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Fractal analysis in the description of soil particle-size distribution under different land-use patterns in Southern Amazonas State, Brazil

José M. Cunha[1]*, Milton C. C. Campos[1], Denilton C. Gaio[2], José S. Nogueira[2], Marcelo D. R. Soares[3], Douglas M. P. Silva[1] and Ivanildo A. de Oliveira[4]

[1]Federal University Amazonas, Institute of Education, Agriculture and Environment, 69800-000, Humaitá, Amazonas State, Brazil.
[2]Federal University Mato Grosso, Physics Institute, 78060-900, Cuiaba, MatoGrosso State, Brazil.
[3]University of Campinas, School Agricultural Engineering, 13083-875, Campinas, Sao Paulo State, Brazil.
[4]Estadual University Paulista - UNESP, Faculty of Agriculture and Veterinary Sciences, Department of Soils and Fertilizers, 14870-900, Jaboticabal, SP, Brazil.

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Understanding the variability of soil properties is crucial to identify areas susceptible to physical degradation. The soil degradation is often determined by the current state of the soil structure, that is, the aggregate size distribution. Therefore, this article suggested evaluating aggregate sizes' distribution by using the fractal theory. The goals were: (i) to calculate the fractal mass dimension of soil aggregates in areas under agroforestry, forestry, sugarcane, cassava and pasture in Southern Amazonas state, Brazil, showing correlations with soil properties; (ii) to compare the means of fractal dimension mass of the distribution of particle sizes on different soil under the different uses; and (iii) to investigate spatial variability of such fragmentation for each management system. Fragmentation was determined from fractal mass dimension. Aggregates were sampled within a depth range of 0.00 to 0.10 m, over a regular sample grid of 70 × 70 m, with georeferenced sample points, and regular spacing each 10 m, totaling 64 points per mesh. Higher mean values of fractal mass dimension were found in agroforestry use system and the lowest under native forest and pasture, with no statistical difference fractal mass dimension, when assessed in relation to the type and land use. The degree of fragmentation of soil aggregates was found to be influenced by the type of soil and strongly correlated with fine particles, higher in Red-Yellow Oxisols with better physical quality when compared with other areas. It showed a strong spatial dependence and the exponential model that got the best adjustment of the semivariogram.

Key words: Soil physics, geostatistics, fractional dimension.

INTRODUCTION

Changes in vegetation composition of natural ecosystems associated with management practices, which are attributed to factors such as farm, livestock, bring consequences not only in relation to biodiversity, but also when analyzing the damage caused to the soil and its ability reuse and / or storage (Chaves et al., 2012). The quality of the soil structure is a good indicator of sustainability management systems, which in turn is influenced by pedogenetic conditions. On the other hand, the use and comprehensive management of soil can result in irreparable consequences for the physical soil quality, reducing it in their productive potential. Researchers have investigated soil use quality, assessing the relationships between direct and indirect measures over the soil (Usowicz and Lipiec, 2009; Campos et al., 2012; Oliveira et al., 2013). In contrast, soil management and crop type would change the aggregates and, consequently, its structure.

The soil is considered a complex system resulting from the interaction of geological, topographical and climatic factors, among others, which together form indicators (variables) that characterize (Freitas et al., 2014). Compositions difference of the soil particles sizes exhibit fractal features with irregular shapes and structures of self-similarity (Tyler and Wheatcraft, 1992). This aroused the academic community to use the fractal as an effective descriptive tool to characterize the size of the soil particles' (Prosperini and Perugini, 2008; Xia et al., 2015), structure, aggregation and soil erodibility (Ahmadi et al., 2011; Xu et al., 2013; Tang et al., 2013; Xiao et al., 2014).

Thus, the fractal theory has contributed to characterize the size distribution of soil particles as a way to assess the impacts of the soil use and quantify relationships between the use the soil and physical and chemical properties of the soil. Accordingly, the mass fractal dimension of size distribution of particles is useful parameters able to monitor the degree of degradation of the soils (Su et al., 2004).

Studies have revealed significant correlations of soil attributes with the dimension of fractal mass. Gui et al. (2010) found that the fractal dimension increases with small particles and decreases to larger particles in addition to positive correlation with soil organic matter. Different soil uses and plant communities or vegetation revealed that the size of the soil particles differed significantly between the different systems of management and land use, influencing also the values of the fractal mass dimension of soil (Wang et al., 2006, 2008; Zhao et al., 2006; Liu et al., 2009; Xu et al., 2013).

Overall, soil properties have a high degree of spatial variation due to pedogenic features (Oliveira et al., 2013; Aquino et al., 2014). A large number of studies have made use of geostatistics to characterize and compare the various soil attributes and search for a corresponding statistical correlation (Allaire et al., 2012; Usowicz and Lipiec, 2009; Millán et al., 2012). Castrignanó and Stelluti (1999) used fractal geometry and geostatistics to describe the importance of clay variability on soil clustering. Carvalho et al. (2004) ascertained the fragmentation of soil aggregates through the fractal theory, assessing the spatial dependence under varied treatments. Millán et al. (2012) used the multivariate spatial analysis for some soil physical attributes that have correlations to physically degraded areas.

