Journal of Cleaner Production 104 (2015) 109–120

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Improving the monitoring, control and analysis of the carbon accumulation capacity in *Legal Reserves* of the Amazon forest

Miriam Harumi Okumura [a,*], Alexandre Passos [a], Beck Nader [b], Giorgio de Tomi [c]

[a] *Department of Mining Engineering and Petroleum at the Polytechnic School of the University of São Paulo, Av. Prof. de Mello Moraes, 2373, CEP 05508-030, Brazil*

[b] *Department of Mining Engineering at the Federal University of Minas Gerais – UFMG, Brazil*

[c] *Department of Mining Engineering and Petroleum at the Polytechnic School of the University of São Paulo, Brazil*

A R T I C L E I N F O

Article history:
Received 3 February 2014
Received in revised form
1 September 2014
Accepted 13 October 2014
Available online 28 October 2014

Keywords:
Amazon forest
Legal reserve
Carbon accumulation

A B S T R A C T

The Amazon forest is host for a large number of deforestation activities caused by artisanal mining and mainly by agriculture and livestock businesses. In order to regulate these activities and relieve the environmental impacts, local authorities have been trying to guide them towards more responsible operations. This paper describes the initiative of monitoring forest areas located near deforestation regions since fundamental elements such as biomass and carbon accumulation of trees may be adequately controlled and monitored against occasional disturbances brought by these activities. The current standard approach in the Amazon is to monitor all trees in the forest within an area called *transecto*, in order to keep a rigorous record of their behavior and growth. However, these control activities are restricted to controlling portions that are located in strategic areas, therefore they do not represent the entire region to be monitored. This research exploits a new methodology based on geostatistics, aimed at optimizing sampling, and allowing the extension of the study to much larger forest areas, while keeping unitary utilization of human resources unchanged and at the same time, increasing the studied areas footprint and the precision of the results. The proposed methodology also allows the selection of the *Legal Reserve* (RL) area to be made according to the actual carbon-accumulation distribution on the property's contained forest, allowing the determination of a location target for the RL, what is not possible with the current used methodologies that rely simply on a percentage area utilization for the RL, inside the property. This methodology was applied using the available data set in this paper in order to optimize the samples and to monitor the capacity of the forest to store carbon at Tapajós National Forest, in Pará, Brazil. It is expected that this methodology will contribute to an overall cost decrease per unit area of the monitoring activities, increase the precision for the RL location and simplify the needed procedures through the application of a user friendly toolkit, that can be developed using the proposed methodology, whose complexity is totally transparent to the land and business owners, regulators, environmental scientists and workers involved. This, if correctly applied could ultimately contribute to the sustainable development of the affected regions.

1. Introduction

The Brazilian legislation is majorly concerned with preserving the Amazon forest, thus, it has created the so-called *Legal Reserve – RL*, where 80% of the property located in rural areas must be preserved and notarized as RL, allowing the exploration of 20% of the area. However, there is no concern as to determine what would be the most appropriate area in which this RL should be located, and this decision is entirely up to the landowner.

This paper proposes:

1. A methodology that is based on geostatistics, optimizing sampling, and allowing to extend the study to much larger forest areas
2. A propose of methodology allows the selection of the RL area to be made according to the actual carbon-accumulation distribution on the property tropical forest

The shrub and arboreal-pattern plants are the ones that offer the longest carbon-stocking cycles in nature since photosynthesizing

* Corresponding author. Tel./fax: +55 11 3091 6038.
E-mail addresses: miriam.okumura@usp.br, miriamok@gmail.com (M.H. Okumura).

http://dx.doi.org/10.1016/j.jclepro.2014.10.049
0959-6526/

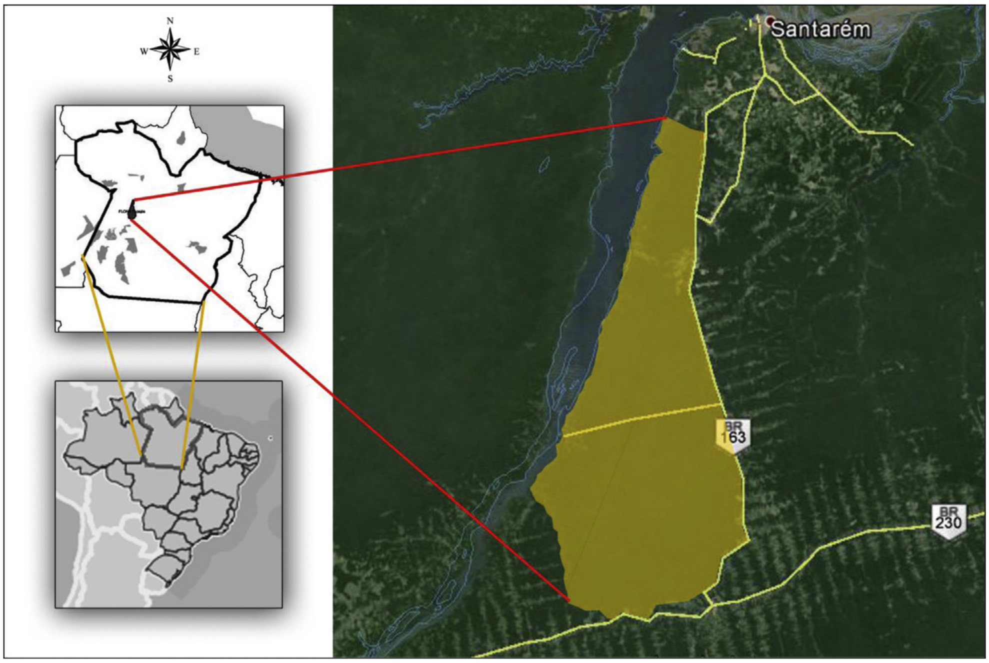

Fig. 1. Location of the Tapajós National Forest. Source: INPA.

organisms are majorly responsible for the atmospheric CO_2 sequestration, and plants are responsible for stocking two-thirds of the carbon on Earth (Totten, 2000).

Several ecological studies reveal that most, if not all, communities are spatially structured, and that the sampling methods need to be robust in order to detect different levels of spatial autocorrelation.

The most used form of sampling is the transect, that aims to characterize the transition areas (ecotone) or areas in different successional stages (Brower and Zar, 1984), the transect lines are widely used by ecologists fauna, characterized by the establishment of ranges of known lengths (Garcia and Lobo-Faria, 2009). Transect belts are used for better representation of the composition of the area (Brower and Zar, 1984). For the detection and prediction of the spatial structure is best described with samples plots (Oda-Souza, 2009). The sampling methodology allows parcels in the repetition of the methodology in a large community, allowing adequate representation of local diversity (Garcia and Lobo-Faria, 2009).

Geostatistical analysis was chosen because it allows the evaluation of the spatial distribution of the samples, uniquely associating the dependency degree between samples with the spacing measurements among sampled points and it may be associated to the kriging method, which generates values for non-sampled locations (Matheron, 1971). Thus, in addition to the geostatistical analysis of the carbon accumulation, we may also optimize the forest sampling, which is currently exhaustively performed, that it, it is performed in the entire area, sampling species by species.

For this study, the carbon accumulation was analyzed based on geostatistics, establishing a relationship between the samples of georeference arboreus species, in order to provide carbon accumulation models in tropical forest areas located near the artisanal mining regions, with the purpose of monitoring such carbon accumulation, offering grounds to determine the most appropriate location for the RL area. Sampling was performed at the Tapajós National Forest, in the state of Pará.

1.1. Tapajós National Forest

The Tapajós National Forest, who was created by decree no. 73,684 from 02/19/74. Art 1: It is instituted, in the State of Pará, the Tapajós National Forest (Fig. 1), under the jurisdiction of the" Chico Mendes Institute for Biodiversity Conservation" – ICMBio, a federal agency under the Ministry of the Environment of Brazil, responsible for the management, monitoring and protection of 312 units of existing nature conservation in Brazi. This forest has an estimated area of 600,000 ha (six hundred thousand hectares), within the following boundaries and confrontations: West – Tapajós River; East – Cuiabá Road - Santarém; North – A line that goes through the 50 (fifty) kilometer mark of the Cuiabá-Santarém Road and through a point with latitude equal to 2°45′S (two degrees and forty five minutes South), at the right bank of the Tapajós River; South - Cupari River and its affluent, Santa Cruz, also called Cupari Leste, up to its intersection or axis prolongation, with the Cuiabá – Santarém Road.

The soils occurring are, according to the American classification, Oxisolos clay with low organic matter content, acidic pH, low cation exchange capacity (CEC) and high aluminum saturation (Chavel, 1982; Parrota et al., 1995; Ferraz et al., 1998; Telles et al., 2001) according to the classification Brazilian oxisols are called red yellow distróficos. The vegetation is classified as rainforest dense terra firme (Higuchi et al., 1997; Clark and Clark, 1996). The study area is located on a large plateau with water very deep water table, sometimes to more than 100 m deep.

