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Original Article

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Mapping Three-dimensional Moisture Content of Wood Chip Piles for Energy Production

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ABSTRACT

The aim of this study was to apply geostatistics to predict the spatial pattern of variations in moisture content of eucalyptus wood chip piles to generate subsidies for adequate sampling and material handling. Wood chip piles were installed in three different storage cycles using newly cut material for 7, 30, and 60 days. Sampling was performed in axial (top, middle, and base) and lateral positions, so that all samples were georeferenced in relation to the distance from the ground and the center of the pile. Moisture values were submitted to geostatistical analysis and kriging. The results confirmed the spatial dependence of moisture content over the piles stored at 7 and 30 days; however, the effect of rainfall was crucial to reduce the spatial dependence of moisture content. The results showed that geostatistics is a useful tool for the creation of reliable sampling protocols.

Keywords: spatial dependence, kriging, bioenergy, moisture content, biomass.

1. INTRODUCTION

The use of biomass for energy production has increased globally, especially in cogeneration systems, due to instrumented policies and financial incentives (Kumar et al., 2015).

Among the multiple categories of energy production using wood, residual chip is commonly used in the industrial sector. However, the quality of chips depends on aspects such as origin of raw materials and methodologies applied at all production stages, which is related to the control of intrinsic biomass variables and environmental factors (Eleotério et al., 2017).

In this sense, the storage process is an integral part of using wood chips for energy purposes, as ideal conditions can ensure greater efficiency in the energy conversion process through better control of the physical and chemical properties of the stored material (Eleotério et al., 2017; Daassi-Gnaba et al., 2017; Manzone et al., 2013).

Among biomass properties, the moisture content has higher degree of interference in energy attributes related to combustion, obtaining greater efficiency with wood chips presenting reduced and homogeneous values (Nikolaevich et al., 2016; Eleotério et al., 2017). The moisture content required for energy production from biomass depends on the size of the processing plant. In the case of large installations, the greatest demands are related to the homogeneity of moisture contents and not to the maintenance of low moisture values, because large boilers are already adjusted for certain moisture levels, while large oscillations from heterogeneous raw materials require equipment readjustment and, consequently, efficiency reduction (Verma et al., 2017).

Therefore, variables such as the seasonality and storage time should be considered for the processing of wood chips, as these factors affect the speed and homogeneity of biomass moisture reduction, influence the chemical alteration, and change in the energy content of the material (Brand et al., 2014).

For the proper management of stored materials and for greater efficiency, it is necessary to understand the distribution and variation in the moisture content of wood chips during the storage period. However, the difficulty in determining variation patterns in the moisture content of biomass stored in stacks depend on the sampling form and intensity (Erber et al., 2012). Depending on the sampling strategy adopted, the variability in the characteristics may not be properly captured, offering difficulties to obtain significant results, representative of the characteristics of the entire pile.

Traditional sampling methods do not consider the occurrence of possible spatial correlations between neighboring observations; in many cases, only the information given by variance is insufficient to explain the phenomenon, which is an important source of variability.

In the specific case of wood chip piles, the analysis of the spatial distribution of moisture values inside chip stacks can subsidize decision-making regarding the indication for the use of biomass and the appropriate management in relation to the storage period of structures, especially when directly exposed to certain environmental conditions.

According to the above, this study aimed to determine and map the spatial variability in the moisture content of wood chip piles stored outdoors for the production of energy during three different storage periods.

2. MATERIAL AND METHODS

2.1. Experimental area

The experiment was conducted at the Federal University of São Carlos, campus of Sorocaba (23º35'12.20"S; 47º31'11.70"W) between September and November of 2015. The climate of the study area is tropical, hot, and humid, and it is considered to have Cwa climate at peripheral depression and Cwb in places of higher altitudes, according to the Köppen classification.

2.2. Sampling of chips in the stack

A wood waste company provided wood chips of *Eucalyptus grandis* for the study. The particle size distribution of chips was approximately 57.48% between 25.40 and 19.50 mm, followed by 40.73% between granulometry of 12.70 and 6.35 mm, and 1.79% lower than 6.35 mm.

After production, chips were stored outdoors for September–November, distributed in three conical piles, which were sampled in the axial (top, middle, and bottom) and lateral positions. Samples were georeferenced in relation to the distance from the ground and center of the pile, in all positions. Samplings were performed in three storage periods and the number of sampling points per pile was found to vary according to the height and width of structures (Table 1).