Despite of the great contributions related to physical and chemical properties, a better understanding is required about its use in soil science; thus, this research is a way to use such attribute as a tool for empirical analysis that can be added to other research of this nature.

Therefore, the goals of this research were: (i) to calculate the fractal mass dimension of soil aggregates in areas under agroforestry, forestry, sugarcane, cassava and pasture in Southern Amazonas state, Brazil, showing correlations with soil properties; (ii) to compare the means of fractal dimension mass of the distribution of particle sizes on different soil under the different uses; and (iii) to investigate spatial variability of such fragmentation for each management system.

MATERIALS AND METHODS

The study was performed in the counties of Humaitá and Manicoré, which are located in Southern Amazonas state, in Brazil, under different management systems and soil types. The treatments were areas under agroforestry on Red-Yellow Latosol (Oxisol), sugarcane and cassava on Haplic Cambisol (Inceptisol), and areas under natural forest and pasture on Yellow Argisol (Ultisol). Both municipalities are placed near BR 364 and 230 road (also called "Transamazônica"), toward Apuí city in Amazonas state (Figure 1). The studied areas are situated under the same climatic zone, which belong to group A (rainy tropical climate) and Am (monsoon type climate) according to Köppen's classification, with a short dry season. Rainfall ranges from 2.250 and 2.750 mm and rainy season starting in October up to June. Annual mean temperatures alternate between 25 and 27°C and air relative humidity from 85 to 90%.

Five management systems were selected under different traditional uses. A squared sample grid was set on each soil use area, which has an area of 0.49 ha and soil samples were collected from each mesh cross point (grid point), whose regular spacing was each 10 m, totaling 64 sample points for each grid. These points were georeferenced by means of a GPSMAP 76CSx Garmin device (Garmin Ltd., Taipei, Taiwan).

Samples were collected within August to October of 2012. Soil deformed samples were taken from a depth range of 0.00 to 0.10 m at each grid point, keeping a preserved structure within soil clod to determine the stability of aggregates via wet sieving, totalizing 320 soil samples for all five sample grids.

Soil clods were slightly crushed, manually, and passed through a 9.51 mm sieve being retained on a 4.76 mm one; then, they were shade dried for stability analysis. Aggregate separation and stability were determined by method proposed by Kemper and Chepil (1965), with modifications in the following diameter classes: 4.76 to 2.0; 2.0 to 1.0; 1.0 to 0.50; 0.50 to 0.25; 0.25 to 0.125; 0.125 to 0.063 mm. 20 g of aggregates retained in the sieve of 4.76 mm were used and placed in contact with water in sieve 2.0 mm and

*Corresponding author. E-mail: maujmc@gmail.com.