1.2. Deforestations activities

Reducing the size of natural forests around the world has occurred as a result mainly of fires, cuts trees for commercial purposes, devastation of land for agricultural use, or even natural phenomena (Arraes et al., 2012). According to Ruviaro et al. (2012) in recent years, the debate about environmental sustainability has broadened to include the impact of agricultural production. In addition to deforestation, agriculture causes many environmental

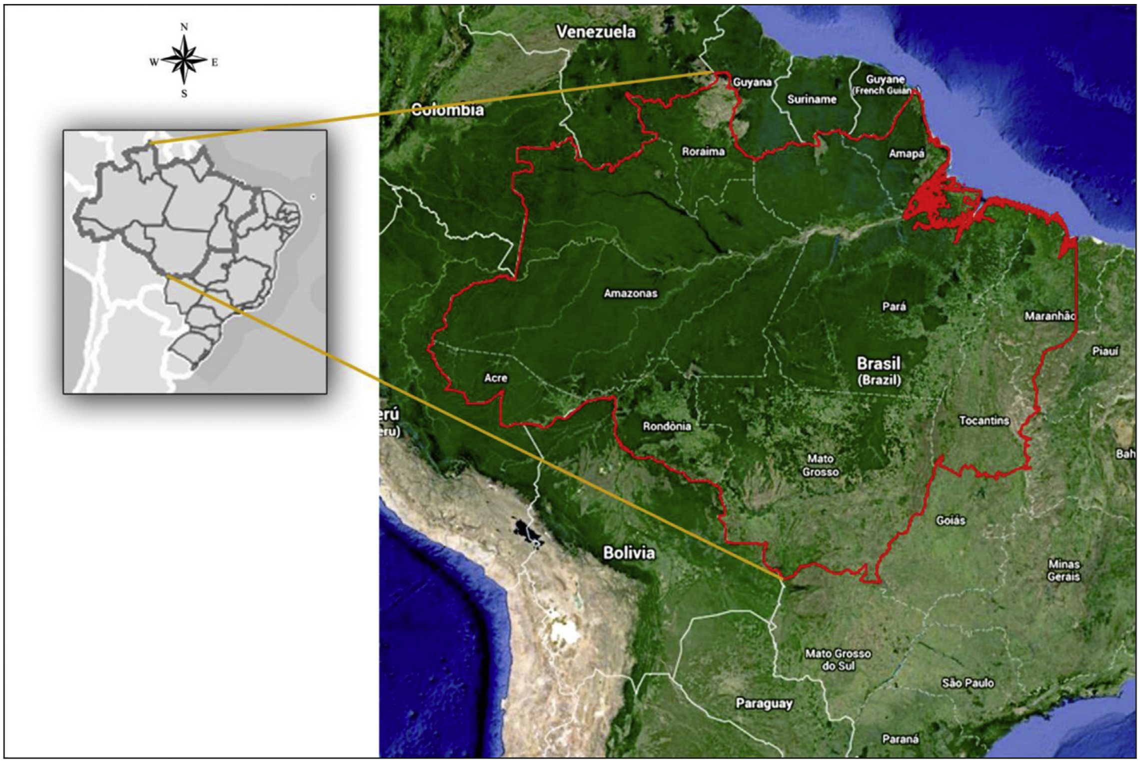

Fig. 2. Representation of the Brazilian Legal Amazon.

problems are caused by excess manure and dung in the multiple-stand cowsheds (Galka, 2004).

When it comes to mining activity, Monteiro (2005), states that the dynamics derived from activities related to the extraction and processing of industrial minerals are among the most significant elements that have contributed and contribute to the realization of significative changes in the eastern Brazilian Amazon. Hinton et al. (2003) states Artisanal and small-scale mining provides an important source of livelihood for rural communities throughout the world, these activities are frequently accompanied by extensive environmental degradation.

According to the Program Calculation Amazon Deforestation - PRODES (http://www.obt.inpe.br/prodes/index.php), that monitors the Brazilian amazon forest by satellite and was developed by the National Institute for Space Research, the rate of deforestation in the Amazon in 2012 was 4571 km^2 $year^{-1}$, and in the state of Pará that rate was 1741 km^2 $year^{-1}$ (38%), the highest rate of deforestation between the states that make up the Amazon.

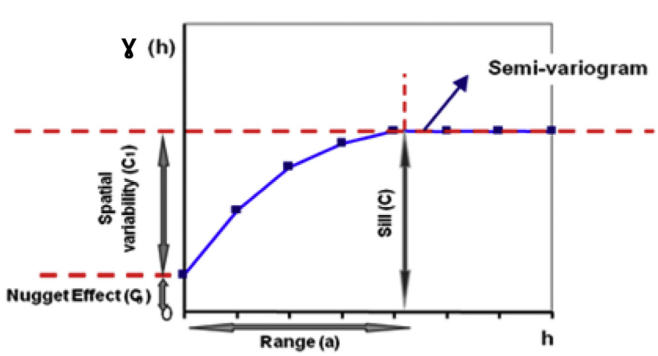

Fig. 3. Example of a variogram with ideal characteristics.

The causes of deforestation in tropical forests cannot be reduced to a single variable, by contrast, there are combinations of several factors that favor environmental degradation, such as the interaction between agricultural expansion, the timber trade, population growth and the construction of roads, public governance, and that may interact differently, depending on the spatial and temporal dynamics in each region (Geist and Lambin, 2001).

In an attempt to preserve forests Brazilian forest code was developed establishing the Legal Reserve (RL).

1.3. Legal reserve

The concept of Legal Reserve (RL) was only added to the Forestry Code in 1965, and it is defined as the forest space that must be preserved, in addition to the Permanent Protection Areas.

The Legal Reserve comprehends the preservation of part of a greater area with a specific characteristic, with the purpose of preserving the existing vegetation. According to art. 3, III, from the 2012 Forestry Code, Legal Reserve is deemed as the area located inside a rural property or landowning, defined according to the terms of art. 12, with the purpose of assuring the sustainable economic use of the natural resources in the real estate, helping to preserve and rehabilitate the ecological processes, and promoting the conservation of biodiversity, as well as providing a shelter and protection for the native fauna and flora.

The size of the Legal Reserve is determined according to the region where the property is located. The city of Santarém-Pará is located in the Legal Amazon, as defined by Act No. 1,806, from January 6th, 1953, where Legal Amazon is defined as the Brazilian Amazon, as established by the political, and not the geographical viewpoint. Such a concept was necessary so that the government could plan and promote development in the region. The Legal Amazon (Fig. 2) covers the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, Tocantins and part of Maranhão

(44th meridian west) (SUDAM— Superintendência do Desenvolvimento da Amazônia - http://www.sudam.gov.br/sudam).

According to Sirvinskas (2013), the Provisional Decree No. 2166-67/2001 has substantially changed art. 16 from Act No. 4771/65, presenting four modalities of legal reserves: a) 85% of the rural property located in a forest area in the Legal Amazon; b) 35% of the rural property located in a *cerrado* area in the Legal Amazon, with at least 20% of the property and 15% of compensation from other area, as long as the latter is located in the same watershed, according to the terms of § 7 of the abovementioned article; c) 20% of the rural property located in a forest area or other forms of native vegetation located in other regions of the country; and d) 20% of the rural property in general field areas located in any region of the country.

Act No. 12,651, from May 25th, 2012 changed these values again for areas located in the Legal Amazon: a) 80% of the real estate located in forest areas; b) 35% of the real estate located in *cerrado* areas; c) 20% of the real estate located in general fields. For properties located in the other areas other than the Legal Amazon, the minimal percentage is 20%.

According to Miranda and Mattos (1993), a major challenge is to hinder the destruction of the forest that is still intact, planning its reasonable occupation. For this purpose, it is necessary to use the Legal reserve in order to preserve the existing biodiversity and to allow the exploration of the area. Schmidt (2008) states that biodiversity has an important role in most policy documents on state of the environment and environmental policy.

Despite the existence of a complex law that defines what is the size of the area to be considered as a Legal reserve, there is no methodology in order to define, within the property, which would be the best area to be determined as a Legal reserve, or the area that best represents the native forest, preserving the biodiversity, and also the one that has the greater carbon accumulation or increase. Prioritizing the purpose of creating a methodology driven towards forest conservation, we will use geostatistics as a basis, optimizing sampling and preserving the representation of the native forest.

Following an international trend, environmental legislation in Brazil has become more stringent, but the effectiveness of legislation is highly debatable in the context of areas with a vast territory like the Amazon (Sousa et al., 2011).

1.4. Carbon accumulation

Climate change poses numerous measurement, attribution, performance monitoring and verification challenges, from the global to the organizational and even down to the individual level. For example, the science of climate change relies on the assimilation of vast quantities of direct and indirect measurements of past and present greenhouse gas fluxes to and from the atmosphere, coupled with economic models of human activity, in order to develop predictive models of future climate change and the associated impacts (Ascui and Lovell, 2012).

Carbon is one of the basic chemical elements of the biological constitution, and living beings represent the major reserve for this element, in their biomass (Rezende, 2000). Carbon dioxide (CO2) is one of the elements that represent the greenhouse gases (GHG), and it is currently one of the main pollutants. The major CO2 reservoirs are in the oceans and the soil, considering that the atmosphere has a low part of CO_2 (Rezende, 2000).

