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FRACTAL ANALYSIS OF SPATIAL VARIABILITY OF ORGANIC CARBON IN ANTHROPOGENIC SOILS. CASE STUDY: KASTELA BAY, CROATIA

SUMMARY

Soil organic carbon (SOC) is a key variable of the soil, agriculture and whole environment. The spatial variation of SOC is controlled by many spatially independent processes and their complex interactions which operate on its own discrete scale. Understanding the causes and characteristics of SOC spatial variation can help knowing how to measure it and to design better site-specific management strategy or precision farming. The objectives of the research are to characterize spatial variability of SOC in the anthropogenic soils and identify the principal factors that determine its spatial pattern. In the total of 206 top-soil samples (0-30 cm) collected on a 4 960 ha of the anthropogenic soils at the Kastela Bay, Croatia, SOC was analyzed. The mean SOC content was 22.19 g C kg^{-1} and ranged between 7.75 and 40,87 g C kg^{-1}. The SOC has shown a multifractal behavior characterized with partial spatial indepedence over a scale of 5 000 m separated with break point. Estimated fractal parameters for SOC, derived by variogram method, for maximum distance between point par of 21 000 m, were: fractal dimension (D) 1.92, ordinate intercept - gamma (γ) 1.09 and associated coefficient of determination (R^2) 0.50. The very high fractal D value, high gamma (γ) value and low R^2 indicated a very small spatial continuity of SOC. This has shown that short-range effects prevail over long-range ones in affecting the overall complexity of distribution and that variations of SOC at small scale are significant. The results of research showed that spatial variability of SOC, at selected scale, probably is related with the differences of parent material, composition of the colluvial deposits and its spatial periodicity as well as differences and repeatability of topography.

Keywords: soil organic carbon, fractal dimension, break point.

INTRODUCTION

Soil organic carbon (SOC) content and its spatial pattern are an important issue in the context of soil productivity, soil degradation risks (Lal, 2004), biological diversification and climate changes (EC, 2006). Therefore, the issues of the spatial variability and amount of SOC were a frequent subject of interest of numerous studies which have focused on different aspects of SOC spatial pattern.

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However, despite of its importance an understanding of the spatial variability of SOC has remained poor.Agricultural soils typically have a lower SOC contents than natural. The forecasted climate change will likely result in further reductions in SOC. This is especially so in the Mediterranean area which is the most sensible ones to climate change (IPCC, 2007) and where the SOC content in soils is generally low (Jones et al., 2005). Therefore study of the spatial variation of SOC, particular in typical Mediterranean area is vitally important for the sustainable land management and preservation of soil quality and whole environment. Also, we hope that better understanding of the causes of SOC variation can help to advance field investigations, improve sampling design and interpolation procedures for mapping.

The spatial pattern of SOC is controlled by many different factors which may operate independently or in combination with other factors over a wide range of spatial and temporal scales with different intensities. Generally, parent material and climate are assumed to define large-scale patterns of SOC content (McLauchlan, 2006), while other factors, like topography and human impact, define the SOC variation at smaller scales (Dendoncker et al.; 2004; Sleutel et al., 2007; Schulp et al., 2008). Therefore the spatial pattern of SOC is very complex and more complicated than landform and other environmental matrices.

The objective of this paper is to establish characteristics of spatial variability of the organic carbon in the anthropogenic soils by using fractal theory. According to fractal theory introduced by Mandelbrot (1967) fractals are defined as objects with structures partially correlated at all spatial scales with a scale-dependent self-similarity. The fractal dimension (D) is a single and constant parameter appliable to all scales. Mathematicaly, fractal is a self-similar object which is exactly similar to a part of itself. In the real world many objects are only statistically self-similar natural features which often show self-similarity or scale invariance in more scales and a distinct fractal dimension for each particular scale.

The soils are fractal because increase of the scale resulting in an increase of quantity of details. We used fractal dimension (D), as a measure of the complexity of the SOC spatial pattern. The fractal analysis has been shown as a widely used technique for spatial analysis of the landscape and natural processes (Burrough, 1981;1983a,b; Mark and Aronson, 1984; Goodchild and Mark, 1987; Krummel et al., 1987; DeCola, 1991; Milne, 1988). We expect that the results of the study contribute to a identification and better understanding of the factors and processes that determine the spatial pattern of SOC.

MATERIAL AND METHODS

Study area

Kastela Bay is situated in the Middle Adriatic, centred on 43°33′26" N; 16°21′55" W. The research area covers total of 4 960 hectares and occupies a narrow zone between towns of Split and Trogir, steep slopes of mountain Kozjak in the north and the urbanized area along the coast in the south. The study area had mean annual precipitation of 1 062 mm and mean air temperature of 15.9ºC. According to Köppen climate classification (1918) climate of study area is classified as Mediterranean with hot summer (Csa).

