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Diagnosis of the Spatial Variability of Soil Nutrients and Economics of Precision Management in Degraded Pastures

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Abstract: Most Brazilian pastures are in some stage of degradation, either by the reduction of soil fertility or inadequate management. The objective of this study was to diagnose the stage of pasture degradation and the diagnosis and management of the spatial variability of available phosphorus (P) and potassium (K^+). A total of 100 soil samples were collected at a depth of 0–20 cm for available P and K^+ contents determination. Geostatistical analyses of the obtained data were carried out to produce maps of the spatial distribution of available P and K^+, using kriging, and allow the recommendation of fertilizers doses. The cost/benefit ratio of fertilizer recommendation and application was evaluated at fixed and variable rates. The different stages of pasture degradation were directly related to the reduction of soil fertility, as well as to the adopted management. The variability of soil available P and K^+ presented spatial dependence, and the pattern of distribution resulted in the stage of the pasture degradation. The diagnosis of the level of pasture degradation associated with the use of geostatistical techniques under a precision agriculture perspective favors the efficient use of fertilizers, as well as correct decision-making and cost reduction regarding soil management.

Keywords: geostatistics; pasture management; precision agriculture; soil fertility

1. Introduction

Livestock farming occupies nearly 20% of the total area of Brazil, corresponding to 156 million hectares covered with pastures [1]. Half of this area is in the process of degradation. Degradation reduces soil quality and influences the soil-plant–animal interface, resulting in low rates of bovine productivity and low economic return [1–5].

Although most of the Brazilian pastures are at some stage of degradation, they are still the basis of cattle production in the country. However, this degradation has resulted in the reduction of forage productivity and is often related to the reduction of soil fertility, which causes a decrease in the carrying capacity of animals and compromises the sustainability and profitability of livestock farming [3,6].

The degradation of pastures is seen as the process that results in loss of vigor, causing productivity and natural forage recovery capacity reduction. It also reduces the ability to overcome the harmful effects of pests, diseases and the development of weeds [3,7,8].

The determination of the stage of degradation of pastures allows the elaboration of diagnosis and provides subsidies for management decision-making to be adopted (recovery

or reform). However, it is very difficult to establish criteria that quantify the degradation of cultivated pastures, given the diversity of the cultivated forage species [3].

The most important factors that result in the degradation of pastures are mainly related to neglected management. Nevertheless, although it is known that degraded soils present high erosion rates, nutrient losses and soil compaction, little is known about how this degradation is reflected in the soil. A relevant factor is related to animal management and inadequate grazing, characterized by excessive stocking rate and lack of nutrient replenishment to the soil, which may be aggravated by water deficit, pest incidence, disease and lack of knowledge on the management of variability of soil properties [2,4,5,8–12].

The knowledge of the spatial variability of the soil properties using geostatistical techniques emerges as a way of establishing the relationship between the degradation of pastures and the reduction of soil fertility, which can help in the decision-making processes and specific management of these areas [4,12–14].

The introduction of geostatistics in the study of the spatial variability of soil properties allows the quantification of the magnitude and spatial dependence degree of the studied variables [15,16]. It also allows the interpretation, projection of the results and a better understanding of the influence of soil properties variability on the production and degradation of pastures over an area of interest [15,17]. Furthermore, through this specific evaluation of soil properties that are related to pastures degradation, precision management can be performed, reducing the costs of soil fertilization and other management practices. Since soils under Cerrado vegetation have low P availability and insufficient K^+ reserve for good crop development [18], in this study, we studied the spatial variability of these two nutrients, using geostatistical and precision agriculture techniques, and its relation with pasture degradation.

In this sense, geostatistical tools are of great importance to aid in the identification of nutrients variability and to determine where to reform or recovery the degraded pastures. The objectives of this study were: (i) to diagnose the pasture degradation stage; (ii) to evaluate the spatial variability of available P and K^+ in soils under pasture in order to support the recommendation of fertilizers application for the implantation and maintenance of grass pastures *Megathyrsus maximus* cv. Mombasa, using geostatistical and precision agriculture techniques; (iii) to access the final monetary costs of fertilizer application at varied rates in comparison to the conventional method (fixed rate).