Photosynthesizing organisms are majorly responsible for the atmospheric CO_2 sequestration, and plants are responsible for stocking two-thirds of the carbon on Earth (Totten, 2000). Among plants, the shrub and arboreal-pattern ones offer the longest carbon-stocking cycles in nature, through their aerial sustention parts (trunks and branches) or underground parts (roots) before releasing this material on the atmosphere by decomposition and/or burning (Totten, 2000; Chang, 2002). Carbon sequestration by the forest is defined as sink, and its release is defined as source (Totten, 2000; Chang, 2002). Moist tropical forests are one of the main representatives of this sequestration, and it is during the early growth stages that the main part of the atmospheric CO_2 incorporation occurs (Rezende, 2000; Totten, 2000; Chang, 2002). Chang (2002) states that there are three simple forms of carbon sequestration:

a) preserving the carbon stock of the already existing forests through protection measures.
b) combined actions of sustainable forest management practices, forest regeneration, recovery of degraded forest areas, and agroforestry practices in agriculture fields.
c) replacing fossil fuel sources by sustainable vegetal biomass fuels.

Carbon accumulation or sequestration in forest areas is based on two main premises. First, CO2 is a global circulation gas, thus, its removal is equally important if it is made close to the emission source or in more distant locations. The second premise is that plants absorb CO2 from the atmospheric air through the photosynthesis process, using it to produce glucose and other organic compounds used for their growth and metabolism. Woody plants store carbon in the wood and other tissues until their death and decomposition, where the carbon in the wood may be released as CO2, CO, or CH4, or even be incorporated in the soil as organic substances. Thus, there can be said that plants have a permanent capacity to capture and fix carbon during their lives, and, as such, they are important carbon sinks for long periods (Matheus, 2012).

The concept of carbon sequestration was suggested during the Conference of the Parties (COP) from the United Nations Framework Convention on Climate Change (UNFCCC), held in the city of Kyoto, Japan, in 1997. The idea is preserving the native vegetation and/or reforesting in order to absorb CO2 through photosynthesis and/or keeping the carbon stock in plants (Yu, 2004; Matheus et al., 2005).

According to Resende et al. (2001), the carbon accumulation in ground ecosystems comprehends both the capture of carbon from the atmosphere and the prevention on the emission of greenhouse gases of the ecosystems, and there are two basic ways to approach the carbon fixation issue in these ecosystems: protecting the ecosystems that stock carbon in order for this process to be maintained or even increased (the Amazon, for instance); and managing the ecosystems to increase carbon fixation (direct planting and/or reforestation of degraded or traditionally naked areas).

The Amazon rainforest absorbs approximately five billion metric tons of carbon dioxide (CO2) every year (Cama et al., 2013). Within its biomass are great carbon reserves (from 70 to 80 billion tons) (Asner et al., 2004 cited in Cama et al. (2013)).

1.5. Georeferenced systems

According to Geist and Lambin (2001), communities are spatially structured, and that the sampling methods need to be robust in order to detect different levels of spatial autocorrelation. Although the importance of spatial autocorrelation in ecological surveys is acknowledged, little quantitative information is available (Goslee, 2006). Over 80% of the publications in ecological literature do not take into consideration the structure of spatial dependence (Dormann, 2007). Oda-Souza et al. (2008) attested that the geostatistical methods applied were adequate in order to verify the existence of a spatial dependence of the fan systematic design on data from forest spacing assays.

Fig. 4. Location of database samples.

Several methods adopted for spatial analysis were originally developed in other scientific disciplines, mainly mining. Among these methods is geostatistics based on variograms (Journel and Huijbregts, 1991; Issaks and Srisvastava, 1989; Goovaerts, 1997).

1.5.1. Geostatistics

The development of geostatistics began from 1951 on, when a South African mathematician, D. G. Krige, studying data from gold concentration, got to the conclusion that the variability obtained made no sense without taking into consideration the spacing between the samples (Krige, 1951). However, Matheron (1963, 1971) was the one who offered Geostatistics a great advance, with the development of the Regionalized Variable Theory. Regionalized Variable is based on random variables that consider spatial aspects, that is, the relative positions where the several values to be introduced in the models were observed. They also have qualitative characteristics that are strictly connected to the structure of the natural phenomenon they represent, such as, location, continuity, and anisotropy (varying according to the direction). In order to determine whether classic statistics or geostatistics must be used, the semi-variogram that expresses the spatial dependence among samples is used. In the case of spatial dependence, property values may be estimated in the study for non-sampled locations within the field, with no bias and minimal variability, through a method called kriging (Vieira, 2000).

The study of the spatial structure offered by the analysis of the spatial covariability function (semi-variogram) is not the final purpose of spatial analysis. In fact, it is necessary to estimate the values of the variables in non-sampled locations in order to attest the spatial distribution of a certain variable being studied. Thus, the analysis of the spatial structure must be considered as a fundamental, rather than final step that precedes the estimation techniques (interpolation) for any value in any position in the studied area, with no bias and little variability.

One of the most widely used methods to estimate the space or time dependence of neighbor samples is through autocorrelation which has also been applied in Soil Science (Webster, 1973; Webster and Cualanalo, 1975; Vieira et al., 1981).

Semi-variability requires a less restrictive stationarity hypothesis in relation to other measures, such as covariability, that requires second-degree stationarity. This lower requirement for the random function model offers no consequences for most practical cases (Deutsch and Journel, 1992). This is why semi-variability may be used in a broader number of situations.

The analysis structure for the regionalized phenomenon consists in building a variogram model, which operationally characterizes the main regionalization features (Journel and Huijbregts, 1991).

The variogram is generated from the calculus equation:

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

where:

$2\hat{\gamma}(h)$ – is the estimated variogram;
$N(h)$ – is the number of pairs of measured values, $z(x_i)$ and $z(x_i + h)$, separated by a distance vector h
$z(x_i)$ and $z(x_i\ h)$ – are the values of ith observation of regionalized variation, collected in points x_i and $x_i + h$ ($i = 1, \ldots, n$), separated by the vector (Fig. 3).

The parameters of the variogram may be directly observed in Fig. 1, where:

Range (a): distance within which the samples are spatially correlated.

Sill (C): it is the value of the variogram corresponding to its *range* (a). From this point on, it is considered that there is no more spatial dependence between samples, because the variability of the difference between pairs of samples (Var[$Z(x) - Z(x + h)$]) becomes invariant with distance.

Nugget Effect (C_0): by definition, $\gamma(0) = 0$. However, in practice, as h tends to 0, $\gamma(h)$ converges to a positive value called *Nugget*

Effect (C_0). The value of C_0 reveals the discontinuity of the variogram for distances smaller than the spacing between samples. A portion of such discontinuity may also be associated to measurement errors, but it is not possible to quantify whether the greater contribution is due to measurement errors or to the small-scale variability not captured by the sampling.

Spatial variability (C_1): it is the difference between sill (C) and the Nugget Effect (C_0).

According to Journel and Huijbregts (1991), the variogram shows the best way to characterize a regionalized phenomenon. The structural information is obtained through analyses and it must be constantly compared to the characteristic of the phenomenon sampled in the field.

With the variogram, it is expected that closer values are more similar amongst themselves than more distant values, and that the difference between the two values depends only on their relative position. Also, a more detailed study of directional variograms may evidence the occurrence of anisotropies. Anistropy is simply the preferred direction in which the phenomenon occurs.

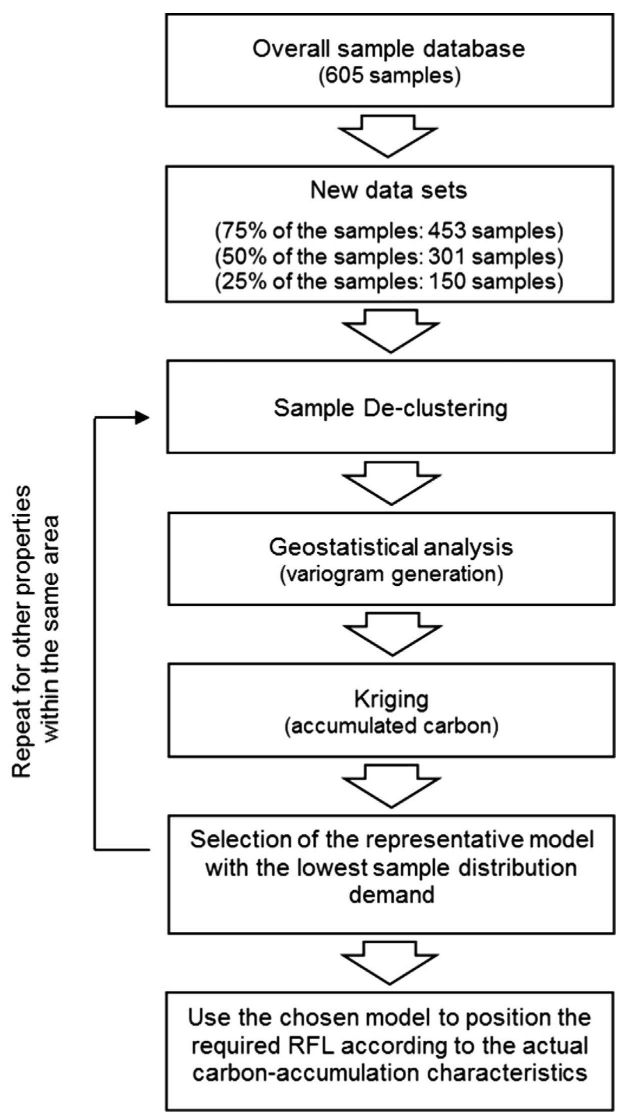

Fig. 5. Proposed methodology for the optimum sampling distribution for modeling carbon-accumulation for the appropriate positioning of RLFs.