To mark the sampling place, metallic rods graduated at every 30 cm in height (representing the distance from the ground) were laterally arranged from each 50 cm in the pile (representing the distance from the center of the stack). Samples were collected by means of the opening of profiles in piles in pre-determined fixed positions on rods.

2.3. Moisture content

To determine the moisture content of samples collected from the three storage periods, gravimetric method recommended by NBR 14929 was applied according to Donato et al. (2015).

2.4. Geostatistical analysis

Based on the moisture values at each sampling point, considering the four quadrants (north, south, east, and west) and the different longitudinal and lateral stack positions, it was possible using geostatistics to check the spatial variability of the moisture content of stacks based on the analysis of semivariograms adjusted by the Gstat Package (Pebesma, 2004), and by applying the ordinary kriging interpolator method. Adjustments were made by the weighted least squares method, which consists in the adoption of the division of the mean square error by the number of pairs of points at each distance in the semivariogram, causing weighting of the semivariance, since the weighting by variance of estimates is not known. Thus, the method included minimizing the function according to Equation 1 (David, 1977).

$$Q(\theta)=\frac{\sum_{i=1}^{k}\left[g\left(h_j\right)-y\left(h_j;\theta\right)\right]^2}{m\left(h_j\right)} \tag{1}$$

Table 1. Storage period, pile volume, and number of sampling points per wood chip pile.

	Storage period (days)	Pile Volume (m^3)	No. of samples
Pile 1	7	7.50	174
Pile 2	30	6.57	150
Pile 3	60	7.51	172

Where, θ represents the vector of estimated parameters that define the semivariogram, with each estimate denoted by $g\left(h_j\right)$; k refers to the number of "lags" of the semivariogram.

Quantity $y\left(h_j;\theta\right)$ is the semivariance calculated by the model and depends on estimated parameters θ, and, after minimization, the function becomes the estimation of the least squares. m(hj) represents the pairs of points at each distance in the semivariogram (David, 1977).

The correlation function used was an exponential model, as shown in Equation 2:

$$\gamma\left(h\right)=C_0+C_1\left(1-e^{-\frac{3h}{a}}\right),0<\left|h\right|<d \tag{2}$$

Where, γ (h) is the correlation between pairs of points separated by distance h, so that d represents the maximum distance at which the variogram is defined. The analysis of experimental adjusted semivariograms allowed the definition of parameters nugget effect (C_0), range of spatial dependence (a), level (C), contribution (C_1), and degree of spatial dependence of samples (C_0/C).

The classification for soil attributes proposed by Cambardella et al. (1994) was considered for the analysis of the degree of spatial dependence, which in turn considered strong spatial dependence of semivariograms with leveled nugget effect of ≤25%, moderate effect of 25-75%, and weak effect at >75%. Semivariograms and the three-dimensional maps generated were adjusted to the moisture values for each storage period.

3. RESULTS AND DISCUSSION

3.1. Analysis of the moisture content

Table 2 presents the averages, variation coefficients, and the minimum and maximum values of the moisture content of *E. grandis* wood chip piles during stack 7 (i), 30 (ii), and 60 (iii) days of storage.

The average moisture content of wood chips is in accordance to the 44–66% range (wb) as reported by Gejdos et al. (2015) for newly processed materials of two different species, Norway spruce (*Piceaabies* L.) and silver fir (*Abies alba* L.). This range is also in accordance with values verified by Thörnqvist & Jirjis (1990) in Sweden with wood chips stored in stacks of

90 m in length, 14 m in width, and 7 m in height, in the open air without any external ventilation. The authors found average value of 38.8% wb for chips stored for approximately 7 days, 32.8% wb for those stored for 30 days, and 35.7% wb for those stored for 60 days. The variation in these values can be attributed to the moisture content of particulate materials affected mainly by the regional climatic conditions, size of particles and storage method (Barontini et al., 2014; Gejdos et al., 2015; Jirjis, 2005; Manzone et al., 2013) as well as by the physical structure and anatomy of the species that influenced water loss.

An average reduction of 4.22% was observed in the moisture content for piles stored for 7 days (collection at the beginning of September) and 30 days (collection at the beginning of October). However, at 30-60 days of storage (collection at the beginning of November), an increase of 30.32% in the average moisture content was observed, resulting in 24.82% moisture increase at the end of 60 days (Table 2). The increase in moisture content of wood chips from 30 days of storage occurred due to precipitation rates in this period, as illustrated in Figure 1.