2. Materials and Methods

2.1. Study Area

The present study was carried out in a representative area under the pastures of the Brazilian Cerrado (Figure 1). The climate of the region is of type Aw, being characterized as a tropical climate, with dry winters, hot and humid, according to the international classification of Köppen [19]. The study was carried out in an area under pasture, located at 11°37.1′48.11″ of latitude South and 49°2′49.28″ of longitude West, at an average altitude of 296 m. The region has an annual average temperature of 26.7 °C and annual rainfall of 1500 mm. The soils of the study area are classified as Oxisols (65.2 ha) and Entisols (5.64 ha), according to the USDA Soil Taxonomy classification system [20].

2.2. Soil Sampling and Laboratory Analyses

A total of 100 soil samples were collected at a depth of 0–20 cm in an area of 70.84 hectares, making up a sampling density of 1.41 samples per hectare. Each sampling site was georeferenced to elaborate the soil fertility maps using geostatistical tools (Figure 1).

The analysis of mean fertility was performed by collecting all samples located on each pasture type and separating them in order to obtain a composite sample based on the conventional method of sampling and recommendation according to Cantarutti et al. [21]. The samples were submitted to fertility analysis according to the methodology of Raij et al. [22] to determine pH, exchangeable calcium (Ca^{2+}), exchangeable magnesium (Mg^{2+}), aluminum or exchangeable acidity (Al^{3+}), hydrogen + aluminum or potential acidity (H + Al),

available phosphorus (P), available potassium (K+), soil organic matter (SOM) and soil sand, silt and clay content (Table 1).
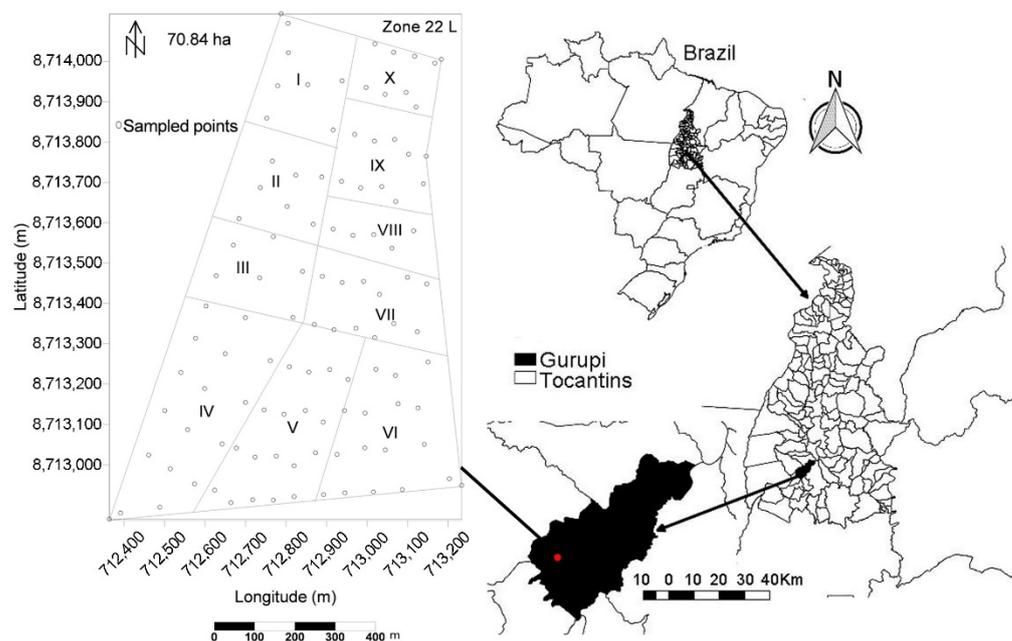
Figure 1. Location of the studied area, sampling grid and pastures identification. Numbers I to X are the evaluated pasture areas.

Table 1. Characterization [a] of the mean fertility of soil by conventional method [b].