1.5.2. Kriging

The interpolation method called Kriging is based on sampled data of regionalized variables, and the structural properties of the variogram obtained from these data. Kriging is a method of spatial interference, which estimates the values in non-sampled points from collected samples, considering the spatial dependence structure of the phenomenon. Kriging is a weighted linear combination of the observations (Moreau et al., 2012).

The estimation is obtained from the following expression:

$$Z(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \tag{2}$$

Where $Z(x_0)$: unknown value to be estimated; λ_i: the weight obtained by solving the linear system of equations (the *kriging system*); and $z(x_i)$: set of n data available. This estimator was firstly introduced by Matheron (1963).

Kriging generates the best non-biased linear estimation of data related to an attribute in a non-sampled location, by the modeling of the variogram (*BLUE – Best Linear Unbiased Estimator*). The most usual methods are simple kriging and ordinary kriging, along with some non-linear methods such as indicator kriging (Journel and Huijbregts, 1991).

Simple kriging is used when the average is assumed as statistically constant for the entire area. Ordinary kriging, on the other hand, considers the floating or moving average for the entire area. Indicator kriging consists basically on the application of ordinary kriging to the transformed variable, that is, the variable resulting from applying the non-linear function $f(z) = 0$ or 1. The initial concept was presented by Journel (1986) as a suggestion to build a conditional cumulative distribution function for spatial distribution estimation.

1.5.3. Preferential grouping of samples

When data are sparse and do not allow grouped values to be ignored, it is necessary to use some mechanism that, by attributing weights to data, attenuates or moderates their influence. Intuitively, data from densely sampled areas could receive a lower weight than those from sparsely sampled areas. Such weighting is equivalent to the ungrouping of data (Souza et al., 2001).

Some factors such as: accessibility conditions; expected attribute values; and sampling strategy make sampling a preferred method, or even in cases where the location of samples is not regular.

Data ungrouping by the polygonal method is a method in which the weights attributed to the samples are directly proportional to the area of the Voronoi Polygon around them (Williams, 1979). In zones with grouped data, the areas of the polygons tend to be small, receiving smaller weights.

The weights attributed to each ungrouped sample depend on the influence area of the sample. The ungrouping average for the samples is provided by the following expression:

$$m = \frac{1}{A} \sum_{\alpha=1}^{n} \omega_\alpha Z(u_\alpha) \tag{3}$$

In which m is the ungrouped average of data, A is the sum of all areas of the polygons, ω_α is the area of the centered polygon, and $u_\alpha \cdot e \cdot z(u_\alpha)$ is the value of the resulting variable observed in the sample.

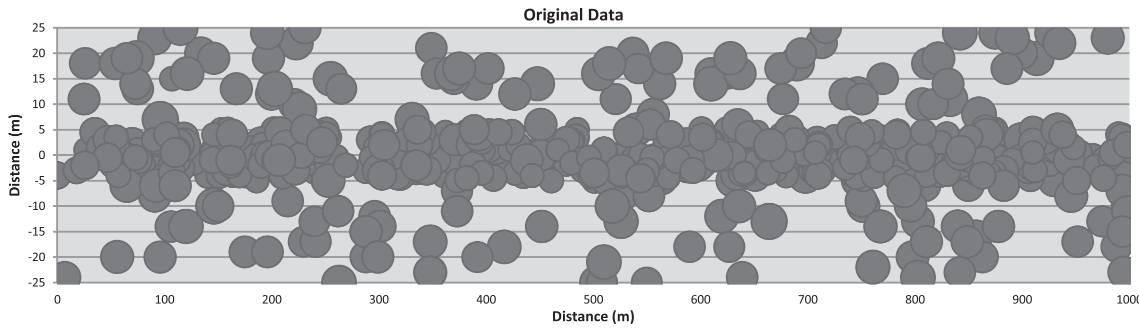

Fig. 6. Georeferenced samples.

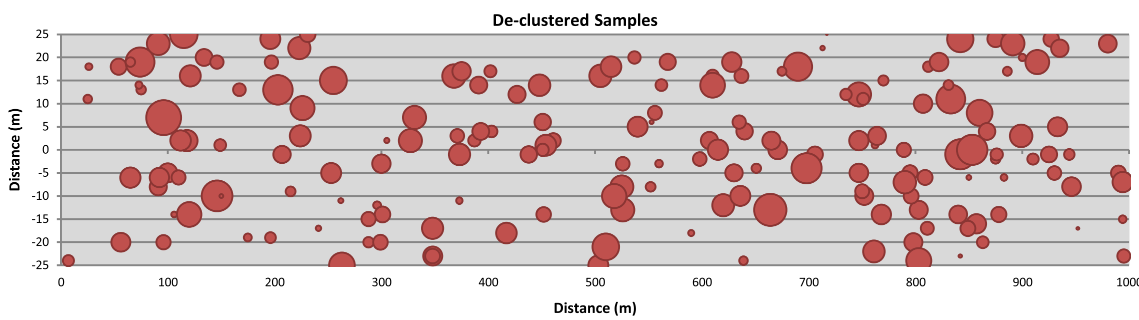

Fig. 7. De-clustered samples.

2. Materials and methods

This study used data sampled from the Tapajós National Forest, located in the city of Santarém, state of Pará, Brazil. The sampled database consists in 1 transect, which is 1000-meter long and 50-meter wide. This transect is located within the research area of LBA's Amazon Biosphere-Atmosphere Large-scale Program (Amazon Biosphere-Atmosphere Large-scale Program http://lba.cptec.inpe.br/lba/site/?). LBA is a research program initiated in 1998 through international cooperation agreements, which in Brazil is coordinated by the National Institute of Environmental Research. The current research plan incorporates three integrated areas: the interaction biosphere-atmosphere, the hydrologic cycle and the social-political and economical dimensions of the environmental changes in the Amazon. This same database has been used in Vieira (2003) and the data collection area is located at the coordinates 2,85611°S; 54,95806°W (Fig. 4).

All arborous species, or individuals, with diameter at breast height (DBH) equal to or greater than 35 cm (DBH ≥ 35 cm) were identified, georeferenced and measured. Diameter at breast height, or DBH, is a standard method of expressing the diameter of the trunk or bole of a standing tree. In the central area of the transect, individuals with 10 cm < DBH <35 cm were also sampled. Carbon accumulation in the arboreus biomass is related to the arborous diameter (Vieira et al., 2008).

The initial analysis was performed by distributing the frequency of total DBHs of sampled individuals, generating the histogram of DBH intervals, as well as distributing the carbon frequency, where

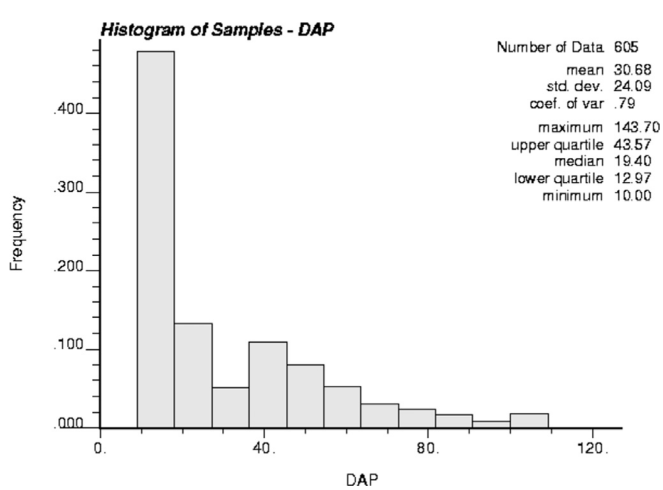

Fig. 8. Histogram of the frequency distribution of DBHs in the total area (1000 m × 50 m).

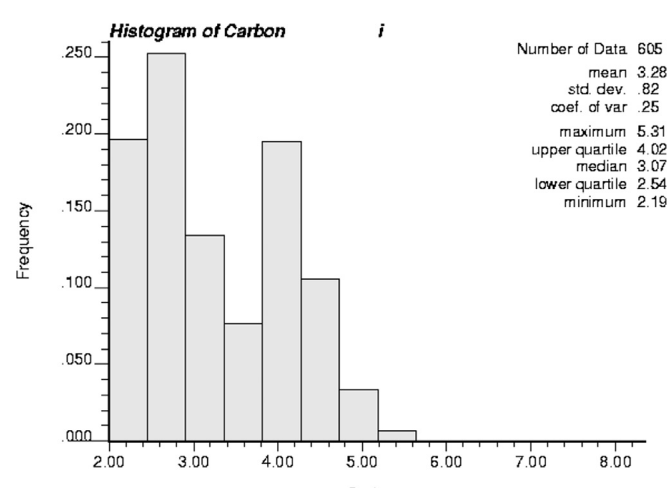

Fig. 9. Histogram of the frequency distribution of the carbon variable (Mg of C).