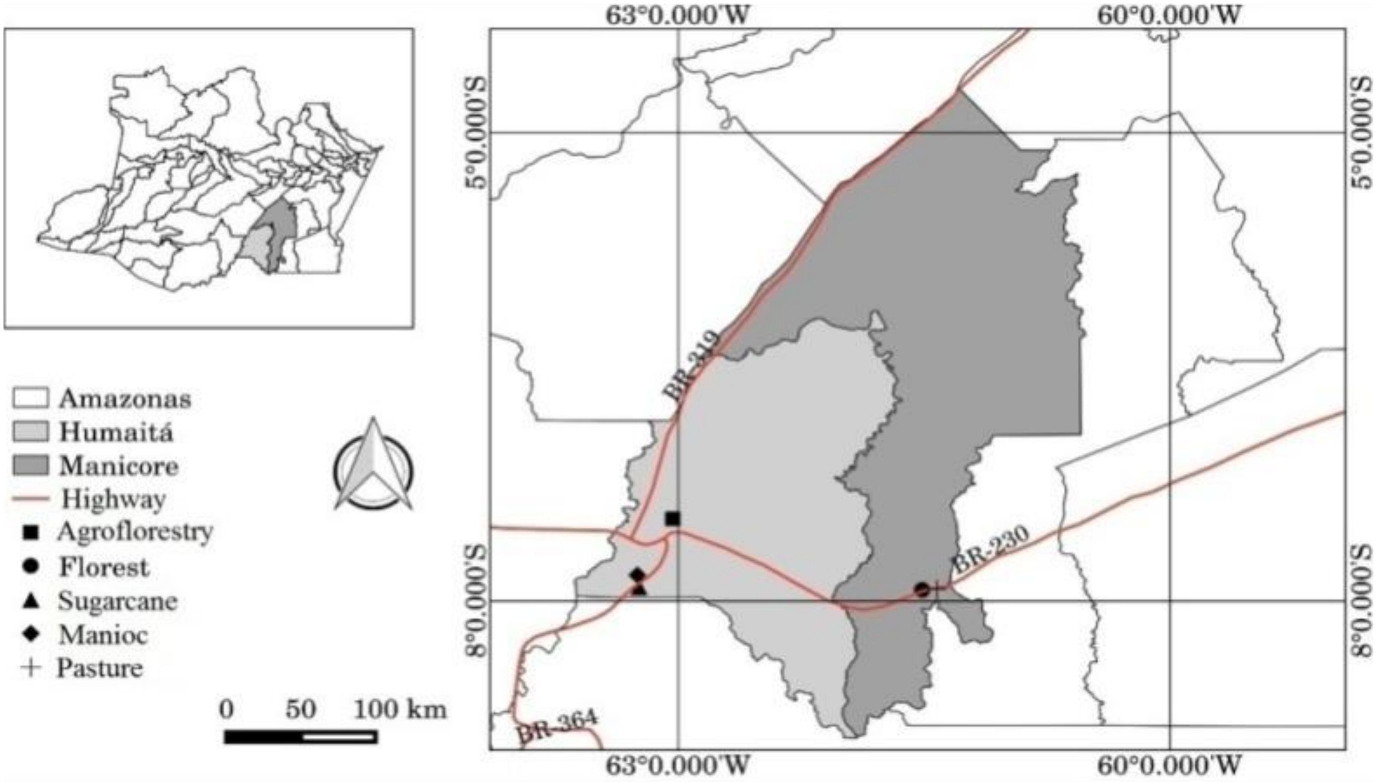


Figure 1. Location of the studied area.

subjected to vertical shaking in Yoder device (SOLOTEST, Bela Vista, São Paulo, Brazil) for 15 min. The content retained on each sieve size was then placed in an oven at 105°C for further weighting on digital scale.

Results expressed in aggregate mass retained at each sieve size and analyzed for spatial variability determination of soil aggregation by means of fractal geometry and geostatistics.

Fractal definition in soil physics can be based on the relationship of aggregate number and particle size distribution as the following equation (Mandelbrot, 1982; Turcotte, 1986):

$$N(X > x_i) = k x_i^{-D_f}, \tag{1}$$

wherein N (X > x_i) is the number of accumulated particles (objects) at a certain size that is bigger than x_i, established by the sieve size, k is the number of elements in a size unit set and D_f is the fractal dimension, which ascertains the fragmentation of soil aggregates (Carvalho et al., 2004). Equation 1 cannot be used directly to study soil aggregates, because it would be unfeasible to count the number of particles of each size. Therefore, a method which estimates the number of particles retained by a sieve size using the fractal mass model, developed by Tyler and Wheatcraft (1992), can be used and it is defined by the equation:

$$\frac{M(r < R_i)}{M_T} = \left(\frac{R_i}{R_{máx}}\right)^{3-D_f}, \tag{2}$$

wherein M (r <R_i) is the accumulated mass of particles of an r size lower than sieve size (R_i), M_T is the total mass of the particles, $R_{máx}$ is a parameter that determines the diameter of the largest aggregate and D_f is the fractal mass dimension of the aggregates. This dimension has as superior and inferior limits the values within 0 to 3. This way, such limitation demonstrates a physical mismatch of the accumulated mass to surpass the total mass within a system when $D_f < 0$ and $D_f > 3$.

Aggregate stability data for each sample point were transformed into log-log scale for accumulated mass $\left(\frac{M(r<R_i)}{M_T}\right)$ and particle size ($\frac{R_i}{R_{máx}}$), being set in the Equation 2. They show that a function of power law index is required to describe soil aggregates' fragmentation, based on sieve fragmentation. The amounts retained at each sieve were measured in percentage, which is the ratio between the mass of aggregates of each sieve by the mass of aggregates used in the Yoder (20 g) multiplied by one hundred. These proportions related to the diameter of sieves, following a power law scale set to the sieve diameters, as raised by the fractal theory (Mandelbrot, 1982). The D_f and $R_{máx}$ parameters were determined by fitting the log-log transformation curve from Equation 2, using the *nls* function of the R software (R Core Team, 2013) to set the parameters.

The values of means, maximum and minimum differences, variance, standard deviation, asymmetry, kurtosis and variation coefficients were calculated via data exploratory analysis. Comparisons of aggregate stability means, GMD, WMD and fractal mass dimension for all soil management systems were analyzed by the Tukey test at 5% significance. Pearson correlations were carried out between the size of fractal mass and granulometric parameters of the soils. The statistical analyses were performed by Statistica 7.0 version (StatSoft, 2005).