Geologicaly, study area was built of Eocene Flysch marls and sandstones, sometimes a sedimentary sequence consisting of coarse conglomerates or breccia's (Marinčić et al. 1971). Flysch sediments are partly covered by Quaternary colluvial skeletal and non-skeletal deposits thickness of 20(30) cm to several meters. Colluvium is a loose, unconsolidated sediment composed of the various deposits (soil mixed with rock fragments of various sizes and quantities). Elevation of the location varies from 10-305 m above sea level and continues with a massive of mountain Kozjak 779 m above sea level.

The topography is characterized by huge relief differences and a variety of terrain slope. The most common are gently sloping terrain (slope 2-5%) and very gently sloping terrain (slope 1-2%) covering 34.3 % and 22.7% of total area, respectively. Sloping terrain (5-10%) occupies 18.4% of area, while 17.0% of area are nearly flat terrain (0-1%). The strongly sloping terrain (10-15%) and very strongly sloping terrain (15-30%) covering the smallest area, 5.1 and 2.5 % respectively. Described relief characteristics and a watertight geological base with a wide elevation interval made this area vulnerable to erosion. Therefore terracing is a basic measure for soil protection in this typical torrential area.

According to the Croatian Soil Classification System (Škorić et al., 1975) soils of the study area are classified as Rigosol, non-skeletal silty clay loam, strongly calcareous, medium deep and deep formed on Flysch sediments and Rigosol, skeletal clay loam, slightly to moderately calcareous, medium deep and deep formed on Quaternary colluvium. According to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014) investigated soils we classified as Terric Anthrosols (Siltic/Clayic/Loamic) and Terric Anthrosols (Clayic/Loamic, Skeletic). Current agriculture is characterized by the small, mixed and dislocated parcels of the olive groves, vineyards, orchards of Mediterranean species, ploughed and abandoned land.

Soil data set

Point (pedon) data on soil organic carbon (SOC) which consists of 206 point observations from the topsoil (0−30 cm) were derived from Kastela Bay Soil Databases (Miloš 1992, 2002). The soil samples were collected randomly with a sample distance of approximately 500 meters. Maximum distance between point pars was 21 057 meters. The SOC content was determined by Kotzman method (JDPZ, 1966).

Measurement of fractal dimension

The fractal dimension (D) represent geometry of fractal pattern. The variogram method in the estimation of the fractal dimension was used, because of its applicability to dataset with irregular grid of point data set. The semivariance γ (h) for soil properties at distance "h" or lag h is defined in equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z_{x+h} - z_x)^2$$

where,

g(h) is the semivariance at lag „h“, refers to interval between neighboring sampling points

$Z_{(x)}$ and $Z_{(x+h)}$ – values of the variable (soil property) at location x_i and x_{i+h}, respectively and

N(h) is the number of pairs considered

The fractal dimension was calculated from the slope of a double logarithmic plot of the semivariance, γ(h), versus the lag distance h by fitting a straight line by the method of last squares. The calculation of D was made on the following relationship (Burrough 1981):

$$2g_h = h^b$$

where,

b = 4-2D (the slope of the log-log plot variogram)

D = 2 - b/2 (Hausdorff-Besicovitch statistic)

For a linear fractal function, the D dimension falls between 1 and 2 (Burrough 1981). Variables with strict spatial dependence at all scales, b=2 have a dimension D = 1. Conversely, those with complete spatial independence, b=0 have the fractal dimension D = 2.

Determination of break point

In this study we calculated fractal dimension (D) for the soil carbon content (g C kg^{-1}) for the maximum point pairs distance (all lag h) and for the first linear segment of the log–log variogram defined with break point. The break point (BP) defined break distance (BD) within which the log-log variogram can be fitted by a line provided that the coefficient of determination as a goodness-of-fit measure R^2>0.90 (Klinkenberg 1992). The additionally fractal parameters was gamma (g) defined as the intercept of the best-fitting line with the ordinate (Klinkenberg and Goodchild, 1992). In addition to these following requirement for the definition of break-point was the minimum of 100 point pairs at a distance with goodness-of-fit measure R^2>0.90.

RESULTS AND DISCUSSION

Descriptive statistics of SOC

The mean SOC content was 22.19 g C kg^{-1} and ranged between 7.75 and 40,87 g C kg^{-1}. The variability of SOC expressed by the coefficient of variation was 30.58 %. The histogram for SOC data shows nearly symmetrical (Skewness 0.34) and slightly flatter distribution (Curtosis -0.39), Figure 1.