Table 2. Average values, minimum and maximum values, and variation coefficient in the moisture content of wood chip pile at different storage periods.

Pile	MC_{Wb} (%)	Minimum (%)	Maximum (%)	CV (%)
i	49.04	11.05	183.54	45.46
ii	46.97	10.30	225.28	56.47
iii	61.21	13.81	284.29	34.86

Where, i = pile with 7 days of storage; ii = pile with 30 days of storage; iii = pile with 60 days of storage; MC_{Wb} = moisture content wet basis; Minimum and Maximum in dry basis; CV = variation coefficient.

Pluvial precipitation during the storage period (September to November) was intense considering the annual distribution (Figure 1). In addition, rains were concentrated mainly in the beginning of November, precisely in the period of pile sampling of 60 days, reaching values of 57 mm/day.

Afzal et al. (2010) observed that in the biomass of *Betula papyrifera* chips stored without cover and exposed to environmental conditions during 12 months, the moisture content increased continuously during the entire storage period from 59% to 160% (dry basis).

The interaction between moisture content and pluviometric indexes may have been intensified by the size of biomass particles, since size directly influences the behavior of the material and the intensity of changes in its chemical, physical, and energetic properties throughout the storage period. Generally, the smaller the particle size, the greater the magnitude of effects of these variations (Brand et al., 2014).

The storage period in this study was insufficient for studying the drying process of wood chips from the energy production point of view due to the influence of high rainfall, which is linked to increase in moisture content. Therefore, particulate materials should be stored in the driest months, between the end of the autumn and early winter. In addition, the lower exposure of chips to environmental conditions, depending on the storage period, could reduce the period of the material, facilitating the management process. The coverage of storage structures may help avoid the interaction between moisture content and regional rainfall in order to achieve positive energy balances. However, Pari et al. (2015) verified that the coverage of chip stack stored in poplar wood with

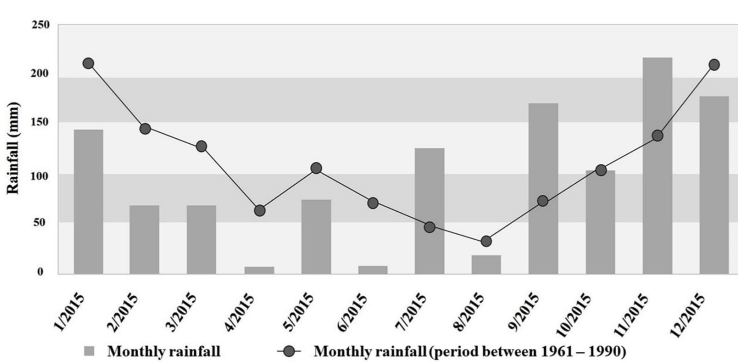

Figure 1. Monthly Accumulated Rain × Normal Climatological between 1961 and 1990 in the city of Sorocaba in 2015. Source: Instituto Nacional de Meteorologia (INMET, 2015).

uniform dimensions did not lead to any significant improvements in the final quality of stored material, although covered materials presented higher low heating values in relation to uncovered material.

The effect of cover on piles depends on the regional climatic conditions. In countries such as Ireland and Finland, the coverage of woodpiles during the wet season, which includes the entire winter and autumn seasons, represent a significant effect on the moisture content of the stored material, so that the coverage of materials could reduce 6% the moisture content in relation to that of uncovered piles (Nurmi & Hillebrand, 2007).

3.2. Analysis of the spatial continuity

Figure 2A, B, and C show semivariograms adjusted for the analysis of the spatial dependence among sampling points of chip piles after 7, 30, and 60 days of storage, respectively.

The plotting of semivariograms provided data to obtain parameters such as reach heights and nugget effect or “nugget” (tausq), which are required for the interpolation of sample data (Table 3). By analyzing semivariograms, it was possible to obtain the parameters reach, plateau and nugget effect or “nugget” (tausq), which information is necessary for the interpolation of sampling data.

The nugget effect value, as indicated by the value on the Y-axis intercept of the semivariogram for piles i and ii, was lower than the baseline value (Table 3). This result indicates a spatial correlation among moisture levels in piles stored for 7 and 30 days, and suggest that geostatistics is a useful tool for the determination of the ideal distance between samples.