The fractal mass dimension was characterized spatially by

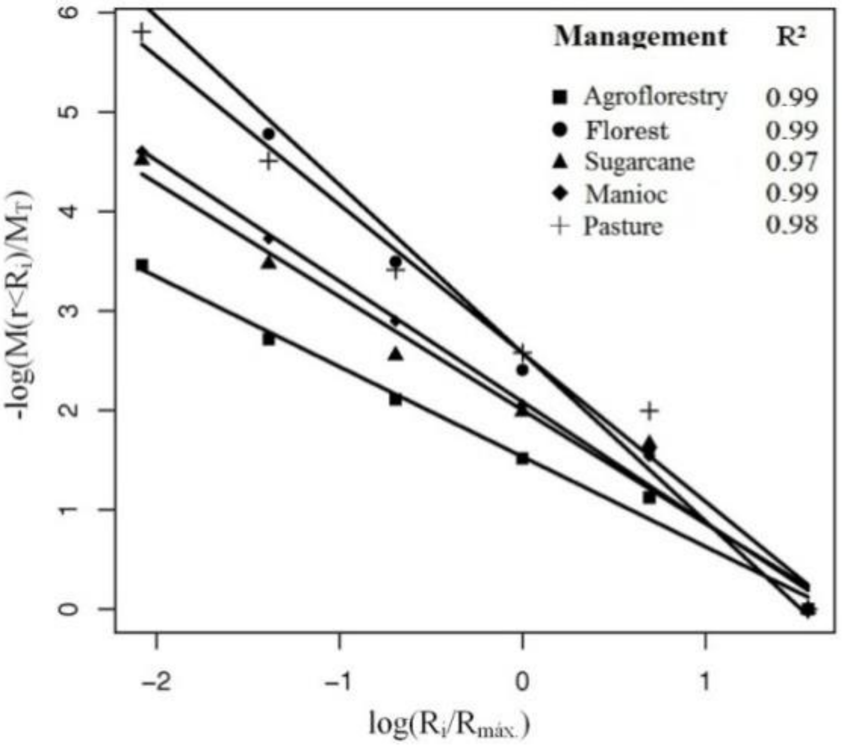


Figure 2. Cumulative mass log-log fit according to particle diameter. The symbol represents experimental data and the straight line stands for the fitted model.

means of geostatistics (Carvalho et al., 2004; Millán et al., 2012). The experimental semivariogram was estimated under an intrinsic hypothesis using the following equation:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2, \quad (3)$$

wherein $\hat{y}(h)$ represents the variance at an h distance, $N(h)$ is the number of pairs in semivariance calculation, $Z(x_i)$ is the value of a Z attribute at an x_i position and $Z(x_i+h)$ is the value of Z at an h distance from x_i.

From a mathematical model fitting to $\hat{y}(h)$ calculated values, theoretical model coefficients are defined for the semivariogram: nugget effect (C_0), structural variance (C), sill (C_0 + C) and range (a_o). The intersection of semivariance and y-axis is the nugget effect and stands for the attribute variability in a shorter spacing than the sampled one (Siqueira et al., 2008). In the spatial dependence analysis of soil properties under study, we used the classification proposed by Cambardella et al. (1994), in which spatial dependence will be strong if the ratio $\left[\frac{C_0}{C_0+C}\right]$ is ≤ 25. If the ratio is between 26 and 75%, spatial dependence will be considered moderate; and when it is from 75 to 100%, approximately, the dependence can be classified as weak. The range (a_o) represents the distance within which attributes are correlated, under a uniform area with an estimated radius. Semivariogram analysis was carried in October using GS + 7.0 software (Robertson, 1998) to check variability presence or absence. The best-fitted semivariogram model was defined in terms of the highest coefficient of determination (R^2), the lower nugget effect and highest coefficient of variation of cross validation.

Once checked, the spatial dependence of soil attributes, semivariance values were obtained and interpolated with ordinary kriging data. It enabled building contour maps of each attribute, helping in their interpretation.

RESULTS AND DISCUSSION

Figure 2 shows a linear trend of logarithmic transformation for aggregate mass and sieve sizes, being in accordance with findings of previous studies such as Liu et al. (2009), Parent et al. (2011) and Xu et al. (2013). Yet Menéndez et al. (2005) and Prosperini and Perugini (2008) had found a multiple linear trend for such parameters, indicating different arrangements for different particle sizes (sieve diameters).

Soil aggregation is strongly influenced by some physical and chemical soil attributes. Soil use and management provide changes on these attributes, since they modify its structure and aggregate stability. Furthermore, other environmental and anthropic factors may alter soil aggregation. In this sense, Table 1 shows some of these chemical properties in agroforestry (AF), natural forest (NF), sugarcane (SC), cassava (CA) and pasture (Pt) systems.

Table 2 presents the descriptive statistics of the

Table 1. Soil chemical properties and texture under different management systems.

Soil management	pH in H_2O	P	H + Al	Ca	Mg	K	V	C_{org}	Sand	Silt	Clay
		mg kg^{-1}	$cmol_c$ kg^{-1}				(%)	g kg^{-1}	g kg^{-1}		
AF	3.8	8.2	18.9	0.2	0.1	0.1	2.5	11.9	220.8	230.1	549.1
NF	4.0	6.1	7.5	0.5	0.2	0.2	10.7	10.8	358.8	313.2	327.9
SC	4.4	6.4	9.0	1.5	0.8	0.1	20.5	17.7	240.6	474.5	284.9
CA	3.9	6.0	15.8	0.2	0.1	0.1	3.2	16.1	158.9	557.6	283.4
Pt	4.3	4.6	6.1	1.0	0.5	0.2	21.4	15.9	410.8	227.6	361.6

AF: Agroforestry; NF: natural forest; SC: sugarcane; CA: cassava; Pt: pasture.

Table 2. Descriptive statistics of the variables aggregate size, geometric mean diameter, weighted mean diameter and fractal mass dimension within the studies areas.