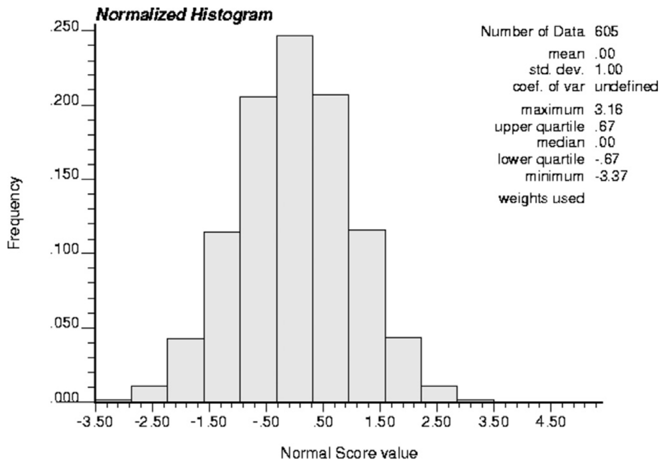

Fig. 10. Histogram of the frequency distribution of the normalized carbon variable (Mg of C).

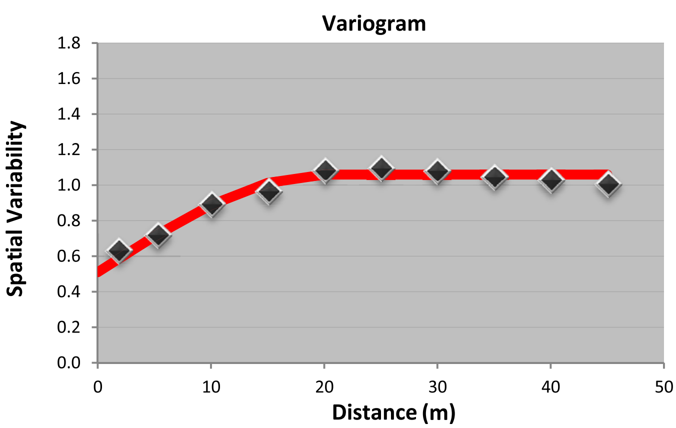

Fig. 11. Omnidirectional variogram, for variable C., where the value of the nugget effect was 0.5, range of 20 m, and sill of 1.06. The type of variogram was adjusted for the spherical model.

the dry biomass above the ground was estimated by applying the allometric equation developed by Chambers et al. (2001) in Central Amazon and successfully tested in other areas (Vieira et al., 2008):

$$\ln\left(\text{biomass}\right) = a + b_1 \ln\left(\text{DBH}\right) + b_2[\ln(\text{DBH})]^2 + b_3[\ln(\text{DBH})]^3 \quad (4)$$

Where: $a = -0.370$; $b_1 = 0.333$; $b_2 = 0.933$; $b_3 = -0.122$;

This equation was used to estimate the accumulation of biomass resulting from the diametric increase in the studied area.

Higuchi et al. (2004) states that the estimated carbon stock can be obtained from the product of the forest biomass carbon concentration. The concentration of carbon in vegetation obtained by Higuchi and Carvalho Jr. (1994) is around 48%, which is within the range of concentrations in tropical forests, between 46% and 52% (Silveira et al., 2008).

For the collected data, it was necessary to de-cluster the samples, using the GSLIB public libraries (Deutsch and Journel, 1998, 1992), and then the new histogram was generated with the normalized samples.

With this normalized database, the geostatistical analysis was carried, and a spherical variogram was generated as a result.

From the data on the variogram, the kriging method was performed so that the carbon values for non-sampled locations could be inserted.

Further to the modeling of the area with the complete sampling database, a set of random samples have been removed from the database, and the remaining samples were employed to model the same are in order to compare the resulting model with the original model of the area. In the first experiment, 25% of the samples were removed, with 152 of the total of 605 samples being randomly removed. In the second experiment, 50% of the samples were removed, with 304 of the total of 605 samples being randomly removed. In the third experiment, 75% of the original samples were removed, with 455 of the total of 605 samples being randomly removed. Fig. 5 illustrates the procedure that has been used to select different data sets from the original sample database though the random removal of samples, so the resulting models from these different data sets could be compared among each other.

3. Results and discussion

The sampling of the area (Fig. 6) shows that there is a grouping of samples in the center of the area; thus ungrouping (de-clustering) was performed, creating weights for each sample (Fig. 7).

The frequency distribution (Fig. 7) of DBHs was performed with 10 cm intervals, where the intervals represent DBHs in intervals of 30 cm $\leq$ DBH $\leq$ 40 cm; 40 cm $\leq$ DBH $\leq$ 50 cm; 50 cm $<$ DBH $\leq$ 60 cm; 60 cm $<$ DBH $\leq$ 70 cm; 70 cm $<$ DBH $\leq$ 80 cm, 80 cm $<$ DBH $\leq$ 90 cm; 90 cm $<$ DBH $\leq$ 100 cm, and greater than 100 cm. Where the minimal value was 35.2 cm, the maximum value was 106.8 cm, and the average was 55.75 cm 204 arboreus individuals were sampled, which represent 52 families; and the families that stood out the most were the following: Rubiacea, Caesalpinaceae, Lecuthidaceae, Burseraceae, and Sapotaceae. The most abundant species was *Coussarea racemosa*, followed by the species *Protium apiculatum* and *Aparisthmium cordatum*.

The histogram of the frequency distributions of DBHs (Fig. 8) shows the mean in 30.68 cm; maximum value of DBH was 143.70 cm and the minimum value of DBH was 10.00 cm. The histogram of carbon (Fig. 9), the samples presents mean in 3.28 Mg of C, the maximum value was 5.31 Mg of C and the minimum value was 2.19 Mg of C.

The new histogram of the normalized samples (Fig. 10), has values ranging from −3.37 to 3.16.

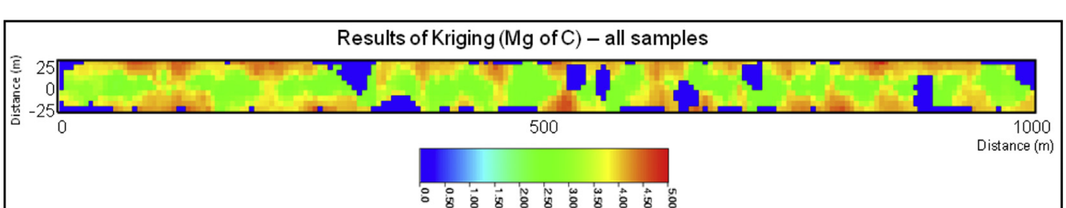

Fig. 12. The results of kriging the variable Carbon (Mg of C) using all samples, with blocks of 10 m × 10 m.