About two-thirds of investigated soils (65.5 %) have medium SOC content (20-60 g C kg^{-1}). Low SOC contents (10-20 g C kg^{-1}) were determined in 33.5% of samples, while only 1% of the investigated soils have reached a very low SOC content of 10 g C kg− 1. This low value is proposed by the EU Soil Bureau as the value below which soils are considered to be particularly vulnerable to enhanced degradation, due to a lower aggregate stability (Jones et al, 2004). Loveland and Webb (2003) proposed a higher SOC threshold (20 g C kg^{-1}) bellow which soil quality can be largely decreased. However, soil degradation thresholds can depend on soil and climatic conditions.

Our data fit into averages for SOC in topsoils of Europe. According to Europe Map of top-soil organic carbon (0-30 cm) 13% of area has very low content of SOC (< 1%), 32% low (1-2%), 45% medium (2-6%) and 5% high (>6%) content of SOC (Jones et al. 2003). However, in southern Europe almost three-quarters (i.e. 74.6%) of the soils have top-soils containing very low (≤1%) or low (≤2%) amounts of SOC. Less than a quarter (24.6%) of southern European top-soils contain medium to high (>2%) amounts of SOC (Zdruli et al, 2004).

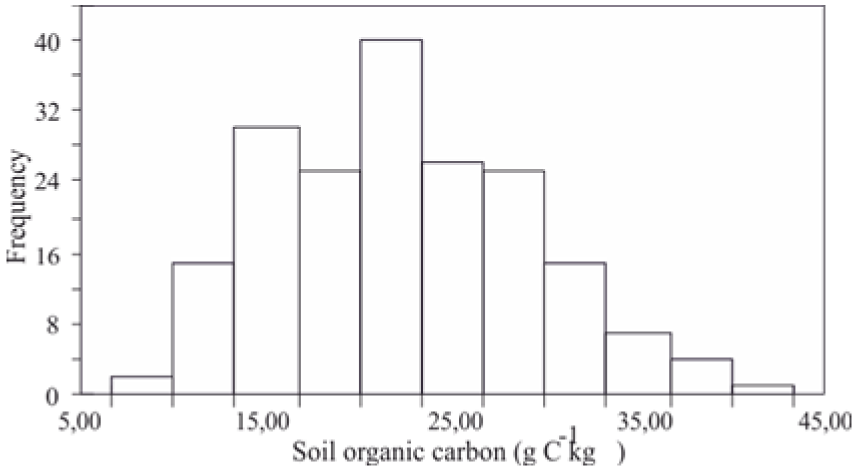

Figure 1. The histogram for top-soil organic carbon

Fractal parameters of soil organic carbon content

The fractal parameters for SOC (fractal dimension -D, gamma value -γ, break-point –BP, standard eror - SE and coefficient of determination -R2) calculated over range of 21 000 m with distance of 500 m as interval lag –h are given in Table 1 and Figure 2. The log-log variogram form shows a great discontinuity at origin (high gamma value) then, gradually increase with separation and having achieved sill at the distance of 5 000 m (Figure 2). After that, it decreases to a distance of 7 500 m, and then increased again to distance of 21 000 m. Described variogram model ilustrates nonmonotonic growth of the semivariance with distance and exhibits a periodic semi-variation structures known as a hole effect, indicating a multifractal behavior of SOC. The hole effect expressed in shape of semi-variogram, may be caused by the confounded effects of a periodic variation of parent material and colluvial deposits, as well as spatial repetition of topography.

Approximation of this variogram form with straight line resulted in a high intercept gamma (γ) of 1.09, a high standard error (SE) 0.329, a low associated coefficient of determination (R^2) 0.50 and consequently very high fractal D value (Table 1). The overall high fractal D value for SOC in our study was in good agreement with other studies which found high fractal dimensions for soil parameters (Burrough, 1981, 1983a; Culling, 1986). This results show a very small spatial continuity of SOC content and indicate that short-range effects of variations of SOC dominate. The domination of the short-range effects of variations indicates that its content in anthropogenic soils of Kastela Bay varies as a result of the various forming factors and processes acting at different spatial scales. The reasons for the observed spatial variability of SOC, at selected scale, mainly can be related with the differences of parent material, composition of the colluvial deposits and its spatial periodicity as well as differences and repeatability of topography.