Soil management	Variable	SW	Δx	Var	SD	C_s	C_k	VC (%)
AF	4.76-2.00 (mm)	ns	40.26	87.3	9.3	-0.60	-0.40	11.4
NF		ns	37.10	87.4	9.4	-0.52	-0.63	12.2
SC		ns	23.79	32.5	5.7	-0.68	-0.10	6.4
CA		ns	30.46	48.6	7.0	-0.66	-0.14	8.2
Pt		ns	22.32	27.7	5.3	-0.74	-0.13	5.8
AF	2.00-1.00 (mm)	ns	8.29	4.5	2.1	0.84	-0.09	56.7
NF		0.29	13.09	10.1	3.2	0.32	-0.59	34.8
SC		ns	5.71	1.8	1.4	0.64	-0.20	66.7
CA		ns	7.82	4.0	2.0	0.58	-0.16	57.1
Pt		ns	8.64	4.1	2.0	0.59	-0.36	64.5
AF	< 1.00 (mm)	ns	18.58	17.5	4.2	0.92	0.70	50.6
NF		ns	28.68	49.1	7.0	0.71	-0.30	50.3
SC		ns	18.93	19.5	4.4	0.71	-0.02	53.7
CA		ns	23.70	28.0	5.3	0.79	0.20	47.3
Pt		ns	16.65	12.4	3.5	1.02	1.01	62.5
AF	GMD (mm)	0.12	2.89	0.36	0.6	0.30	0.37	28.6
NF		ns	1.58	0.16	0.4	-0.40	-0.77	17.4
SC		ns	1.39	0.12	0.34	-0.47	-0.59	13.6
CA		0.19	1.73	0.14	0.38	-0.55	0.08	16.5
Pt		ns	1.21	0.08	0.28	-0.60	-0.21	9.7
AF	WMD (mm)	ns	1.24	0.07	0.27	-0.67	-0.16	10.3
NF		ns	0.92	0.05	0.23	-0.62	-0.48	8.2
SC		ns	0.58	0.02	0.14	-0.69	-0.11	4.5
CA		ns	0.77	0.03	0.18	-0.71	-0.03	6.0
Pt		ns	0.45	0.01	0.12	-0.60	-0.54	3.7
AF	D_f	0.74	0.53	0.013	0.114	0.144	-0.431	5.78
NF		0.24	0.57	0.019	0.136	-0.141	-0.704	9.36
SC		0.71	0.48	0.011	0.106	-0.046	-0.234	6.03
CA		0.52	0.39	0.008	0.088	-0.019	0.018	4.90
Pt		0.15	0.48	0.013	0.113	0.092	-0.777	8.07

SW: Shapiro-Wilk's normality test; Δx: difference between maximum and minimum value; Var: variance; SD: standard deviation; C_s: asymmetry coefficient; C_k: kurtosis coefficient; VC: variation coefficient; ns: not significant; GMD: geometric mean diameter; WMD: weighted mean diameter.

Table 3. Aggregate size distribution and mean test of the variables geometric mean diameter, weighted mean diameter and fractal mass dimension in areas under different uses in Southern Amazonas.

Soil management	Aggregate classes%			GMD (mm)	WMD (mm)	D_f
	4.76-2.00	2.00-1.00	<1.00			
AF	80.79^c	4.04^b	15.17^a	2.1^c	2.9^c	1.97^a
NF	76.38^d	9.44^a	14.17^{ab}	2.3^c	2.8^c	1.45^c
SC	89.64^a	2.12^c	8.24^c	2.5^b	3.1^a	1.75^b
CA	85.07^b	3.59^b	11.34^b	2.3^c	3.0^b	1.79^b
Pt	90.52^a	3.24^{bc}	6.25^c	2.9^a	3.2^a	1.40^c

AF: Agroforestry; NF: natural forest; SC: sugarcane; CA: cassava; Pt: pasture. Means followed by the same letter in the first column do not differ from each other by the Tukey's test (p< 0.05).

variables aggregate size, geometric mean diameter (GMD), weighted mean diameter (WMD) and fractal mass dimension (D_f). Only aggregate size between 4.76 and 2.00 mm, GMD, WMD and D_f had a reasonable standard deviation, resulting in low variance data with regards to mean values. Data showed variance homogeneity ($p < 0.05$); however, mean tests (Table 3) of soil physical attributes displayed significant alterations ($p < 0.05$) for all variables when comparing all evaluated systems. All variables had asymmetry and kurtosis values close to zero, which characterizes a symmetric distribution and justify mean and median similar values, although most variables have no normal distribution, it is important to highlight that the distribution has no long tails.

Regarding the variation coefficient (Table 2), fractal mass dimension was low in all management uses, with the lowest values found for cassava (VC = 4.90 %) and the highest one for native forest (VC = 9.36%). It demonstrates a low variation in soil fragmentation degree, what denotes uniformity in mean values. Still, range was larger in NF ($\Delta x = 0.57$) and smaller in cassava fields ($\Delta x = 0.39$), which might be related to soil chemical or physical features. The range (Δx) between maximum and minimum values of the attributes reinforces data suitability to assess spatial patterns of variables. Kurtosis and asymmetry coefficients are compared to a normal distribution with values near zero (Table 2), showing either a symmetric and platykurtic distribution ($C_k < 3$) for all areas. In these, soil fragmentation degree (D_f) presented low values for standard deviation.

However, Table 3 shows a higher percentage of 4.76 to 2.00 mm aggregate size, highlighting pasture and sugarcane fields which have significant differences when compared with the others. This physical feature is owned to fasciculate roots of grasses and sugarcane that favors soil clustering. Such result gives soil a greater resistance to degradation (Oliveira et al., 2013), since roots are responsible for soil restructuring and reduction of erodibility (Neves et al., 2006).

