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MODELLING SPATIAL VARIABILITY OF SOIL CHEMICAL ATTRIBUTES IN *TECTONA GRANDIS* STANDS IN CENTRAL-WEST BRAZIL

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The present study aimed to apply geostatistics to characterise spatial variability of chemical soil properties in a homogeneous teak stand. We plotted 91 samples in an area of 467 ha, sampling the soil at 0–20 cm depth for modelling spatial patterns of soil properties by semivariograms, interpolating and spatialising data by the ordinary point kriging method. Spatial variability of chemical soil properties varied in the area and can be precisely and efficiently modelled by geostatistics. We generated thematic maps for soil properties which were able to identify zones with nutritional deficiencies for teak, according to the recommended levels for the species. Evaluation of the site quality index according to the dominant height of trees revealed that the better site indices were in areas with higher concentrations of calcium and pH. Geostatistics proved to be suitable for the definition of homogeneous strata in teak stands. It can be used as an alternative method to regulate natural soil fertility in function of physiological requirements of the species, leading to a balanced input usage by forest producers and mitigation of environmental impacts.

Keywords: Geostatistics, teak, soil variability, precision forestry, nutritional deficiencies

INTRODUCTION

Teak (*Tectona grandis*) occurs predominantly in tropical and subtropical regions (Zuhaidi Yahya et al. 2011). It is native to southern and south-eastern Asia, occurring naturally in India, Myanmar, Laos and Thailand (Fermino Junior et al. 2009). Teak is cultivated in Africa, South America and Central America and has great importance in the tropical wood market (Bermejo et al. 2004). Besides its wood value, teak has high yield and can adapt to different ecological zones. This makes teak suitable for recovery of desertified or deforested areas (Wahounou et al. 2017).

Relation between the development of forests and edaphic characteristics are commonly described through traditional sampling techniques, generally using mean as a measure of central tendency and variance as a measure of dispersion for each sample units. However, these techniques do not consider the spatial relationships between sample units. Understanding the spatial variation of soil chemical attributes is important for efficient forest management and high productivity (Rufino et al. 2006, Pelissari et al. 2014). In this context, using geostatistics as a precision silviculture technique, it is possible to identify spatial relations between factors (soil conditions, temperature and precipitation) that limit yield and productivity of forest stands (Pelissari 2012).

Precision silviculture represents a management model based on collection and analysis of geospatial data (Ribeiro 2004). It allows the prediction of chemical properties of the soil in non-sampled areas. The primary use of these data is to achieve nutritional management and environmental pollution control, increasing forest productivity and efficiency for sustained management (Nourzadeh et al. 2012). Since spatial modelling can be useful in teak management, the present study was aimed at applying geostatistics to characterise spatial variability of chemical properties of a homogeneous teak stand located in the city of Brasnorte, Mato Grosso State, Brazil.

MATERIALS AND METHODS

The study was carried out in two homogeneous teak plantations, one was 216.4 ha and planted in 1998 and the other, 250.6 ha in 1997. The plantation areas, initially composed of native Amazon forest, are owned by the Berneck Company located in the city of Brasnorte, Mato Grosso State, Brazil (Figure 1). Soil was disked before establishing the plantations. There was no fertilisation or pH correction in both plantations evaluated, except in the latter, phosphate fertilisation was applied in the third year after planting because the plants did not grow well. In 2010, mechanical thinning (removing the sixth line) was carried out in both stands together with selective thinning (removing the less developed and diseased trees) at an intensity of 40%.

The region has a warm and humid equatorial climate, with temperatures varying between 4 and 40 °C depending on the season of the year. Rainfall is distributed between November and March, with an average of 2250 mm year^{-1} (Campello Junior et al. 1991). Classification of the soil in the study is Red Latosols and the terrain is slightly wavy (EMBRAPA 2006).