However, in pile iii, the nugget effect value was higher than that obtained at baseline, which in turn indicates greater variance of the estimate and, consequently, lower spatial dependence.

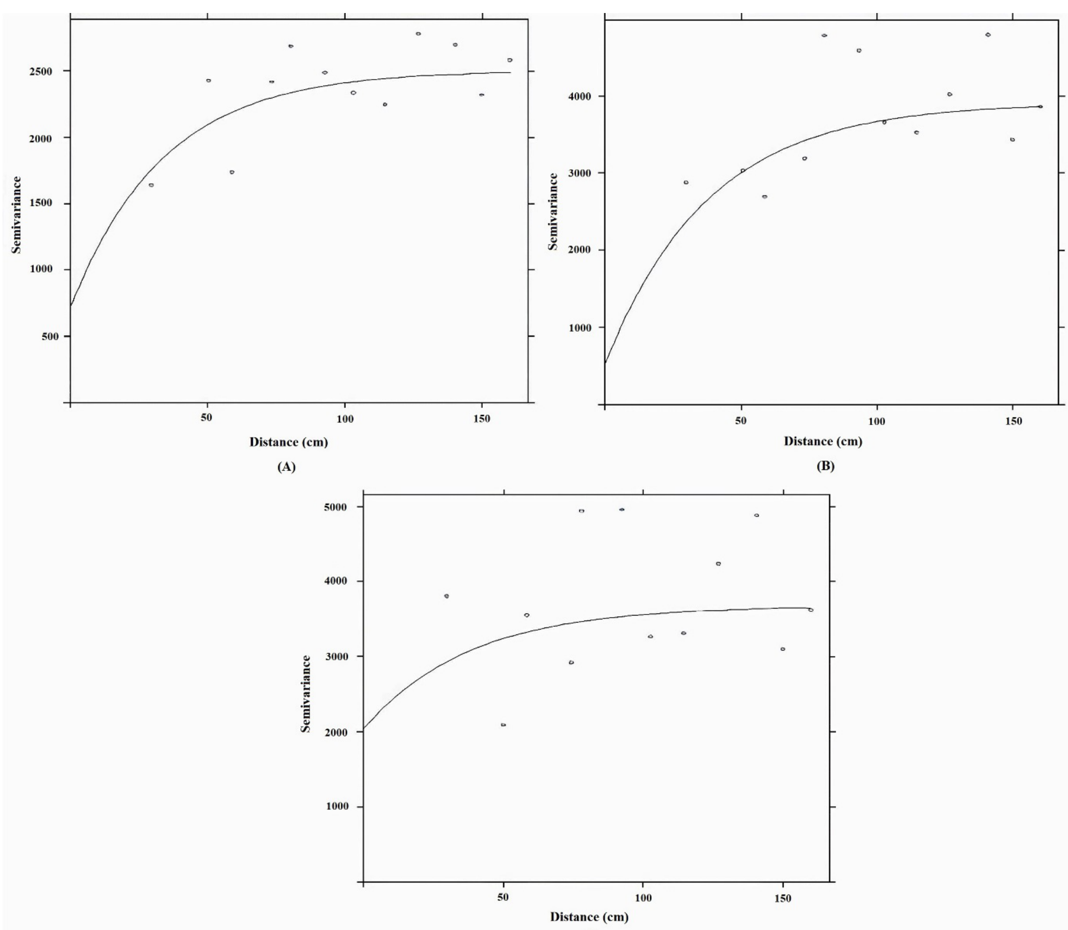

Figure 2. (A) Semivariogram of woodchip pile after 7 days of storage; (B) 30 days of storage; (C) 60 of storage.

Table 3. Parameters obtained by adjusting the exponential model functions of the experimental semivariogram set to woodchip piles after 7 (i), 30 (ii), and 60 (iii) days of storage.

Pile	C	C_0	C_1	a	GDE
i	1784,77	718.04	1066,73	101.43	0.40
ii	3389,39	522.29	2867,10	113.73	0.15
iii	1636,15	2038,98	-402,83	**	1.25

Where, C_0 = nugget effect; C = baseline; C_1 = contribution = C - C_0; a = range (cm); GDE = degree of spatial dependence; **values not estimated.