In order to estimate the maximum distance at which the spatial correlation or scale independence of SOC can be applied, we have singled out first linear regression segment - break distance (BD) on the log-log plot of the semivariogram. The break- point or scale break defines point or border between correlated and uncorrelated values and provides information abouth the spatial organization of SOC pattern. The results have shown that SOC point values are correlated and scale independent over a scale of 5 000 metres (Table 1). This result is consistent with research of Burrough (1981) which pointed out that soils may exhibit self similarity over only a limited range of scales. Fractal parameters for estimated break distance (first linear segment with R^2>90) were: fractal value (D) 1.81, ordinate intercept - gamma (γ) 0.51 and associated coefficient of determination (R^2) 0.96 (Table 1).

Table 1. Fractal dimension (D), ordinate intercept - gamma (γ), standard error (SE) and associated coefficient of determination (R2) of the SOC (g C kg-1) for maximum distance between point par (all lag h) and for break distance (BD).

Statistics	All lag **-h**	Break-distance (BD)
	21 000 m	5 000 m
Fractal D	1.92	1.81
Gamma (γ)	1.09	0.51
R^2	0.50	0.96
Standard error (SE)	0.329	0.122

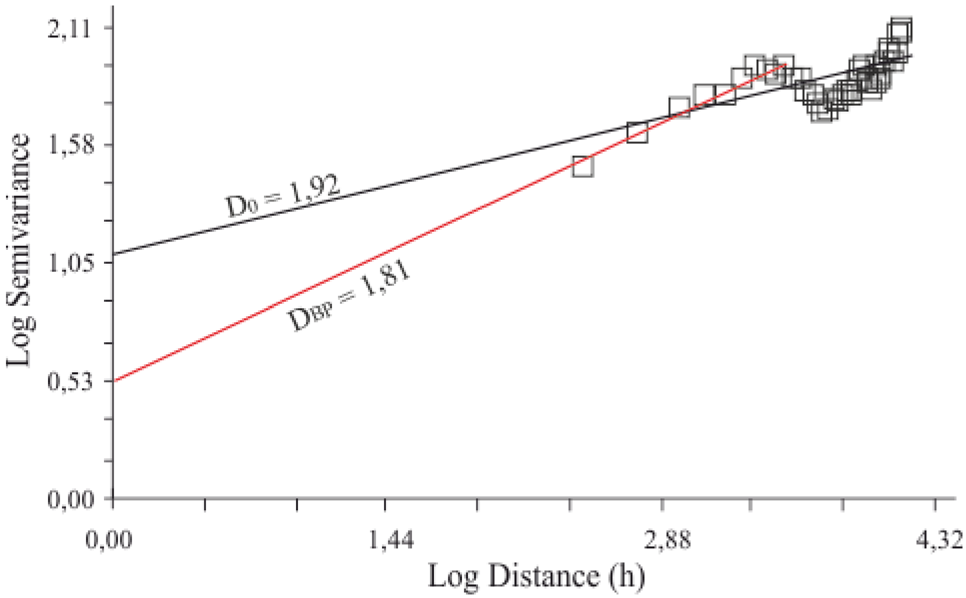

Figure 2. Log-log plot of the empirical semivariogram for soc, fractal dimension for the regression line estimated for the maximum distance between point par (D_o) and for first linear segment of the log–log plot defined with break-point (D_{BP})

CONCLUSIONS

Estimated fractal parameters for top-soil organic carbon (SOC) in investigated anthropogenic soils, including high fractal D value, high value of gamma (γ) and low coefficient of determination (R^2), have shown domination of short-range variations, implying its very small spatial continuity.

The log-log semi-variogram model of SOC has shown a multifractal behavior characterized with hole effect. We found that the SOC point values are correlated and scale independent over 5 000 metres separated with break point. The established fractal parameters indicated that SOC pattern is mainly related with differences of parent material, composition of the colluvial deposits and its spatial periodicity, as well as, differences and repeatability of topography.

This study showed that fractal analysis can be useful tool in studying SOC spatial variability and identification of soil forming factors which have caused it.

REFERENCES

Burrough, P.A., 1981. Fractal dimensions of landscapes and other environmental data, Nature 294:240-242.

Burrough, P.A., 1983a. Multiscale sources of spatial variation in soil. I. The application of fractal concepts to nested levels of soil variation. Journal of Soil Sci. 34(3): 577-597.

Burrough, P. A., 1983b. Multiscale sources of spatial variation in soil. II. A non-brownian fractal model and its application in soil survey. Journal of Soil Science 34(3), pp. 599–620.

Culling, W.E.H., 1986. Highly erratic spatial variability of soil-pH on Iping Common, West Sussex, Catena, Volume 13, Issues 1–2, Pages 81-98.

De Cola, L. 1991. Fractal analysis of multiscale spatial autocorrelation among point data. Envir. Plan. A 23: 545-556.