Plantation areas evaluated were initially divided into a grid with plots of 20 m × 30 m. From this division, systematic selection was used to choose the plots for evaluation in every 5.13 ha, totalling 91 sampling plots georeferenced using a receptor GPS. In the centre of each plot, we collected soil samples at a depth of 0–20 cm. Soil properties determined were pH in H_2O, aluminum (Al), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Determination of the soil properties followed the methodology recommendations by EMBRAPA (1997). We performed a descriptive analysis of the soil properties and verified the normality of data using Kolgomorov–Smirnov test at 5% level of significance.

Verification of the spatial dependence of chemical attributes under study was done by determining the semivariances. The factors considered were the position of soil collection point in each plot (x, y), distance computation (h) and the numerical differences of each soil properties evaluated (Z) in the point grid. The spherical, exponential and Gaussian semivariograms (Table 1) were adjusted to model the spatial patterns using the software GS + 7.0. With the data, we generated thematic maps using software Surfer 11.0. Interpolation and spatialisation was obtained by ordinary punctual kriging method, which considered

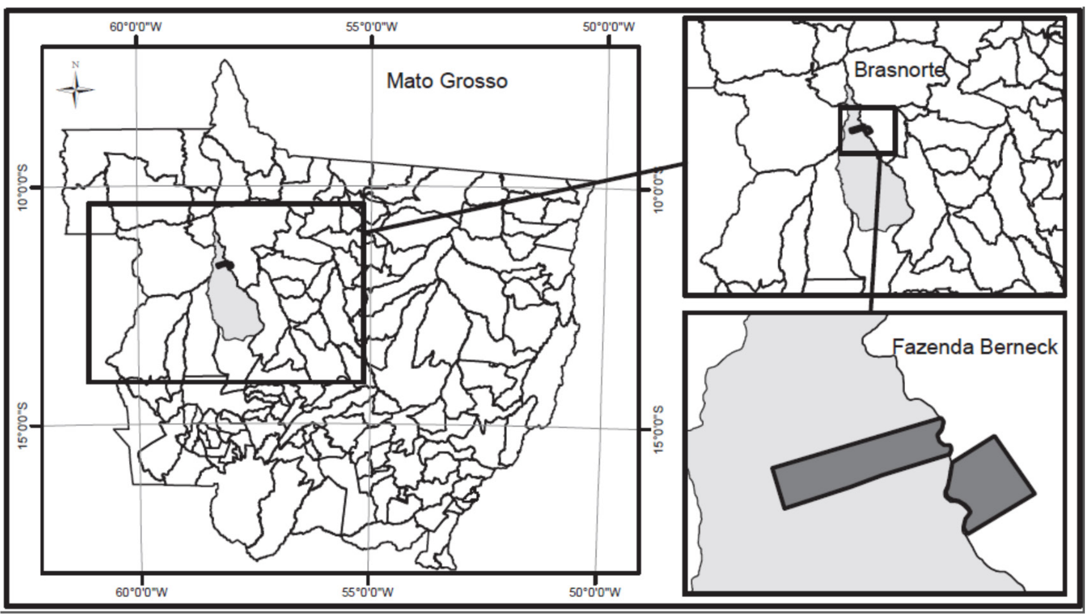

Figure 1 Location of the stand of *Tectona grandis* located in Brasnorte, Mato Grosso State, Brazil

Table 1 Semivariograms models adjusted for chemical attributes of the soil in *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil

Model	Denomination
$\gamma(h) = C_0 + C \times \left[\left(\frac{3}{2}\right) + \left(\frac{h}{A}\right) - \left(\frac{1}{2}\right) + \left(\frac{h}{A}\right)^3\right]$	Spherical
$\gamma(h) = C_0 + C \times (1 - e^{-h/A})$	Exponential
$\gamma(h) = C_0 + C \times (1 - e^{-h^2/A^2})$	Gaussian

γ(h) = semivariance of each soil properties evaluated, C_0 = nugget effect, C = sill, A = reach, h = distance, e = exponential

spatial dependence and generated estimates without trend and with minimum variance (Corá & Beraldo 2006).

