values of fractal dimensions (D). The 3D and isoquant graphical representations for equation (7), as example, are presented in Figure 2 a, b.

When the leaf surface (SLA) with each leaf parameter (L, W, Per) was considered together, the resulting equations led to obtaining the fractal value D with higher accuracy, appreciation based on the p values. The values of the F test indicated the best description of the variation of the D value according to the perimeter (Per) and the leaf surface (SLA): F = 269016.2 in the case D = f(Per, SLA), equation (9), figure 3 a, b; F = 103204 in the case of D = f(L, SLA), and F = 69267.15 in the case of D = f(W, SLA) respectively.

$$D = ax^2 + by^2 + cx + dy + exy + f \tag{7}$$

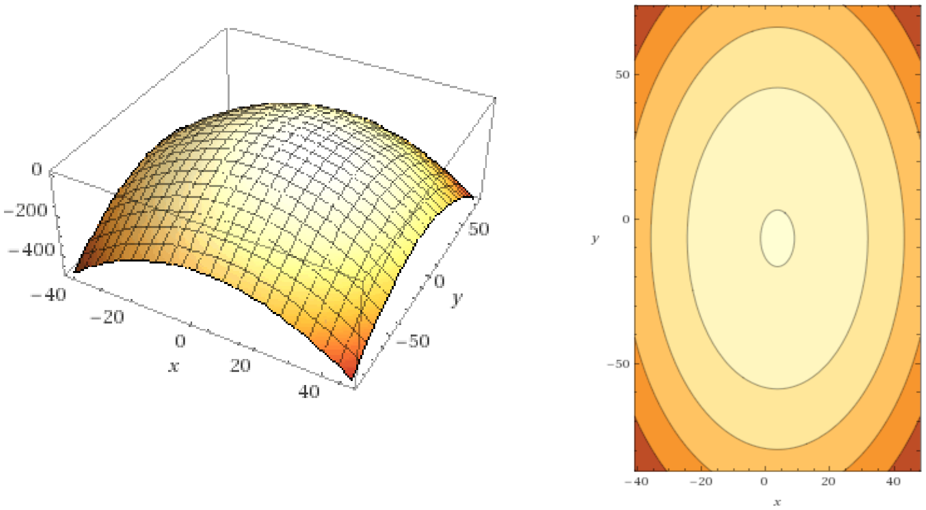
where: x – L – leaf length;
y – W – leaf width;
a, b, c, d, e, f - the equation (7) coefficients;
a= -0.131015323791136;
b= -0.0382441232157529;
c= 0.969826215291039;
d= -0.513763983011542;
e= 0.142354323387578;
f= 0.

$$D = ax^2 + by^2 + cx + dy + exy + f \tag{8}$$

where: x – W – leaf width;
y – Per – leaf perimeter;
a, b, c, d, e, f - the equation (8) coefficients;
a= -0.0340246299945366;
b= -0.000163168952235456;
c= -0.933039520684597;
d= 0.0402541620015277;
e= 0.00585110570318677;
f= 0.

TABLE 4. Statistical safety parameters of the (7) and (8) equations

Equation parameter	Equation (7)			Equation (8)		
	R^2	F	P-value	R^2	F	P-value
x^2	0.995	8175.983	0.000672	0.994	7039.715	0.429747
y^2			0.32631			7.64E-06
x			6.9E-24			1.68E-12
y			7.79E-08			6.79E-25
xy			0.064621			0.016813
Intercept			-			-



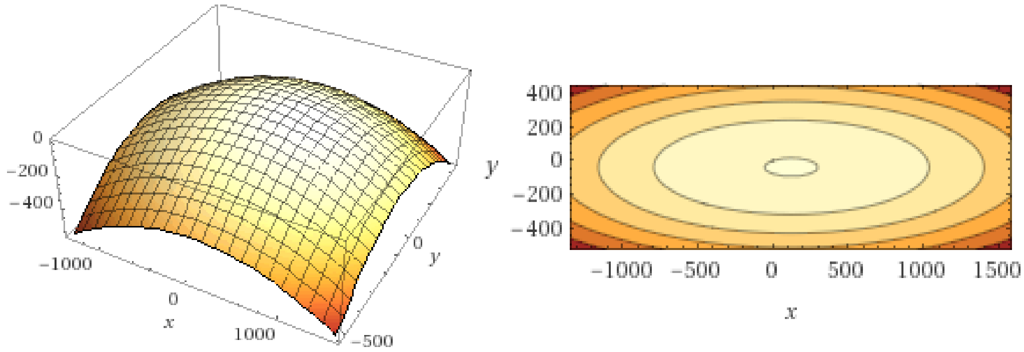
a

b

FIGURE 2. Graphical distribution of fractal dimension (D) in relation to L (x) and W (y); a – 3D graphic distribution; b – distribution in the form of isoquants