Both GMD and WMD were higher in pasture and sugarcane fields, filling soil with greater contents of organic carbon (Table 1), which also plays an important role in soil aggregation (Rozane et al., 2010). This result also corroborates the Matos et al. (2008), when evaluating the stability of aggregates on the impact of organic and mineral fertilizers to the soil. Actually, a larger amount of dry matter is found on such environments, increasing as consequence soil organic matter. Grain size is another element with great importance to soil aggregation; Table 1 shows that agroforestry soil has higher contents of clay. Yet for sugarcane soil, there is predominance of silt fraction and for pasture, it is sand.

Contrarily, fractal mass dimension has been pointed to describe qualitatively distribution of particle size, aggregates and the degree of soil fragmentation (Carvalho et al., 2004; Filgueira et al., 2006; Prosperini and Perugini, 2008). The greatest fractal mass dimension was seen in agroforestry areas ($D_f = 1.971$), highlighting soils with greater physical stability as cited by Xu et al. (2013).

There was no significant difference of fractal mass dimension between sugarcane and cassava ($D_f = 1.758$ and $D_f = 1.796$, respectively). Millán et al. (2012) found values similar to sugarcane in a Vertisol in Bayamo, Cuba. These areas seem to have a lower quality compared to agroforestry areas, which might be related to machinery use (soil compaction, pedogenic aspects and crop burnings). In addition, native forest and pasture had no differences among each other ($D_f = 1.453$ and $D_f = 1.401$, respectively), which had the smallest fractal mass dimension, what denotes a lower quality compared to the others. This result is inverse to the aggregate stability for pasture system (Table 3), having a greater percentage of grain sizes >2.00 mm. It may be related to cattle stamping and machinery use on grazing areas, what could have favored soil compaction, favoring with that in denser clusters, but under lower structural resistance. Another fact is that both pasture and forest environments have similar chemical and textural characteristics (Table 1).

Comparing the soil types, characterized by the size of

Table 4. Aggregate size distribution and mean test of the variables geometric mean diameter, weighted mean diameter and fractal mass dimension at different soil types in Southern Amazonas.

Soil types	Aggregate classes			GMD (mm)	WMD (mm)	D_f
	4.76-2.00	2.00-1.00	<1.00			
Latosol (Oxisol)	80.79^b	4.04^b	15.17^a	2.1^b	2.9^b	1.97^a
Argisol (Ultisol)	83.72^b	6.21^a	7.21^b	2.5^a	3.0^a	1.78^b
Cambisol (Inceptisol)	87.53^a	2.69^b	5.61^c	2.4^a	3.0^a	1.41^c

Means followed by the same letter in the first column do not differ from each other by the Tukey's test ($p < 0.05$).

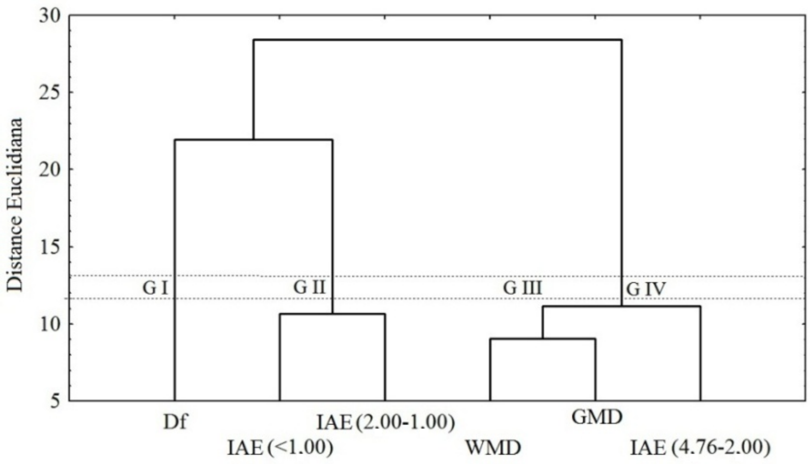


Figure 3. Dendrogram of hierarchical cluster analysis showing the clustering of the analyzed variables in Southern Amazonas. Df = Fractal mass dimension; IAE (%) = aggregate stability index; GMD = geometric mean diameter; WMD = weighted mean diameter.

the soil particles, Red-yellow Latosol (agroforestry), Yellow Argisol (forest and pasture) and Haplic Cambisol (sugarcane and cassava), a greater percentage of aggregates with 4.76 to 2.00 mm were seen in the Cambisol (Table 4), which differed from the other types. The attributes GMD and WMD had no significant differences in comparing Argisol against Cambisol; however, both differed from Latosol.

Nevertheless, regarding the size class of <1.00 mm, we observed a higher percentage in Latosols, which showed the highest value for the fractal mass dimension. Recent research has identified strong correlation of the fractal mass dimension with fine particles (Gui et al., 2010; Xia et al., 2015), found that the mass fractal dimension increased with clay content, but decreased with sand content. This explains the fact that D_f is more correlated to <1.00 mm classes, in which the hierarchical cluster analysis identifies the separation of groups (Figure 3) assuring such statement, with D_f strongly correlated with aggregate stability index, IAE <1.0 mm and IAE between 2.00 and 1.00 mm. From Figure 3, it can be observed a group formation G I and II (D_f and 2.00 to 1.00 mm and <1.00 mm). However, GMD and WMD (G III) have a strong correlation with the size class of 4.76 to 2.00 mm (G IV), which substantiates its greater influence on estimated values of GMD and WMD.