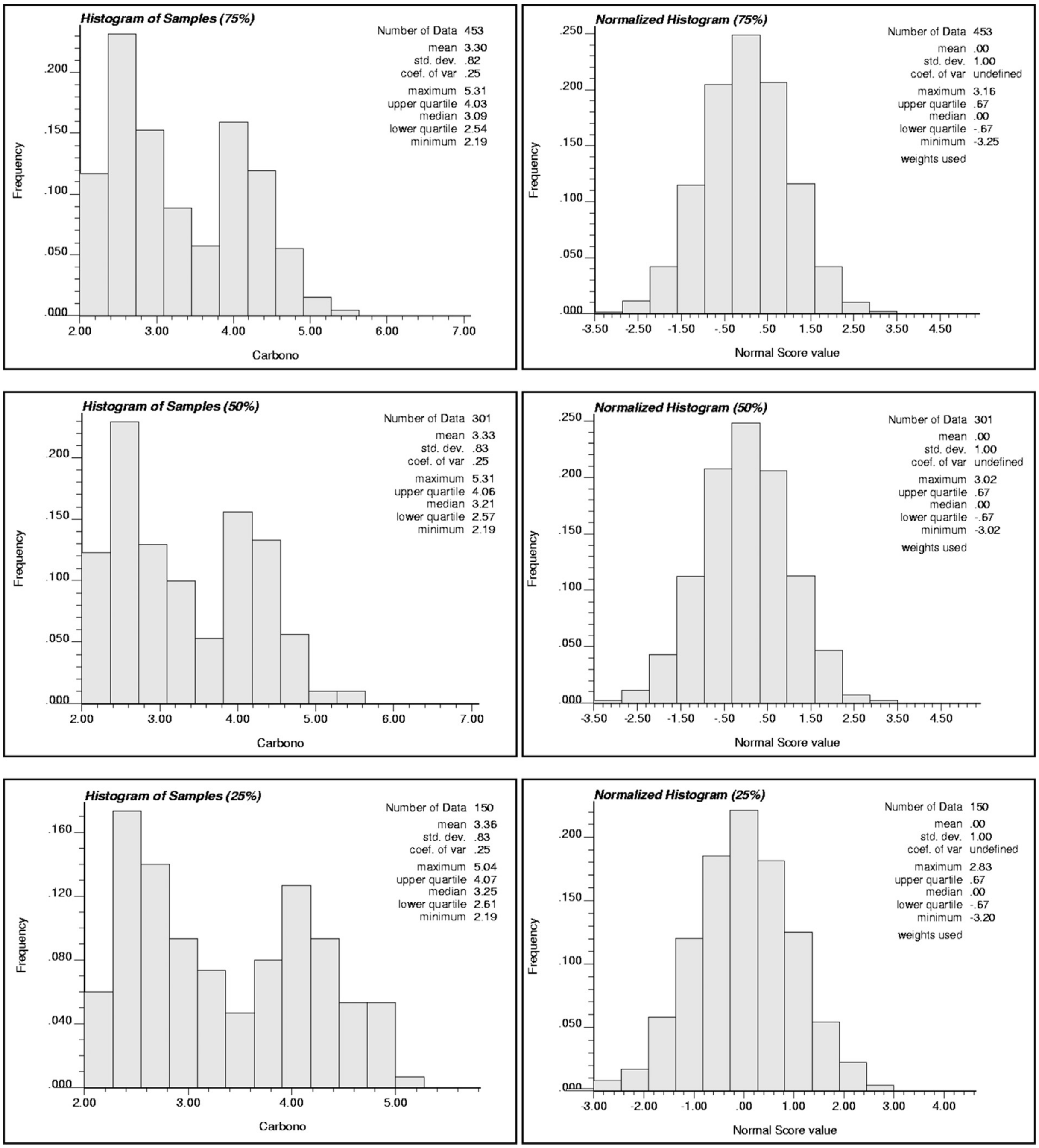

Fig. 13. Histogram of samples: 75% of samples (453 samples) and normalized histogram; 50% of samples (301 samples) and normalized histogram; and; 25% of samples (150 samples) and normalized histogram.

With this new database, or declustered database, and the use of geostatistical analysis, the variogram was generated, showing that there is an organized structure for this variable, with no preferential direction, that is, the variogram is omnidirectional. The model that had a better adjustment was the spherical one, with a nugget effect of 0.5, range of 20 m, and sill of 1.06 (Fig. 11).

With the data from the variogram, the kriging method was applied in order to estimate the amount of Carbon (Mg of C) per area (Fig. 12).

For the following stage, in order to check the sampling optimization, were used 75%, 50% and 25% the total of samples, respectively 45, 301 and 150 samples, generated the histogram of samples and the normalized histogram (Fig. 13).

The geostatistical study was made with the new database; generate the omnidiretional variogram for variable Carbon (Fig. 14). The variogram with 75% of samples, or 453 samples, and with 50% of samples, or 301 samples, has the better adjusted model theory was spherical model; the variogram with 25% of samples (150 samples) has no defined structure. The variogram parameters were similar for variogram with 75% and 50% of samples (Table 1).

The kriging process (Fig. 15) were performed for this variograms, with 5 m $\times$ 5 m blocks, and the kriging results with the 75% and 50% of samples results were similar.

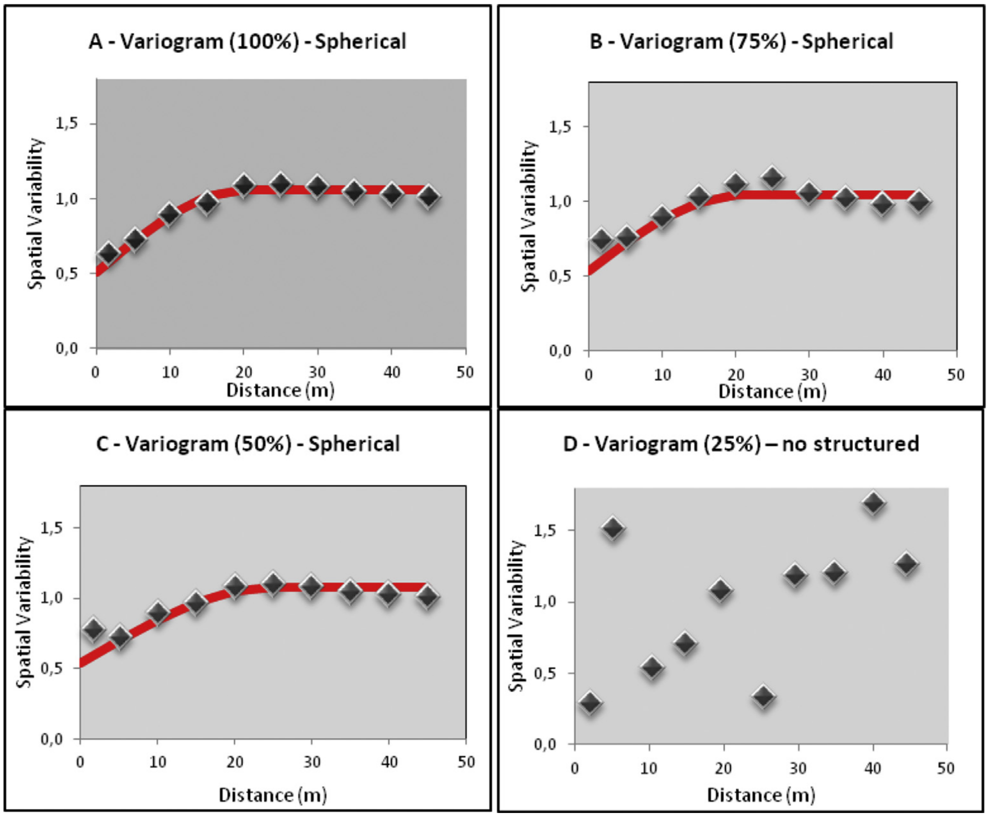

Fig. 14. Generate omnidirectional variograms. Variogram with 100% of samples, adjusted spherical model. Variogram with 75% of samples, adjusted spherical model. Variogram with 50% of samples, adjusted spherical model. Variogram with 25% of samples with no structure.

The results of the kriging carbon modeling process show that the datasets with 75% and 50% of the samples produced similar models, which indicates that in this particular area, further models could be built with a much smaller sampling distribution. Whereas that the choice of Legal Reserve (RL) is in a particular area where there is similarity of biodiversity, flora and fauna, the issue of carbon accumulation becomes important.

RL is an important instrument established in the Brazilian Forestry Code that constrain the use of private owned properties in the whole Country, in order to promote the sustainable utilization of the natural resources, the preservation and rehabilitation of the ecological processes and of the biodiversity. In order to achieve these objectives, a RL must be selected and preserved, however there is no definition on the criteria that should be used for the selection of this area. In the light of this context, the adoption of a specific methodology would contribute in the determination of the best area inside a particular property to fulfill the objectives of the RL as mentioned above. The methodology based in geostatistics allows working on regionalized variables (Matheron, 1971) and their special relationship, where each arboreous neighbor is treated as a regionalized variable that keeps some special relationship with other individuals of the population and each spatial relationship between these variables is measured by the variogram (Isaaks, Srivastava, 1989), that is dependent on each specific area being studied. This methodology allows the search for areas that contain greater amounts of accumulated carbon, thus creating a criteria for the RL selection and guaranteeing that the objectives set for this area are achievable.

The resulting kriged carbon model allows a more objective decision making process for the location of the RL within a certain property. For instance, if a 600 ha particular area property located within a forest area inside the Legal Amazon is taken into account, the Brazilian legislation requires 80% of this area to be allocated as a legal reserve, or RL. The proposed methodology allows the selection of the RL position to be made on the basis of the actual carbon-accumulation characteristics of each particular area, as shown in Fig. 16A. On the other hand, if the particular area property is located outside any forest area within the Legal Amazon, the requirement is that 20% of the property is allocated as RL. Again, the proposed methodology allows the selection of the RL area to be made according to the actual carbon-accumulation distribution on the property, as shown in Fig. 16B.

Table 1
Variogram parameters.

Variogram	Nugget effect	Spatial variability	Sill	Range
100% of samples	0.5	0.56	1.06	20 m
75% of samples	0.53	0.51	1.04	20 m
50% of samples	0.54	0.54	1.08	25 m
25% of samples	No structure			

4. Conclusion

The studied area close to prospect areas in Santarém, state of Pará, Brazil, was exhaustively sampled; the study showed that this sampling could be optimized, reducing the sampled, still maintaining the representativeness of the total area, and the amount of C (Mg of C) per area.