Properties	Pastures									
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VII**	**IX**	**X**
SOM (%)	2.60	3.10	2.60	3.10	2.90	2.90	2.60	2.40	2.60	2.10
pH (CaCl$_2$)	5.30	5.00	4.70	4.80	3.50	4.70	4.60	4.80	4.70	5.10
Ca^{2+} (cmol$_c$ kg^{-1})	3.00	2.80	1.70	2.40	3.60	2.10	1.30	1.70	1.90	1.70
Mg^{2+} (cmol$_c$ kg^{-1})	1.30	1.20	0.80	0.90	1.00	0.80	0.60	0.70	0.80	0.70
K$^+$ (mg kg^{-1})	113	78.0	93.6	50.7	66.3	39.0	42.9	58.5	62.4	66.3
P (mg kg^{-1})	18.0	15.0	3.00	9.00	18.8	11.0	2.00	3.00	8.00	35.0
Al^{3+} (cmol$_c$ kg^{-1})	0.00	0.00	0.30	0.00	0.00	0.10	0.20	0.00	0.10	0.00
H + Al (cmol$_c$ kg^{-1})	2.00	2.90	4.00	3.30	2.20	3.60	3.80	2.90	3.10	2.00
SB (cmol$_c$ kg^{-1}) [c]	4.59	4.20	2.74	3.43	4.77	3.00	2.01	2.55	2.86	2.57
CEC (cmol$_c$ kg^{-1}) [c]	6.39	7.10	6.74	6.73	6.97	6.60	5.81	5.45	5.96	4.57
V (%) [c]	69.7	59.2	40.7	50.9	68.4	45.5	34.6	46.8	48.0	56.2
m (%) [c]	0.00	0.00	1.50	0.00	0.00	1.50	3.40	0.00	1.70	0.00
Sand (g kg^{-1})	79.2	68.6	63.2	63.1	55.2	59.7	55.6	63.1	67.9	82.1
Silt (g kg^{-1})	3.40	7.80	8.50	8.20	10.8	9.50	10.3	8.40	6.50	2.90
Clay (g kg^{-1})	17.4	23.6	28.3	28.7	34.0	30.8	34.1	28.5	25.6	15.0

[a] P and K available (Mehlich-1 method); Ca^{2+}, Mg^{2+} and Al^{3+} (KCl 1 mol/L method); H + Al [Calcium acetate 0.5 mol/L method]; SOM (Walkley and Black method); [b] Conventional method of collection with a representative sample of each area formed by 10 subsamples. [c] SB: sum of bases (Ca^{2+} + Mg^{2+} + K$^+$); CEC: cation exchange capacity (Ca^{2+} + Mg^{2+} + K$^+$ + H + Al); V: base saturation (100 × SB/CEC); m: aluminum saturation [100 × Al^{3+}/(Ca^{2+} + Mg^{2+} + K$^+$ + Al^{3+})].

For the evaluation of the spatial variability of available phosphorus and potassium, the sampling and recommendation were based on the analysis of each collected point to perform the recommendation by precision agriculture techniques. The recommendations were made according to Cantarutti et al. [23]. The study area presented different forage species (Table 2) with different management.

Table 2. Characterization of the pastures.

Pastures	Age [c]	Predominant Forage [b]	Area (ha)	Management [a]
I	9	*U. brizantha* cv. Marandu	5.90	Fertilization to implantation plus 30 tons of tanned cattle manure
II	9	*U. brizantha* cv. Marandu	6.15	Fertilization to implantation
III	9	*U. Brizantha* cv. Marandu	5.60	Fertilization to implantation
IV	7	*M. maximus* cv. Mombasa	13.05	Fertilization to implantation plus 30 tons of tanned cattle manure
V	7	*M. maximus* cv. Mombasa	10.08	Fertilization to implantation plus 30 tons of tanned cattle manure
VI	7	*M. maximus* cv. Mombasa	10.09	Fertilization to implantation plus 30 tons of tanned cattle manure
VII	9	No pasture	6.24	Fertilization to implantation
VIII	9	No pasture	3.93	Fertilization to implantation
IX	9	*M. maximus* cv. Mombasa	5.62	Fertilization to implantation plus 30 tons of tanned cattle manure
X	9	*U. brizantha* cv. Marandu	3.22	Fertilization to implantation plus 30 tons of tanned cattle manure

[a] Fertilization to implantation according to Cantarutti et al. [23]: 70 kg ha^{-1} of P_2O_5, 40 kg ha^{-1} of K_2O and 50 kg ha^{-1} of N; [b] *U.*: *Urochloa*, *M.*: *Megathyrsus*.; [c] Age: in years.

2.3. Diagnosis of Pastures Degradation Stages

The diagnosis of the pasture degradation stage was performed according to the quadrant proposed by Pires [24], which is based on the population of forage plants, weed plants, presence of other plants and soil fertility, assigning scores from 0 to 10 according to the levels observed for these variables. Diagnosis is carried out through the evaluation of the delimited area, identifying the percentage of area occupied by the interest forage, weeds and other non-target forage plants with potential for infestation but which are not of interest to the animals.