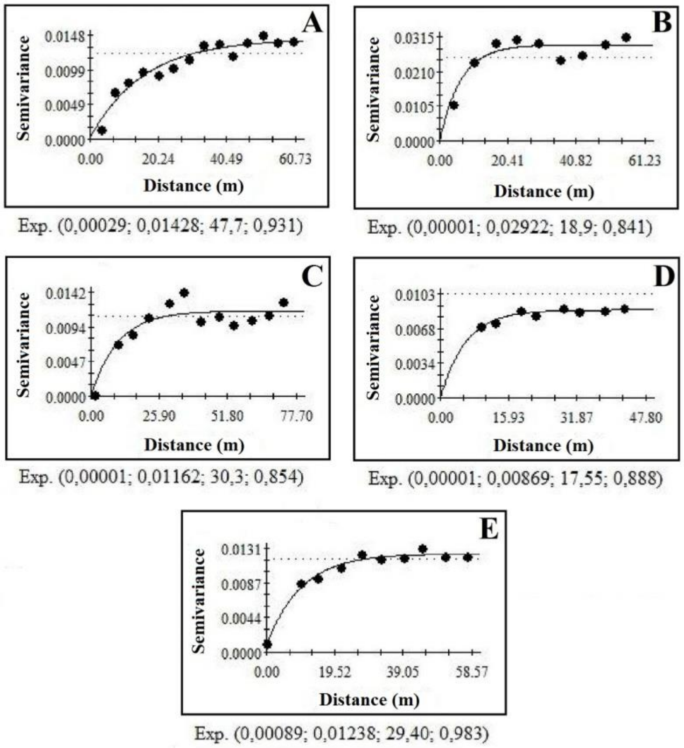
Another relevant point is that D_f did not differ among management systems (Table 3) and soil types (Table 4). It may be related to strong correlations between fractal mass and some physical and chemical attributes that characterize the soil types.

Thus, it was observed in Latosols positive correlation ($r_{cor} = 0.45$) of the mass fractal dimension with the sand content and a negative ($r_{cor} = -0.35$) with the clay content; in Argissolos positive correlation ($r_{cor} = 0.18$) the fractal dimension of the mass with silt content and negative ($r_{cor} = -0.22$) with the soil organic matter. There was no evidence of correlation of fractal mass dimension with the soil properties of the order of Cambissolos. It is possible that the mass fractal dimension is more sensitive to different types of soils which uses the ground. Soil quality is closely related to its chemical properties, but also has a strong relation as the particle size and content of soil organic matter, these in turn favoring the a good ground support structure and drainage of water and nutrients. Still, different land uses and communities of plants and vegetation (Wang et al., 2006; Wang et al., 2008; Zhao et al., 2006; Liu et al., 2009; Xu et al., 2013) revealed that

Table 5. Geostatistical analysis of fractal mass dimension in the studied areas.

Study area	Model	Nugget effect (Co)	Sill (Co+C)	Range (m)	$\left[\frac{C_o}{C_o+C}\right] \times 100$ *	R^2 **
AF	Exp.	0.00029	0.01428	47.7	2.03	0.93
NF	Exp.	0.00001	0.02922	18.9	0.03	0.84
SC	Exp.	0.00001	0.01162	30.3	0.09	0.85
CA	Exp.	0.00001	0.00869	17.5	0.11	0.89
Pt	Exp.	0.00089	0.01238	29.4	7.19	0.98

Exp: Exponential; *Spatial dependence degree; **Determination coefficient.



Exp. (0,00029; 0,01428; 47,7; 0,931)

Exp. (0,00001; 0,02922; 18,9; 0,841)

Exp. (0,00001; 0,01162; 30,3; 0,854)

Exp. (0,00001; 0,00869; 17,55; 0,888)

Exp. (0,00089; 0,01238; 29,40; 0,983)

Figure 4. Experimental semivariogram of fractal mass dimension Df of the areas. A) Agroforestry; B) Natural Forest; C) Sugarcane; D) Cassava; E) Pasture. Below the pictures, it follows information as: Model (nugget effect; sill; DSD; range; R^2). DSD: Degree of Spatial Dependence; R^2: coefficient of determination.

the size of the soil particles differed significantly between the different management and land use systems, influencing also the values of fractal dimension of soil mass.

From geostatistics, Figure 4A to E semivariogram fits of fractal mass dimension for each studied area. It was observed that soil fragmentation degree has strong spatial dependence for all management systems, which may be expressed in terms of semivariogram model fits (Table 5 and Figure 4). The exponential model was the one that best fit the experimental semivariogram in the areas, which is based on determination coefficient that reached values higher than 84% (Table 5 and Figure 4).