To determine the soil spatial characterisation of production capacity, we used a non-linear model to estimate the dominant height (H_{dom}) of trees in each age category (Chapman 1961, Richards 1959):

$$H_{dom} = 22{,}75251(1 - e^{0.17971})^{1.06819}$$

The adjustment has an adjusted coefficient of determination of 0.65 and standard error of 18.45%. Based on this first adjustment for the data and on the guide curve method, site index curves were performed for reference age of 19 years. We considered three site index curves—in each, the dominant height expressed the site index. Thus, the sites were stratified in three classes following Vásquez and Ugalde (1995), with sites of high, medium and poor quality. For the geostatistical modelling, the site index of the reference age was applied as variable Z, with interpolation and spatialisation of the sites through punctual ordinary kriging.

RESULTS AND DISCUSSION

Table 2 presents the descriptive analysis of the chemical attributes. None of the variables presented normal distribution, with data of K and Ca transformed by ln(x), and of pH by $\sqrt{x}$. Aluminum and P presented a non-normal distribution data and these were used in their original scales, since data normality was not a geostatistical assumption (Azevedo & Dalmolin 2004, Pelissari 2012). However, estimation by kriging method presents better results when the normality of data is corrected (Paz-Gonzalez et al. 2001).

Mean pH was 5.22 ± 0.48 (Table 2), indicating that the soil samples were slightly acidic for the species, limiting the growth of the trees in comparison with the growth of other plantation areas in the region. Teak prefers soils with pH ranging from 6.5 to 7.5. Teak cultivated in soils with pH lower than 5.5 shows limited growth due to reduction in the availability of several essential elements in the soil (Bertsch 1998, González 2010).

In the study sites, there was no chemical fertilisation incorporating K. Potassium content was 24.82 ± 10.15 mg dm^{-3}, which was higher than the critical limit established by Mollinedo (2003) and Alvarado et al (2014), i.e. 4.5 and 5.0 mg dm^{-3} respectively. In the same region of this study, K content in a 2-year-old teak stand was 132.3 ± 39.49 mg dm^{-3}. Although the K content was above the critical levels, the area was still amended with K fertilisation (100–150 kg ha^{-1} of potassium chloride) when the trees were 9 years old (Pelissari 2012). Nutritional requirements of teak are in the following order: K > Ca > N > P > Mg, and such requirements increase with the age of the trees (Alvarado 2006).

Phosphorus levels below 0.5 mg dm^{-3} are harmful for the development of teak (Mollinedo 2003). The mean of P for the study area was 1.58 ± 1.96 mg dm^{-3}. Variation was high due to the phosphate fertilisation applied at some areas (plantation of 1997) in the third year after planting. The area with the lowest P content had 0.6 mg dm^{-3}, and the area with the highest, 14.4 mg dm^{-3}. However, all soil samples analysed presented P concentration above the critical level established by Mollinedo (2003).

Teak has high demand for Ca and responds significantly to the addition of this nutrient in the soil (Matricardi 1989). Mean Ca content for soil samples in the study area at 0 to 20 cm in depth was 1.97 ± 1.50 cmol dm^{-3}. The content of Ca in this study was below the critical limit established by Mollinedo (2003) and Alvarado et al (2014), i.e. 10 cmol dm^{-3} for the first soil horizon. In the sampled area, 75% of the samples had ≤ 2.71 cmol dm^{-3} of Ca and that the maximum value concentration was 6.88 cmol dm^{-3}. With the high requirement of teak for Ca, we concluded that the soil was lacking in this nutrient to allow for a satisfactory production.

Small amounts of Mg are sufficient to satisfy the requirements of teak (Matricardi 1989). Sites having Mg contents < 5.0 cmol dm^3 will have negative effects on the growth of teak (Mollinedo 2003) but Alvarado et al. (2014) suggested an even lower minimum value, i.e. 3.0 cmol dm^3. Average Mg observed in the samples of the present study was 0.75 ± 0.52 cmol dm^{-3}. No samples had Mg higher than the critical limit established by Mollinedo (2003) and Alvarado et al. (2014).

As a calcareous species, teak is remarkably sensitive to high Al contents (Matricardi 1989) and can have low productivity in sites with Al contents higher than 1.3 cmol dm^{-3} (Vaides López, 2004). Average Al in the study area was 0.20 ± 0.20 cmol dm^{-3}, which was below the critical limit established by Vaides López (2004). In the same region, Pelissari (2012) observed values similar to those obtained in the present work.