$$D = ax^2 + by^2 + cx + dy + exy + f \qquad (9)$$

where:
x – Per – leaf perimeter;
y – SLA – scanned leaf area;
a, b, c, d, e, f - the equation (9) coefficients;
a= -0.000124311614807094;
b= -0.00133565634546919;
c= 0.0303471921735137;
d= -0.108231438569611;
e= 0.000839994428690411;
f= 0.



a

b

FIGURE 3. Graphical distribution of fractal dimension (D) in relation to L (x) and W (y); a – 3D graphic distribution; b – distribution in the form of isoquants

From the results of multiple regression analysis, the conditions in which each independent foliar parameter can assess fractal dimension D were analyzed. Based on leaves lengths (L), relation (10) describes the variation of fractal dimension (D), with R^2=0.964, RMSEP = 0.10801, SEP = 0.612707.

$$D = 0.0014 \cdot L^2 - 0.0084 \cdot L + 1.7514 \quad (10)$$

Based on leaves widths (W), relation (11) describes the variation of fractal dimension (D), with R^2=0.973, RMSEP = 0.01068, SEP = 0.606469.

$$D = 0.0014 \cdot L^2 - 0.0084 \cdot L + 1.7514 \quad (11)$$

Based on leaves perimeters (Per), relation (12) describes fractal dimension (D) variation, with R^2=0.986, RMSEP = 0.010367, SEP = 0.588325.

$$D = 9E - 07 \cdot Per^2 - 0.0001 \cdot Per + 1.7362 \quad (12)$$

Based on leaves scanned area (SLA), relation (13) describes the variation of fractal dimension (D) with de R^2=0.998, RMSEP = 0.010107, SEP = 0.573504.

$$D = 3E - 06 \cdot SLA^2 + 0.001 \cdot SLA + 1.7266 \quad (13)$$

The leaves are organs that faithfully express the relationship of plants with general environmental conditions, with the nutrition media, stress factors, vegetation stages, production and production quality (Jivan & Sala, 2014; Rawashdeh & Sala, 2015, 2016; Datcu & Sala, 2018). At the same time, the leaves of some species of plants, considered as indicator species, have been used in biomonitoring studies in urban or non-urban habitats (Ianovici, 2011; Ianovici *et al.*, 2015; Datcu *et al.*, 2017; Hajizadeh *et al.*, 2019). Non-invasive analysis is very useful in leaf studies, and different applications have been developed for this (Drienovsky *et al.*, 2017a,b).

Fractal analysis is a very useful method for studying shapes and surfaces (Xu *et al.*, 2009). Fractal analysis has been applied to plants in different studies to identify species, taxonomic studies, pomology studies etc. (Jobin *et al*, 2012; Du *et al.*, 2013; Gazda, 2013; Bayirli *et al.*, 2014; da Silva *et al.*, 2015; Sala *et al.*, 2017).

Starting from the objectives of this study, a series of causality and interdependence relationships between the foliar parameters studied (L, W, Per, SLA) and the fractal dimension (D) were found. The fractal geometry of the leaves, through the defining elements analyzed, was faithfully highlighted in the fractal dimensions D. The causal relationships between the L, W, Per and SLA sheet parameters were identified under high statistical safety conditions.

CONCLUSIONS

This study evaluated fractal dimension of black alder leaves. This index, which can be determined quickly and cheaply, is suitable in biomonitoring studies in urban or non-urban habitats. This species often occurs near rivers, but it can be found in parks in towns and cities. Fractal dimension can be analyzed in relation with various morphometric parameters, as perimeter, scanned leaf area, leaf length and width. In this study, mathematical models between these indices and fractal dimension were developed, statistical safety being assured. Fractal dimension D can be a stable index for the leaves geometry characterization, having a low degree of variability when compared with L, W, Per or SLA, which presented a high degree of variability, noticed based on variation coefficient CV.

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