Thus, this methodology could be used as a reference to define the Legal reserve area, based on the larger amount of Carbon stored

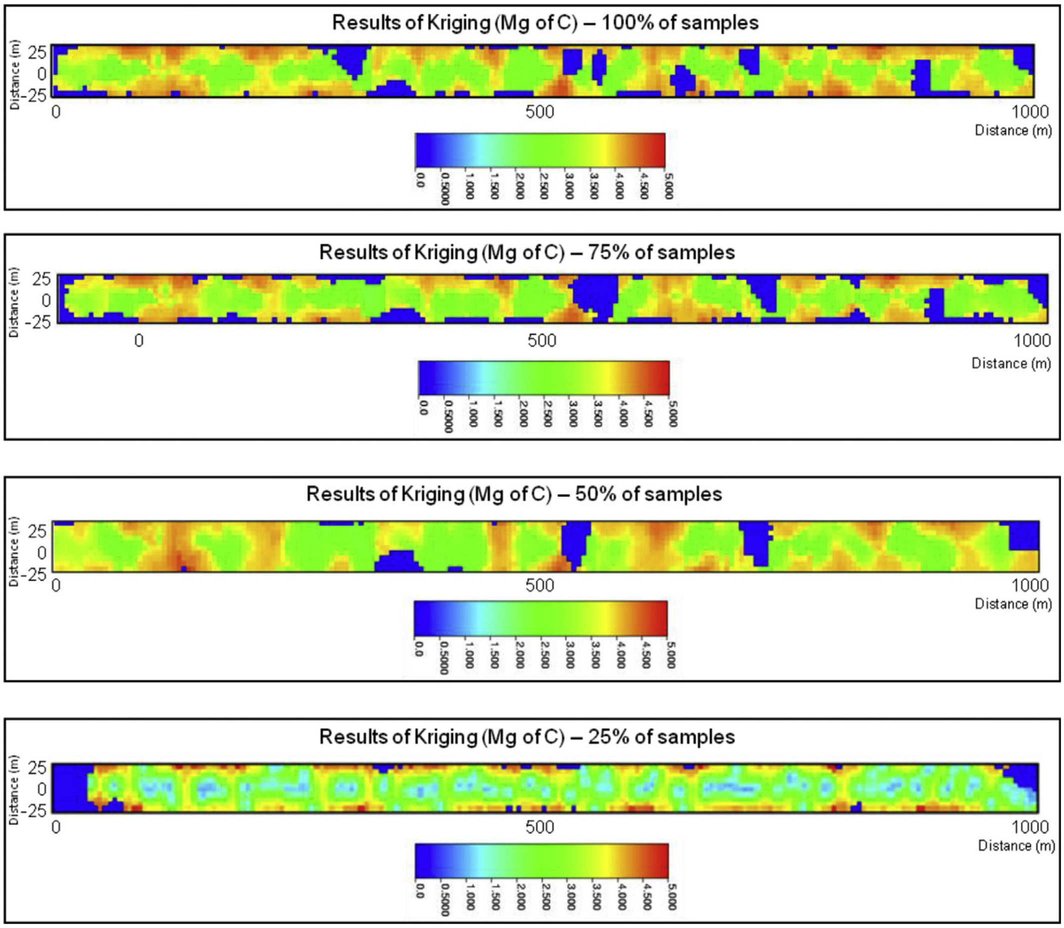

Fig. 15. Kriging results.

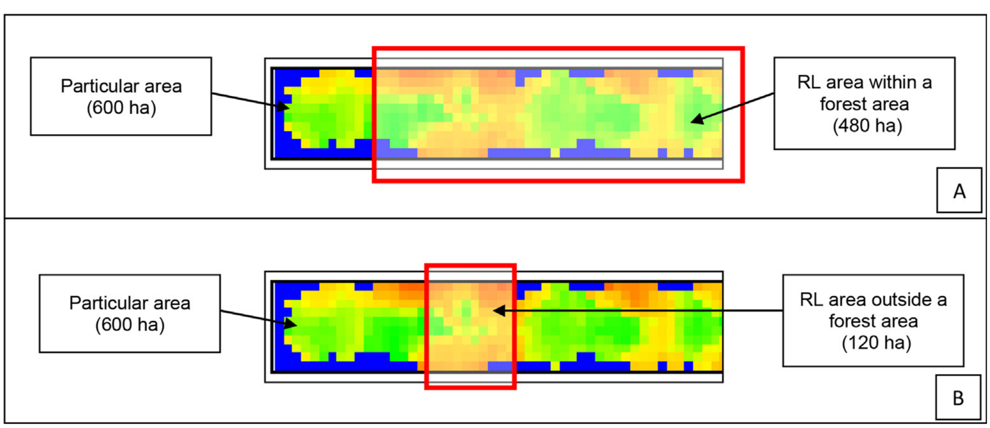

Fig. 16. A: Theoretical particular area of 600 ha within a forest area inside the Legal Amazon, where a RL of 480 ha (80% of the property) has been located according to carbon accumulation parameters. B: Theoretical particular area of 600 ha outside forest areas inside the Legal Amazon, where a RL of 120 ha (20% of the property) has been located according to carbon accumulation parameters.

in that location, contributing to decrease the greenhouse gases, and enabling a greater fixation of carbon in these areas.

The proposed methodology demands a smaller amount of samples to be collected in order to create a representative model of the carbon-accumulation. This model can then be efficiently used for selecting the most appropriate position for the RLs, providing a tangible basis for supporting the decision making process of locating RLs.

References

Arraes, R. de A., Mariano, F.Z., Simonassi, A.G., Mar. 2012. Causas do desmatamento no Brasil e seu ordenamento no contexto mundial. Rev. Econ. Sociol. Rural. Brasília 50 (1). Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-20032012000100007&lng=en&nrm=iso http://dx.doi.org/10.1590/S0103-20032012000100007 (accessed 22.08.13.).

Ascui, F., Lovell, H., 2012. Carbon accounting and the construction of competence. Orig. Res. J. Clean. Prod. 36 (November 2012), 48–59. Climate Accounting and