Among the geostatistical models, spherical and exponential models provided better adjustment for the data (Table 2). Nugget effect was low for all chemical attributes, indicating satisfactory semivariogram adjustments except for K, which presented a nugget effect of 38.3. For the soil properties analysed, we observed a minimum range of 253 m and a maximum range of 2968 m for spatial amplitude correlation between observations. The spatial amplitude correlation using geostatistical techniques expresses the optimal distance that can result in more precise estimations (Chig et al. 2008). The software GS + adopts as the initial criterion 80% of the maximum distance. The justification for this is that with great distances, the number of pairs for the semivariance calculation drastically decreases, causing low precision of semivariance estimation.

Of the chemical attributes evaluated, Ca and Mg showed strong spatial dependence, while the rest presented moderate spatial dependence. Coefficients of determination (r^2) of the semivariograms were higher than 0.90 for Al, K and Ca, demonstrating appropriate adjustments of the semivariograms to estimate these attributes in non-sampled sites of the teak stands. Although pH, P and Mg presented r^2 values lower than the rest of the elements, their sum of squares residuals were low (Table 3). This suggests proper adjustment, as the lower residuals, the better the semivariogram model (Guimarães 2004). Semivariogram models adjusted in this study had linear coefficients (represented by 'a' in Table 3) close to zero, except for K, with a = 1.605 and high angular coefficient (represented by 'b' in Table 3) of 0.932. Cross-validation coefficients of determination were low and moderate, ranging from 0.15 for Mg to 0.28 for pH (Table 3). The cross-validation coefficients of determination were determined by comparing actual sampled data with those estimated using regression. Low cross-validation coefficients occurred due to scattered soil properties in the sampled area. However, the low cross-validation coefficients are not necessarily incorrect (Andriotti 2003). Similar results are commonly found in spatial modelling of soil attributes (e.g. Carvalho 2012, Bottega et al. 2013).

After the adjustment of the semivariograms, observation of spatial dependence and absence of

Table 2 Descriptive analysis of soil chemical attributes in *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil at depth of 0 to 0.2 m

Attribute	Min	1° quartile	Mean	Median	3° quartile	Max	S_x	CV%
pH	4.4	4.9	5.22	5.1	5.6	6.5	0.48	9.37
K	10	18	24.82	22	29	69	10.15	40.93
P	0.6	0.9	1.58	1.1	1.6	14.4	1.96	124.06
Ca	0.25	0.84	1.97	1.55	2.71	6.88	1.49	75.97
Mg	0.14	0.38	0.75	0.63	0.97	3.12	0.51	68.53
Al	0	0.06	0.20	0.13	0.38	0.81	0.20	98.75

S_x = Standard deviation, CV% = coefficient of variation

Table 3 Estimation of parameters of the semivariograms models adjusted for the variables pH(H_2O), potassium (K) (mg dm^{-3}), phosphorus (P) (mg dm^{-3}), calcium (Ca), magnesium (Mg) and aluminium (Al) (cmol dm^{-3}) in *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil at depth of 0 to 0.2 m

Attribute	Model	C_0	$C_0 + C$	R (m)	SD(%)	Class	r^2	SSR	Cross-validation		
									a	b	r^2_{cv}
pH	Spherical	0.101	0.246	861.0	41.25	Moderate	0.77	2.37^{-03}	0.328	0.936	0.28
K	Spherical	38.30	77.040	2968.0	49.71	Moderate	0.96	26.8	1.605	0.932	0.22
P	Exponential	0.047	0.183	271.0	25.90	Moderate	0.64	1.76^{-03}	0.022	0.981	0.18
Ca	Exponential	0.472	2.309	253.0	20.44	Strong	0.91	0.062	0.210	0.887	0.24
Mg	Spherical	0.025	0.162	529.0	15.43	Strong	0.59	2.04^{-03}	0.253	0.635	0.15
Al	Spherical	0.022	0.046	1783.0	48.36	Moderate	0.96	1.73^{-05}	0.004	1.030	0.24