Another important factor for the interpretation of the semivariogram is the determination of the reach, which represents the distance started in the origin, continuing until the extent to which the plateau reaches stable values. Its determination expresses the distance from which the sampling points are not spatially correlated among themselves, becoming random (Landim, 2006). Based on results generated for the range (a) (Table 3), it could be observed that, at 101.43 cm distance from the sample collection point, the moisture content values of wood chips become independent of the distance, and not spatially correlated after 7 days of storage. By day 30 of storage, values separated from 113.73 cm in the pile were not spatially correlated. This important result may subsidize the decision regarding the correct and efficient sampling strategy of chips stored in piles to determine their moisture content.

The contribution is the semivariogram area where there is spatial dependence, which is determined by calculating the difference between the baseline and the nugget effect, with a scope for spatial dependence. The negative value of this parameter evidenced in pile iii indicates low spatial correlation due to the random nature of sampling units regarding the moisture content of wood chips, assumed, probably due to the high rainfall during the 60 days of storage, which resulted in homogenization of moisture content values, giving the lowest variance of the estimate.

After defining the values of the semivariogram parameters (Table 3), the degree of spatial dependence (DGE) or the nugget effect coefficient (CEP) could be determined by means of the ratio between the nugget effect and the baseline. According to classification described by Cambardella et al. (1994), the degree of dependence obtained for the first pile was moderate (≥0.25 and <0.75). For pile samples after 30 days of storage, the degree of spatial dependence was considered to be strong once the nugget effect became <25% of the baseline value; however, for pile sampled after 60 days of storage, the spatial dependence was weak, with the relation between the nugget effect and the baseline being >75%.

Figure 3 illustrates the graphical representation obtained by moisture content values of wood chips after 7 (A), 30 (B) and 60 days (C) of storage via kriging interpolation from the adjustment of the exponential model.

Visual observation of the graph in Figure 3A shows that, in a short storage period, moisture content variation was high. There was a clear trend of reduction in moisture values from the base to the top of the pile and from the central region to the periphery.

The visual analysis of the graph in Figure 3B verifies the existence of more defined classes of moisture content after 30 days of storage than after 7 days of storage. It could be observed that the variation pattern in the moisture content of wood chip piles after 30 days of storage is similar to that obtained after 7 days of storage, demonstrating that the highest moisture content values were obtained in the basal and the central regions of the structure.

However, the drying effect was more homogeneous and without any significant effects of prevailing winds in the study area after 30 days.The visual analysis of graph in Figure 3C indicates a significant increase in the moisture content after 60 days of storage due to high rainfall accumulation during the storage period. Notably, there is no standard established for moisture content variations, so that significant parts of piles show high values of this physical property. It is possible to see that moisture has penetrated into the whole extension of the pile, causing wetting, including in previously dried areas.

The mapping of the moisture content in piles brings practical information of sampling points that truly