Dendoncker, N., Van Wesemael, B., Rounsevell, M.D.A., Roelandt, C., Lettens, S., 2004. Belgium's CO2 mitigation potential under improved cropland management.Agriculture, Ecosystems and Environment 103, 101–116

EC 2006. Proposal for a Directive of the european parliament and of the council establishing a framework for the protection of soil and amending Directive 2004/35/EC - European Community, Brussels (COM(2006)232 final).

Goodchild, M.F. & D.M. Mark. 1987. The fractal nature of geographic phenomena. Ann. Assoc. Amer. Geogr. 77: 265-278.

IPCC: Special report on emissions scenarios – a special report of working group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2000.

IUSS Working Group WRB (2014). World reference base for soil resources 2014 - International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106, FAO, Rome

JDPZ, 1966. Kemijske metode istraživanja zemljišta, Beograd.

Jones, R.J.A, Hiederer, R., Rusco, E., Loveland, P.J. and Montanarella, L. 2003. Topsoil Organic Carbon in Europe. Proceedings of the 4th European Congress on Regional Geoscientific Cartography and Information Systems, Bologna, 17-20.06.2003, p.249-251.

Jones RJA, Hiederer R, Rusco E, Loveland PJ, Montanarella L. 2004. The map of organic carbon in topsoils in Europe, Version 1.2, September 2003: Explanation of Special Publication Ispra 2004 No.72 (S.P.I.04.72). European Soil Bureau Research Report No.17, EUR 21209 EN, 26pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

Jones, R.J.A., Hiederer, R., Rusco, E. & Montanarella, L. 2005. Estimating organic carbon in the soils of Europe for policy support. European Journal of Soil Science, 56, 655–671.

Klinkenberg, B., 1992. Fractals and morphometric measures: Is there a relationship? Geomorphology, 5(1-2):5-20.

Klinkenberg, B., Goodchild, M.F., 1992. The fractal properties of topography: a comparison of methods. Earth Surf. Proc. Land. 17 (3), 217–234.

Köppen, W., 1918. Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf, Petermanns Geographische Mitteilungen, 64, 193-203.

Krummel, J.R., R.H. Gardner, G. Sugihara, R.V. O'Neill & P.R. Coleman. 1987. Landscape patterns in a disturbed environment. Oikos 48: 321-324.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627. DOI:10.1126/science.1097396

Loveland, P. & Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions A review. Soil & Tillage Research, 70, 1–18.

Mandelbrot, B., 1967,. How Long is the Coast of Britain? Statistical Self-Similarity and Fractional Dimension. Science 156 (3775): 636–638.

Marinčić, S., Magaš, N., Borović, I. 1971. Osnovna geološka karta SFRJ list Slit K 33-21, M=1:100000. Institut za geološka istraživanja, Zagreb, 1972. Redakcija i izdanje: Savezni geološki zavod, Beograd.

Mark, D., Aronson, P. 1984. Scale-dependent fractal dimensions of topographic surfaces: an empirical investigation, with applications in geomorphology and computer mapping. J. Int. Assoc. Math. Geol. 16 (7), 671–683.

McLauchlan, K., 2006. The nature and longevity of agricultural impacts on soil carbon and nutrients: a review. Ecosystems 9, 1364–1382.

Milne, B.T. 1988. Measuring the fractal geometry of landscapes. Appl. Math. Comp. 27: 67-79.

review. Ecosystems 9, 1364–1382.

Miloš, B. 1992. Tla kaštelanskog bazena s pedološkom kartom M=1:25000. Institut za jadranske kulture i melioraciju krša – Split

Miloš, B., 2002. Geografski informacijski sustav tala kaštelanskog Zaljeva. Institut za jadranske kulture i melioraciju – Split.

Schulp, C. J., Nabuurs, G.-J., and Verburg, P. H. (2008). Future carbon sequestration in Europeeffects of land use change. Agriculture, Ecosystems & Environment, 127(3):251–264.

Sleutel, S., De Neve, S., Beheydt, D., Li, C., and Hofman, G., 2006. Regional simulation of long-term organic carbon stock changes in cropland soils using the dndc model: 1. large scale model validation against a spatially explicit data set. Soil use and management, 22(4):342–351.

Škorić, A., Filipovski, Đ., Ćirić, M. 1975. Klasifikacija zemljišta Jugoslavije. ANUBiH, Posebna izdanja, Knjiga LXXVIII. Sarajevo.

Zdruli P, Jones RJA, Montanarella L. 2004. Organic Matter in the Soils of Southern Europe. European Soil Bureau Technical Report, EUR 21083 EN, 2004 Office for Official Publications of the European Communities, Luxembourg