C_0 = nugget effect, $C_0 + C$ = sill, R = range, SD = degrees of spatial dependence, r^2 = coefficient of determination, SSR = sum of squares residuals, a = linear coefficient, b = angular coefficient, r^2_{cv} = cross-validation coefficient of determination

anisotropy of chemical properties, we conducted interpolation using ordinary punctual kriging to plot spatial distribution of the chemical attributes of the soil (Figure 2). We observed that in the central and southern regions of the area, pH values were above the critical limit indicated by González (2010), whereas in the east, west and north, the values were below the critical limit. Although no soil correction was performed for the implantation of the teak stand, with the spatial distribution of pH, it would be possible to recommend localised corrections in the area to reduce soil acidity to benefit the management and yield of teak stands.

Potassium and P levels in the study area were higher than those indicated for teak stands in Panama (Mollinedo 2003). Potassium was highest in the south while P, in the north and west of the study area. The Ca and Al maps were inversely proportional. The central and south regions of the area had the most abundant and smallest concentrations of these nutrients respectively. Magnesium levels in the study area were below the values reported by Mollinedo (2003), with the highest concentration of Mg in the central region (< 4.39 cmol dm^{-3}).

Comparing thematic maps of Ca and pH and site indices maps, it was clear that the better sites for planting teak were in the regions with high pH and Ca concentration. On the other hand, when Al concentration increased, the site index quality decreased (Figure 3). The site indices ranged from 11.0 to 33.5 m (Table 4), with most of the areas presenting an average site index similar to that reported by Vásquez and Ugalde (1995) and Mollinedo et al. (2016) in other regions with teak stands. By the analysis of soil properties and tools applied in this study, it is possible for forest producers to manage the soil to ensure better conditions for growth of trees, especially when management is specific to some areas that need amendments in soil nutritional levels and acidity (Alvarado et al. 2014).

CONCLUSIONS

Geostatistics proved to be a reliable alternative technique for the zoning of plantation areas of *Tectona* and other species. Understanding the spatial variability of chemical attributes of the soil is essential for the adoption of silvicultural and management practices for production of *T. grandis*. In this context, the use of geostatistics presented statistical precision and efficiency to display the soil properties. Once the soil conditions are detected by geostatistics, silvicultural and management practices can rationalise the use of inputs to regulate soil fertility and acidity with the aim of improving volume production according to zoned areas. Once the soil matches the physiological requirements of the species, the costs of nutrients and silvicultural practices are reduced. Environmental impacts are also reduced by the use of the right amounts of nutrients.