According to the level or percentage of occupancy of these plants, scores ranging from 0 to 10 are assigned, in which 0 represents 0% occupancy, and 10 represents 100% occupancy. For soil fertility, the level is based on soil chemical analyses, in which the grade is based on available phosphorus (P) content (a nutrient more limiting the agricultural production in the Cerrado), with 0 representing less than 1 mg kg^{-1} of P, 2 (4 mg kg^{-1}), 5 (10 mg kg^{-1}) and 10 (>10 mg kg^{-1} P). The results of the correlation of these grades indicate the degradation stage of the pastures, separated into quadrants 1 (green—good pastures), 2 (yellow—degraded pastures), 3 (yellow—degraded pastures in a more complex stage) and 4 (red—condemned pastures) [24].

2.4. Geostatistical and Exploratory Analysis

The exploratory analysis of the data was performed by calculating the measures of position, variability and central tendency of the evaluated attributes using Excel software. The hypothesis of data normality was verified using the Shapiro–Wilk test [25]. The Warrick and Nielsen [26] classification was used for the analysis of the coefficient of variation (CV), with low variability for values < 12%, mean variability for values between 12–60%, and high variability for values > 60%.

In order to determine the spatial variability, we considered the theory of regionalized variables, which has different methods of analysis of spatial variation, and one of them is the semivariogram. Semivariograms were obtained and adjusted to linear, spherical, exponential and Gaussian experimental models using Vesper software version 1.62 [27]. The prediction of available P and K levels in non-sampled places was facilitated by interpolation using kriging by means of the model of best adjustment, represented in isoline maps using Vesper software [27].

The choice of the theoretical models of semivariograms was carried out by observing the smaller sum of the square of the residuals (SSR) and the greater coefficient of determi-

nation (R^2). The adjustment of the stepped semivariogram model allowed the definition of the following parameters: nugget effect (C_0), threshold ($C_0 + C_1$), range (A_0) and spatial dependence degree (SDD), as shown in Equation (1) below:

$$SDD\ (\%) = [C_1/(C_0 + C_1)] \times 100, \tag{1}$$

in which SDD = spatial dependence degree, C_0 = nugget effect, C_1 = structural variance and $C_0 + C_1$ = threshold. The interpretation of the spatial dependence degree (SDD) was performed according to the classification used by Dalchiavon et al. [28], as follows: SDD < 20%—very low, 20% ≤ SDD < 40%—low, 40% ≤ SDD < 60%—medium, 60% ≤ SDD < 80%—high and 80% ≤ SDD < 100%—very high.

Class maps of the soil fertility diagnosis and the recommendation maps of phosphate and potassium fertilizer applications, according to Alvarez and Cantarutti [29] and Cantarutti et al. [23], were created for the establishment and maintenance of pastures of *Megathyrsus maximus* cv. Mombasa. Maps were also created showing management zones based on the limitation of available P and K^+ levels in the soil. Subsequently, the cost/benefit ratio of fertilizer application at a variable rate, according to the maps was evaluated and compared with the conventional method of recommendation (application at a fixed rate).

3. Results

3.1. Diagnosis of the Pastures Stage of Degradation

Diagnosis of the pasture degradation stage, according to the quadrant of Pires [24], resulted in pastures at all levels of degradation, varied from excellent (quadrant 1 in green color) to totally degraded pasture (quadrant 4 in red color) (Figure 2).
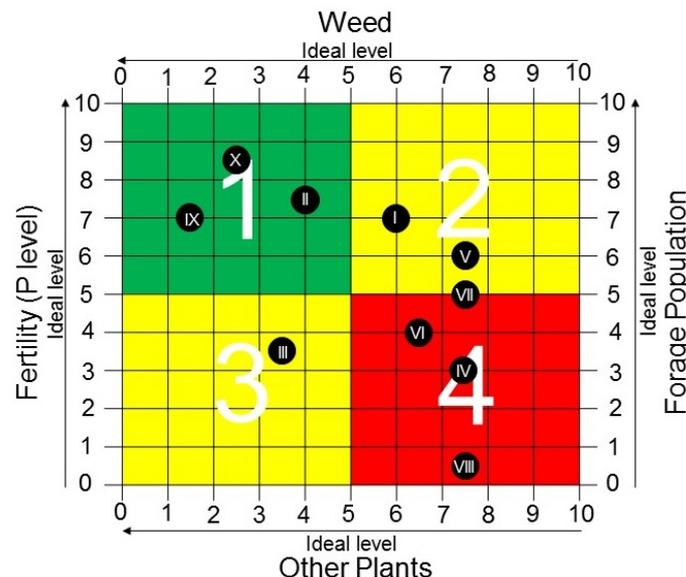
Figure 2. Diagnosis of the level of pastures degradation. Source: Adapted from Pires [24]. Numbers I-X represents the pasture areas; Quadrants 1 in green color are good pastures, quadrant 2 in yellow color are degraded pastures, quadrant 3 in yellow color are degraded pastures in a more complex stage, and quadrant 4 in red color are condemned pastures areas.