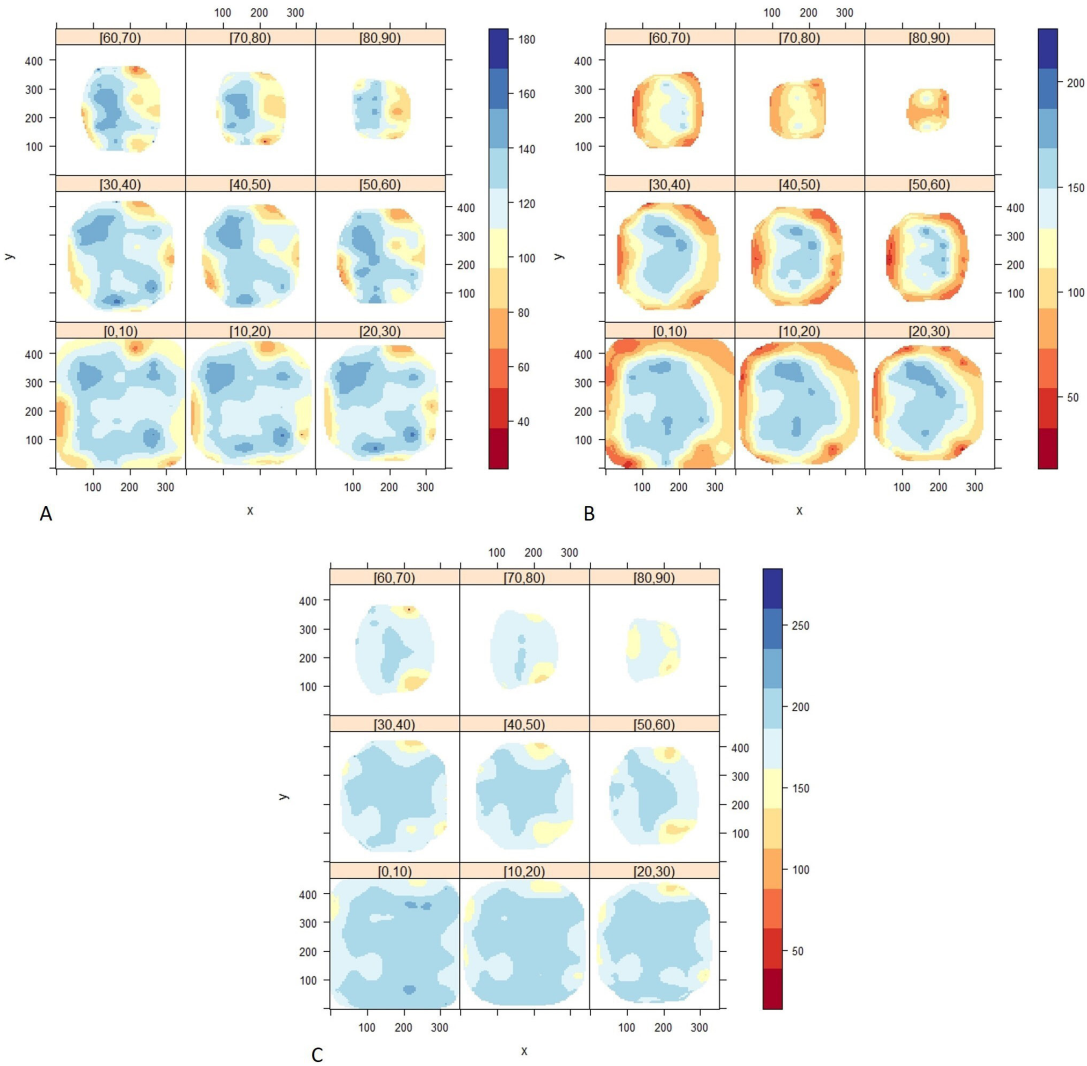

Figure 3. Graphical representation of woodpile moisture after 7 (A), 30 (B) and 60 days (C) of storage, showing variation in the moisture content at every 10 cm in height of the storage structure.

represent the average of this property in the structure, which serves as a subsidy for representative sampling of piles. In addition, geostatistics allows visualization of the moisture content variation pattern of wood chips in a pile, which is important information for energy production, considering that an ideal fuel has low and constant moisture content.

4. CONCLUSION

Spatial dependence of moisture content values was observed in the wood chip pile after 7 and 30 days of storage, indicating that geostatistics is a useful tool for the determination of the ideal distance between samples.

Despite the increase in the spatial dependence during the 30 days of storage, this factor decreased with an increase in the storage period due to the high rainfall accumulation during the 60 days of exposure, causing greater moisture homogeneity in piles.

Based on the graphs of moisture distribution in piles, it was possible to verify that chips are subject to wetting even in the innermost parts of the structure, in function of the high pluviometric indexes.

From results obtained in this work, studies related to energy gains generated by the use of coverings during the storage of material should be developed, in addition to their technical and economic feasibility.

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REFERENCES

Afzal MT, Bedane AH, Skohansanj S, Mahmood W. Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. *BioResources* 2010; 5(1): 55-69.

Barontini M, Scarfone A, Spinelli R, Gallucci F, Santangelo E, Acampora A et al. Storage dynamics and fuel quality of poplar chips. *Biomass and Bioenergy* 2014; 62: 17-25. http://dx.doi.org/10.1016/j.biombioe.2014.01.022.

Brand MA, Muñiz GIB, Brito JO, Quirino WF. Influence of size and shape of forest biomass, stored in piles, on quality of wood fuel. *Revista Árvore* 2014; 38(1): 175-183. http://dx.doi.org/10.1590/S0100-67622014000100017.