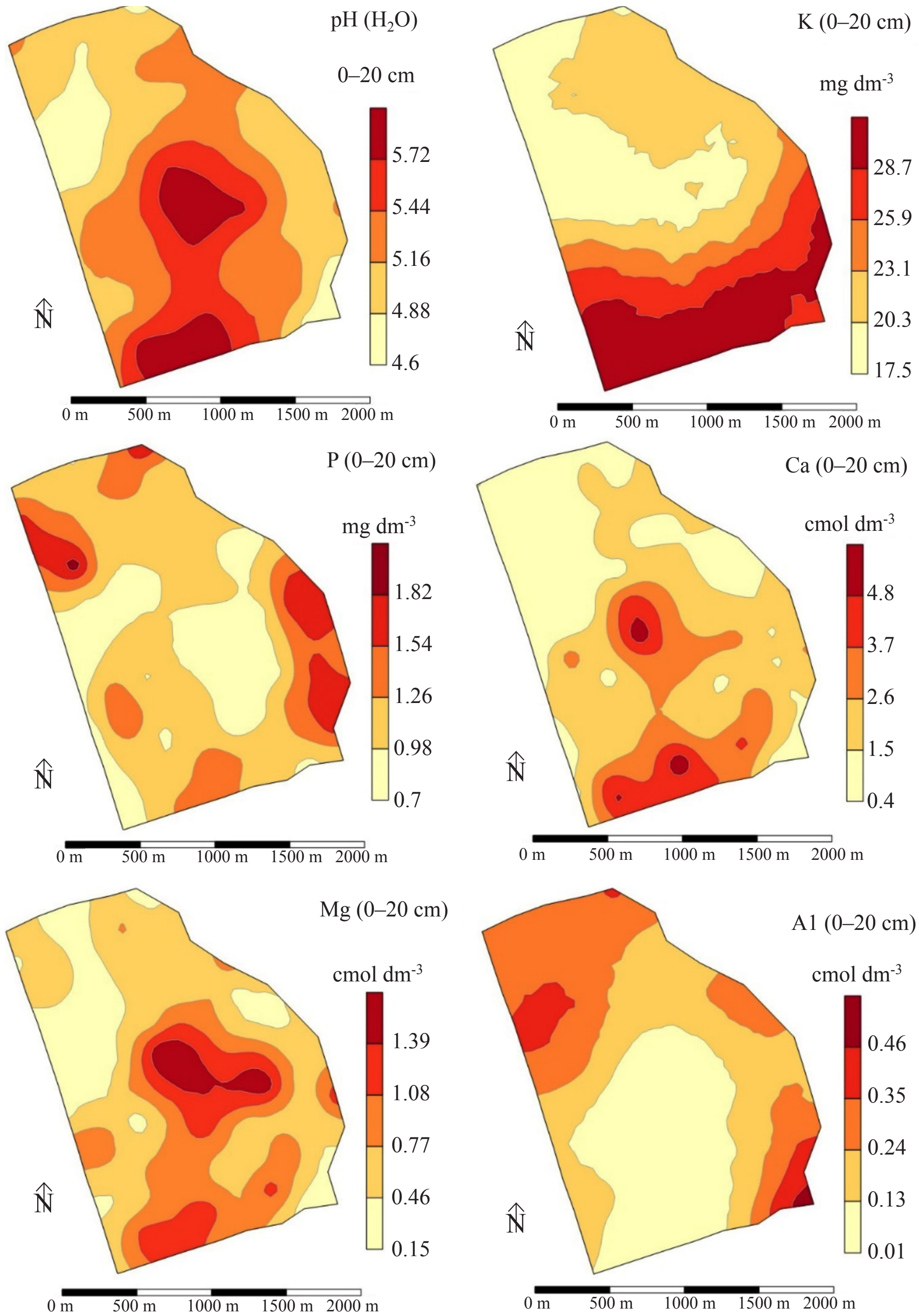

Figure 2 Spatial distribution of pH (H_2O), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg) and aluminium (Al) in *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil at depth of 0 to 0.2 m

Table 4 Site index classification for the sampled plots in the *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil

Site index	Amplitude (m)	Plots (n)	Percentage of the plot area (%)
High	≥ 26.0 < 33.5	2	2.20
Medium	≥ 18.5 < 26.0	17	18.68
Low	≥ 11.0 < 18.5	72	79.12

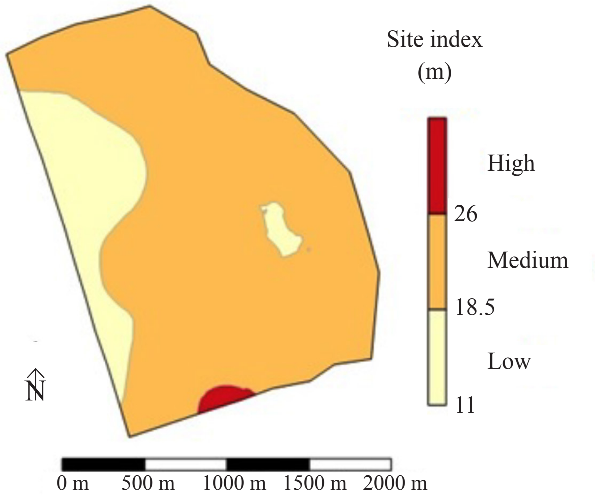

Figure 3 Spatial distribution of the three site indices for *Tectona grandis* stands in Brasnorte, Mato Grosso State, Brazil

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