Based on pasture occupation by forage plants of interest as well as weeds and other plants, in addition to the level of fertility considering the level of phosphorus available in the soil, pastures II, IX and X fit in quadrant 1 in the green color, which represents good pastures with high available phosphorus and forage population. Pastures I and V were located in quadrant 2, which represents pastures in the initial stage of degradation, while pasture III was located in quadrant 3, which is a stage complex of degradation. Pastures IV,

VI, VII and VIII, were classified in quadrant 4, representing condemned pastures, which were characterized by low available phosphorus and forage plants and a high population of weeds and other plants.

3.2. Descriptive Statistical Analysis of Available P and K+

The average level of available phosphorus in the studied pasture area was considered good (20.1–30.0 mg kg^{-1}), and the potassium level was diagnosed as low (16.0–40.0 mg kg^{-1}) for medium-textured soils [29] (Table 3).

Table 3. Descriptive statistics of available phosphorus (P) and potassium (K+) in the soil of the pastures.

Chemical Attribute	Average *	Median	Value		Coefficient			Test W [1]
			Minimum	Maximum	CV [2]	Cs [3]	Ck [4]	
P (mg kg^{-1})	27.40	11.00	2.57	188.08	121.66	2.02	4.83	0.721 [ns]
K+ (mg kg^{-1})	39.83	35.00	12.90	128.00	55.44	1.99	5.21	0.823 [ns]

[1] W: Shapiro–Wilk normality test; [2] CV: coefficient of variation; [3] Cs: asymmetry coefficient; [4] Ck: kurtosis coefficient; [ns] not significant to the Shapiro–Wilk normality test at 5% probability; * Number of observations (n) = 100.

The data did not show normal distribution, so the values of available P and K+ are better represented by their respective medians (P = 11.0 mg kg^{-1} and K+ = 35.0 mg kg^{-1}). The variability of the chemical soil properties can be classified according to their coefficient of variation (CV). Thus, the soil had a mean CV (12% < CV < 60%) for the availability of K+ and high CV (>60%) for the available P distribution in the study area (Table 3).

The values of available P and K+ presented a positive asymmetric distribution, with the highest value observed for P (2.02) and the lowest value for K+ (1.99). The kurtosis coefficients (Ck) for P (4.83) and K+ (5.21) were outside the acceptable limits ($\pm$2.00) with right asymmetry, showing variation of the data in the studied area.

3.3. Geostatistical and Spatial Analyses of Available P and K+ in Soils

The results for the semivariograms adjusted for the evaluated chemical properties (available P and K+) were different. In Figure 3, it can be observed that the range (A_0) values obtained were 383.7 m for P and 168.7 m for K+ and that the attributes presented adjustments to the linear (P) and exponential (K+) models with R^2 of 0.84 and 0.85, respectively. The adjustment to the exponential model for the K+ data presented better quality (cross-validation coefficient = 0.90).

Using the experimental semivariograms, the geostatistical analysis allowed the detection of different spatial variability scales for available P and K+ of the soil, which presented spatial dependence (Table 2), showing that the distribution of these properties in space is not random. The relationships between the contribution (C_1) and the threshold ($C_0 + C_1$) show a very low spatial dependence degree (SDD < 20%) for P and medium (60% $\leq$ SDD < 80%) for K+.

From the adjustment of semivariograms, it was possible to elaborate isoline maps with the interpolation of values in not sampled places in the study area by ordinary kriging using the linear and exponential models to available P and K+, respectively. Figure 4 shows the spatial distribution of available P and K+ levels (Figure 4a,c) and the diagnostic maps (Figure 4b,d) of available P and K+ levels in the studied area.

In the study area, there was predominance of the low (56.9% of the area) and the medium (37.3% of the area) classes for available K+. For available P, the very good (31.3% of the area) and very low (24.8% of the area) classes were predominant.