Cambardella CA, Moorman TB, Parkin TB, Karlen DL, Novak JM, Turco RF et al. Field-scale variability of soil properties in Central Iowa soil. *Soil Science Society of America Journal* 1994; 58(5): 1501-1511. http://dx.doi.org/10.2136/sssaj1994.03615995005800050033x.

Daassi-Gnaba H, Oussar Y, Merlan M, Ditchi T, Géron E, Holé S. Wood moisture content prediction using feature selection techniques and a kernel method. *Neurocomputing* 2017; 237: 79-91. http://dx.doi.org/10.1016/j.neucom.2016.09.005.

David M. *Geostatistical ore reserve estimation*. Amsterdam: Elsevier; 1977.

Donato DB, Castro RVO, Carneiro ACO, Carvalho AMML, Vital BR, Teixeira RU. Teor de umidade da madeira em tora. *Scientia Forestalis* 2015; 43(107): 703-712.

Eleotério JR, Kirchheim da Silva CM, Quintino A, Stramosk AC, Kiefer R. Qualidade da biomassa florestal comercializada no Vale do Itajaí, SC. *Revista Floresta* 2017; 47(2): 213-220. http://dx.doi.org/10.5380/rf.v47i2.42655.

Erber G, Kanzian C, Stampfer K. Predicting moisture content in a pine logwood pile for energy purposes. *Silva Fennica* 2012; 46(4): 555-567. http://dx.doi.org/10.14214/sf.910.

Gejdos M, Lieskovsky M, Slancik M, Nemec M, Danihelova Z. Storage and fuel quality of coniferous wood chips. *BioResources* 2015; 10(3): 5544-5553. http://dx.doi.org/10.15376/biores.10.3.5544-5553.

Instituto Nacional de Meteorologia – INMET. *Estações automáticas: rede de estações meteorológicas de observação de superfície automática* [online]. 2015 [cited 2015 Apr 6]. Available from: http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesAutomaticas

Jirjis R. Effects of particle size and pile height on storage and fuel quality of comminuted *Salix viminali. Biomass and Bioenergy* 2005; 28(2): 193-201. http://dx.doi.org/10.1016/j.biombioe.2004.08.014.

Kumar A, Kumar N, Baredar P, Shukla A. A review on biomass energy resources, potential, conversion and policy in India. *Renewable & Sustainable Energy Reviews* 2015; 45: 530-539. http://dx.doi.org/10.1016/j.rser.2015.02.007.

Landim PMB. Sobre geoestatística e mapas. *Terrae Didactica* 2006; 2(1): 19-33. http://dx.doi.org/10.20396/td.v2i1.8637463.

Manzone M, Balsari P, Spinelli R. Small-scale storage techniques for fuel chips from short rotation forestry. *Fuel* 2013; 109: 687-692. http://dx.doi.org/10.1016/j.fuel.2013.03.006.

Nikolaevich A, Mikhajlovich O, Mikhajlovna V, Jurij N, Medjakov A. The study of biomass moisture content impact on the efficiency of a power-producing unit with a gasifier and the stirling engine. *Journal of Applied Engineering Science* 2016; 14(3): 401-408. http://dx.doi.org/10.5937/jaes14-11010.

Nurmi J, Hillebrand K. The characteristics of whole-tree fuel stocks from silviculture cleanings and thinnings. *Biomass and Bioenergy* 2007; 31(6): 381-392. http://dx.doi.org/10.1016/j.biombioe.2007.01.010.

Pari L, Brambilla M, Bisaglia C, Del Giudice A, Croce S, Salerno M et al. Poplar wood chip storage: effect of particle size and breathable covering on drying dynamics and biofuel quality. *Biomass and Bioenergy* 2015; 81: 282-287. http://dx.doi.org/10.1016/j.biombioe.2015.07.001.

Pebesma EJ. Multivariable geostatistics in S: the gstat package. *Computers & Geosciences* 2004; 30(7): 683-691. http://dx.doi.org/10.1016/j.cageo.2004.03.012.

Thörnqvist T, Jirjis R. *Changes in fuel chips during storage in large piles*. Upsalla: Swedish University of Agricultural Sciences, Department of Forest Products; 1990. Report no. 219.

Verma M, Loha C, Sinha AN, Chatterjee PK. Drying of biomass for utilising in co-firing with coal and its impact on environment – a review. *Renewable & Sustainable Energy Reviews* 2017; 71: 732-741. http://dx.doi.org/10.1016/j.rser.2016.12.101.