Sustainability Management. http://dx.doi.org/10.1016/j.jclepro.2011.12.015 (accessed 23.08.13.).
Asner, G.P., Nepstad, D., Cardinot, G., Ray, D., 2004. Drought stress and carbon uptake in an Amazon forest measured with spaceborne imaging spectroscopy. Proc. Natl. Acad. Sci. U. S. A. 101 (16), 6039–6044 arXiv, URL. http://dx.doi.org/10.1073/pnas.0400168101. http://www.pnas.org/content/101/16/6039.full.pdf+html. http://www.pnas.org/content/101/16/6039.abstract.
Brazil, Law no. 1,806, from January 6th, 1953. Discusses the Economic Recovery Plan of the Amazon, creates the superintendency for its execution and establishes other provisions. Federal Official Gazette from 1/71953.
Brazil, Law no 12,651, from May 25th, 2012. Discusses the protection of native vegetation; amends Acts Nos. 6,938, from August 31st, 1981, 9,393, from December 19th, 1996, and 11,428, from December 22nd, 2006; revokes Acts Nos. 4,771, from September 15th, 1965, and 7,754, from April 14th, 1989, and Provisional Decree No. 2,166-67, from August 24th, 2001; and establishes other provisions. Federal Official Gazette from 5/28/2012.
Brower, J.E., Zar, J.H., 1984. Field & Laboratory Methods for General Ecology, second ed. Wm. C. Brown Publishers, Dubuque, Iowa, p. 226.
Cama, A., Montoya, F.G., Gómez, J., Cruz, J.L., Manzano-Agugliaro, F., 2013. Integration of communication technologies in sensor networks to monitor the Amazon environment. J. Clean. Prod. 59, 32–42. Available online 3 July 2013. http://dx.doi.org/10.1016/j.jclepro.2013.06.041 (accessed 22.08.13.).
Chambers, J.Q., Santos, J., Ribeiro, R.J., HIGUCHI, N., 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon Forest. For. Ecol. Manag. 152, 73–84.
Chang, M., 2002. Sequestro de carbono florestal: oportunidades e riscos para o Brasil. Curitiba: Rev. Parana. Desenvolv. (102), 85–101 (Jan/Jun).
Chavel, A., 1982. O latossolos amarelos, álicos, argilosos dentro dos ecossistemas das bacias experimentais do INPA e da região vizinha. Supl. Acta Amaz. 12 (3), 47–60.
Clark, D.B., Clark, D.A., 1996. Abundance, growth and mortality of very large trees in neotropical lowland rain forest. For. Ecol. Manag. 80 (1–3), 235–244.
Deutsch, C.V., Journel, A.G., 1992. Geostatistical Software Library and User's Guide. Oxford University Press, New York, p. 340.
Deutsch, C.V., Journel, A.G., 1998. GSLIB: Geostatistical Software Library and User's Guide. Oxford University Press, New York, p. 369.
Dormann, C.E., 2007. Effects of incorporation spatial autocorrelation into the analysis of species distribution data. Glob. Ecol. Biogeogr. 16, 129–138. Oxford.
Ferraz, J., Ohta, S., sales, P.C., 1998. Distribuição dos dolos ao longo de dois transectos em floresta primária ao Norte de Manaus (AM). In: Pesquisas Florestais para a conservação da floresta e reabilitação de áreas degradadas da Amazônia, pp. 109–143. Manaus.
Galka, A., 2004. Using a cleaner production preventivestrategy for the reduction of the negative environmental impacts of agricultural production – using cattle husbandry as a case study. J. Clean. Prod. Susteinable Agric. 12 (5), 513–516. Available from: http://dx.doi.org/10.1016/S0959-6526(03)00108-2 (accessed 26.08.13.).
Garcia, P.O., Lobo-Faria, P.C., 2009. Metodologias para Levantamentos da Biodiversidade Brasileira. Universidade Federal de Juiz de Fora, pp. 14–18.
Geist, H.J., Lambin, E.F., 2001. What drives tropical deforestation. LUCC Report Series No. 4. Land Use and Land Cover Change, International Geosphere-Biosphere Programme.
Goovaerts, P., 1997. Geostatistics for Natural Resources Evaluation. Oxford University Press, New York.
Goslee, S.C., 2006. Behavior of vegetation sampling methods in the presence of spatial autocorrelation. Plant Ecol. (187), 203–212. Dordrecht.
Higuchi, N., Carvalho Jr., J.A., 1994. Fitomassa e conteúdo de carbono de espécies arbóreas da Amazônia. In: SEMINÁRIO EMISSÃO x SEQÜESTRO DE CO2 – UMA NOVA OPORTUNIDADE DE NEGÓCIOS PARA O BRASIL, Rio de Janeiro. CVRD, Anais... Rio de Janeiro, pp. 125–145.
Higuchi, N., dos Santos, J., Ribeiro, R.J., Freitas, J.V., Vieira, G., Cöic, A., Minette, L.J., 1997. Crescimento e Incremento de uma Floresta Amazônica de Terra-Firme Manejada. In: Biomassa de nutrientes Florestais. INPA/DFID, pp. 89–132.
Higuchi, N., Chambers, J., Santos, J., Ribeiro, R.J., Pinto, A.C.M., Silva, R.M., Tribuzy, E.S., 2004. Dinâmica e balanço do carbono da vegetação primária da Amazônia Central. Floresta, Curitiba 34 (3), 295–304 (set./dez).
Hinton, J.J., Veiga, M., Tadeu, A., Veiga, C., March 2003. Clean artisanal gold mining: a utopian approch? J. Clean. Prod. 11 (2), 99–115. Environmental Management. Available on. http://dx.doi.org/10.1016/S0959-6526(02)00031-8 (accessed 23.08.13.).
Isaaks, E.H., Srivastava, M.R., 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, p. 561.
Journel, A.G., 1986. Geostatistics: models and tools for the earth sciences. Math. Geol. 18 (1), 119–140. January.
Journel, A.G., Huijbregts, C.J., 1991. Mining Geoestatistics, fifth ed. Academic Press, London, p. 561.
Krige, D.G., 1951. A statistical approach to same basic mine evaluation problems on the Witwatersrand. J. Chem. Metall Min. Soc. Soth Afr. 52, 119–139.
Matheron, G., 1963. Principles of geostatistics. Econ. Geol. 58, 1246–1266. Littleton.
Matheron, G., 1971. The theory of regionalized variables and its application. Fontainebleau: Les Cah. Cent. Morphol. Math. 56. Fascicule 5.
Matheus, M.T., 2012. Ciências Agrárias e Biológicas. Rev. Trópica 6 (1), 104.
Matheus, M.T., Passos, R.R., Sousa, F.C., Hoffmann, R.G., 2005. Seqüestro de carbono. In: CONGRESSO BRASILEIRO DE DEFESA DO MEIO AMBIENTE, 8., Rio de Janeiro. Anais. Clube de Engenharia, Rio de Janeiro, 2005. CD-ROM.
Miranda, E.E., Mattos, C., 1993. De colonos a munícipes na floresta tropical de Rondonia: Machadinho d'Oeste. EMBRAPA-NMA, Campinas, p. 154.
Monteiro, M. de A., 2005. Meio século de mineração industrial na Amazônia e suas implicações para o desenvolvimento regional. Estud. Av. São Paulo 19 (53). Apr. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-40142005000100012&lng=en&nrm=iso http://dx.doi.org/10.1590/S0103-40142005000100012 (accessed 22.08.13.).
Moreau, V., Bage, G., Marcotte, D., Samson, R., 2012. Statistical estimation of missing data in life cycle inventory: an application to hydroelectric power plants. J. Clean. Prod. 37 (December 2012), 335–341. Available from: http://dx.doi.org/10.1016/j.jclepro.2012.07.036 (accessed 26.08.13.).
Oda-Souza, M., 2009. Modelagem geoestatística em quatro formações florestais do Estado de São Paulo. Tese de Doutorado. Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba. Recuperado em 2013-12-13, de. http://www.teses.usp.br/teses/disponiveis/11/11150/tde-14102009-084049/.
Oda-Souza, M., et al., 2008. Aplicação de métodos geoestatísticos para identificação de dependência espacial na análise de dados de um ensaio de espaçamento florestal em delineamento sistemático tipo leque. Rev. Árvore, Viçosa 32 (3). June 2008. Available at: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-67622008000300011&lng=en&nrm=iso http://dx.doi.org/10.1590/S0100-67622008000300011 (accessed 03.06.13.).
Parrota, J.A., Francis, J.K., Almeida, R.R., 1995. Trees of the Tapajos: a Photographic Field Guide. General Technical Report IITF-1. United States Department of Agriculture, Rio Piedras, Puerto Rico.
Resende, A.S., Santos, A.O., Gondim, A., Xavier, R.P., Coelho, C.H.M., oliveira, O.C., Alves, B.J.R., Boddey, R.M., Urquiaga, S., 2001. Efeito estufa e o sequestro de carbono em sistemas de cultivo com espécies florestais e na cultura de cana-de-açúcar. Embrapa Agrobiologia, Seropédica, p. 23.
Rezende, D., 2000. Sequestro de carbono uma experiência concreta – estudos iniciais o projeto de sequestro de carbono Ilha do Bananal e seu entorno. Gráfica Terra, Goiânia.
Ruviaro, C.F., Gianezini, M., Brandão, F.S., Winck, C., Dewes, H., 2012. Life cycle assessment in brazilian agriculture facing worldwide trends. J. Clean. Prod. 28 (June 2012), 9–24. Available from: http://dx.doi.org/10.1016/j.jclepro.2011.10.015 (accessed 23.08.13.).
Schmidt, J.H., December 2008. Development of LCIA characterisation factors for land use impacts on biodiversity. J. Clean. Prod. 16 (18), 1929–1942. Availabel from: http://dx.doi.org/10.1016/j.jclepro.2008.01.004 (accessed 23.08.13.).
Silveira, P., et al., Mar. 2008. O estado da arte na estimativa de biomassa e carbono em formações florestais. Floresta l. ISSN 1982-4688Disponível em. http://ojs.c3sl.ufpr.br/ojs2/index.php/floresta/article/view/11038/7509. Acesso em: 23 Ago. 2013.
Sirvinskas, L.P., 2013. Manual de direito ambiental, 11 ed. Saraiva, São Paulo.
Sousa, R., Veiga, M.., Zyl, D.V., Telmer, K., Spiegel, S., Selder, J., April–May 2011. Policies and regulations for Brazil's artisanal gold mining sector: analysis and recommendations. J. Clean. Prod. 19 (6–7), 742–750. Access on 23 Aug 2013. Available from: http://dx.doi.org/10.1016/j.jclepro.2010.12.001.
Souza, L.E., et al., 2001. Impacto do agrupamento preferencial de amostras na inferência estatística: aplicações em mineração. Rem. Rev. Esc. Minas Ouro Preto 54 (4). Dec. 2001. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0370-44672001000400005&lng=en&nrm=iso http://dx.doi.org/10.1590/S0370-44672001000400005. access on 05 June 2013.
Telles, E.C.C., Trumbore, S., Camargo, P.B., Martinelli, L.A., Costa, E.S.D., Santos, J., Higuchi, N., Santos, R.C., 2001. Effect of soil texture on carbon dynamics and storage in tropical forest soils of Amazonia. Glob. Biogeochem. Cycles (no prelo).
Totten, M., 2000. Getting it Right – Emerging Markets for Storing Carbon in Forests. Forest Trends and world resources institute, Washington, DC.
Vieira, S.R., 2000. Geoestatística em estudos de variabilidade espacial do solo. In: NOVAIS, R.F., ALVAREZ, V.H., SCHAEFER, G.R. (Eds.), Tópicos em ciência do solo, vol. 1. SBCS, Viçosa, pp. 1–54.
Vieira, S.A., 2003. Mudanças globais e taxa de crescimento arbórea na Amazônia. Piracicaba, p. 103.
Vieira, S.R., Nielsen, D., Biggar, J.W., 1981. Spatial variability of field-measured infiltration rate. Soil Sci. Soc. Am. J. Madison 45, 1040–1048.
Vieira, S.A., et al., 2008. Estimation of biomass and carbon stocks: the case of the Atlantic Forest. Biota Neotrop., Campinas 8 (2). June 2008. Available at: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1676-06032008000200001&lng=en&nrm=iso http://dx.doi.org/10.1590/S1676-06032008000200001 (accessed 03.06.13.).
Webster, R., 1973. Automatic soil boundary location for transect data. Math. Geol. 5 (1), 27–37. New York.
Webster, R., Cuanalo, H.E. de La C., 1975. Soil transects correlograms of north Oxfordshire and their interpretation. J. soil Sci. 26 (2), 176–197. Oxford.
Williams, R., 1979. The Geometrical Foundation of Natural Structure: a Source Book of Design. Dover, New York, p. 43.
Yu, C.M., 2004. Seqüestro florestal de carbono no Brasil: dimensões políticas, socioeconômicas e ecológicas. Annablume/IEB, São Paulo, p. 278.