Each spatial pattern of fractal mass dimension presents different spatial dependence ranges (Table 5 and Figure 4). The agroforestry had the highest average value of the range, showing less variability of the data, justifying the fact that this management system causes less impact to the soil and thus the mass fractal dimension has lower variability. It can be stated that the higher the range, the lower the variability. The range is the distance at which the sampling points are correlated, that is the points

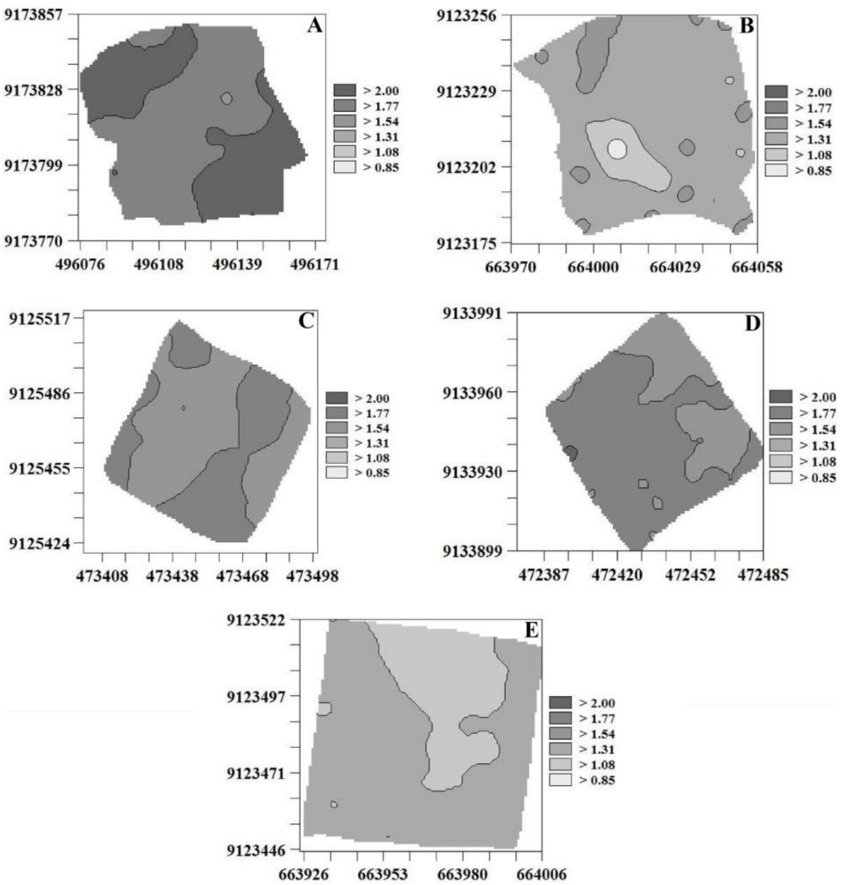


Figure 5. Kriging maps of fractal mass dimension Df in the studied areas: A) Agroforestry; B) Natural Forest; C) Sugarcane; D) Cassava; E) Pasture.

located a distance equal to the range area are more homogeneous with each other (Marques, Jr. et al., 2008). The areas of sugarcane and pasture also presented high and very similar values, perhaps by presenting a very similar radiculare system, even belonging to different soil classes (Cambisol and Ultisol, respectively). Millan et al. (2012) in a study to quantify the spatial structure of physical properties, they found scope of spatial dependence fractal mass dimension greater than 24 m in a Vertissols dedicated to sugarcane cultivation in the last sixty years.

The spatial dependence range of fractal mass dimension apparently has greater influence on the use and management of soil, since the soil structure is strongly affected by inappropriate land use, the use of agricultural machinery, livestock trampling, tickler soil, excessive land use without replenishment of nutrients, among others. The range of areas of native forest and cassava were very similar, also belong to different soil classes, but with lower values to other areas, with higher data variability. Under native forest, due to lack of agricultural practices, justified the fact that the fractal mass dimension present greater independence of spatial correlation, which in turn the soil is kept in conditions conducive to vegetation development and guarantee its own sustainability.

Interpolated values of the semivariogram models were used to build two-dimensional contour maps, whose kriging maps of soil fragmentation are represented in Figure 5A to E. These maps show an overview of the soil fragmentation under cultivated areas, identifying spots with most degraded physical structures.

Figure 5 shows that the fractal mass dimension in native forest (Figure 5B) had a heterogeneous behavior compared to the other areas and, likewise pasture, got the lowest values; therefore, it is a less fragmented soil area.

We have noticed that in the upper left and lower right corners of the agroforestry system (Figure 5A) regions with greater soil fragmentation, in which a best soil physical quality is encountered. Moreover, although there was no difference of fractal mass dimension between sugarcane and cassava areas (means of 1.758 and 1.796, respectively), Figure 5D demonstrates larger and more extensive mean values in cassava field; thus, having a better physical quality.

Conclusions

Agroforestry environments have greater mean values of fractal mass dimension, while native forest and pasture have the lowest ones. There was no difference between fractal mass dimension when evaluated between soil type and land use.

Comparing soil physical attributes among the management systems and soil types, fragmentation degree was influenced by the second, with greater fractal mass dimension in Red-Yellow Latosols, presenting a better physical quality compared to the others. Thus, the fractal mass dimension was found to be strongly correlated with fine particles, that is, IAE between 2.00 and 1.00 mm and IAE <1.00 mm.

Soil aggregate fragmentation described by fractal mass dimension had strong spatial dependence and the exponential model obtained a semivariogram best fit.

Conflict of Interests

The authors have not declared any conflict of interests.

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