3.4. Recommendation of Fertilization, Management Zones and Evaluation of Cost/Benefit

The recommendation maps of potassium and phosphate fertilizers application (Figure 5) were performed according to the requirements of *Megathyrsus maximus* cv. Mombasa.
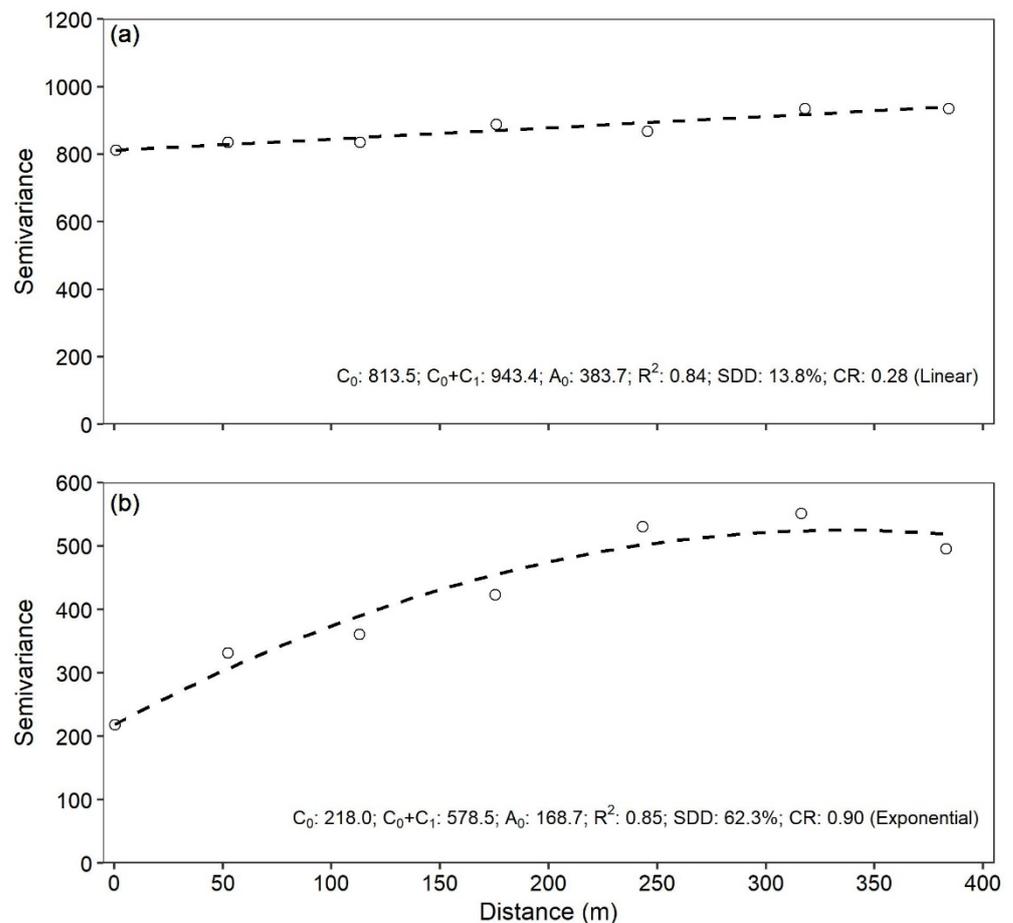
Figure 3. Semivariograms, components of semivariance, spatial dependence degree and cross-validation of available phosphorus (P) (**a**) and potassium (K^+) (**b**) of the pastures. C_0: Nugget effect; C_1: Contribution; $C_0 + C_1$: threshold; A_0: Range; R^2: coefficient of determination; SDD: Spatial dependence degree; CR: Cross-validation regression coefficient.

The fertilizer recommendation maps show that there are areas with higher and lower requirements of these inputs when applied at a variable rate according to the specific needs. Hence, it shows the need for the adoption of precision agriculture in the process of soil fertility management in agricultural production.

Two management zones were created according to available P and K^+. Zone I, with no limitations to the production of Mombasa grass, and zone II in which the available P and K^+ are low and can probably limit the production (Figure 5c,d).

From an economic perspective, comparisons of the amount of phosphate and potassium fertilizers were developed, as well as the costs of the application at a varied rate and application based on the average soil fertility recommendation (Table 4). This latter method is the most common practice of application of fertilizers in Brazilian soils.
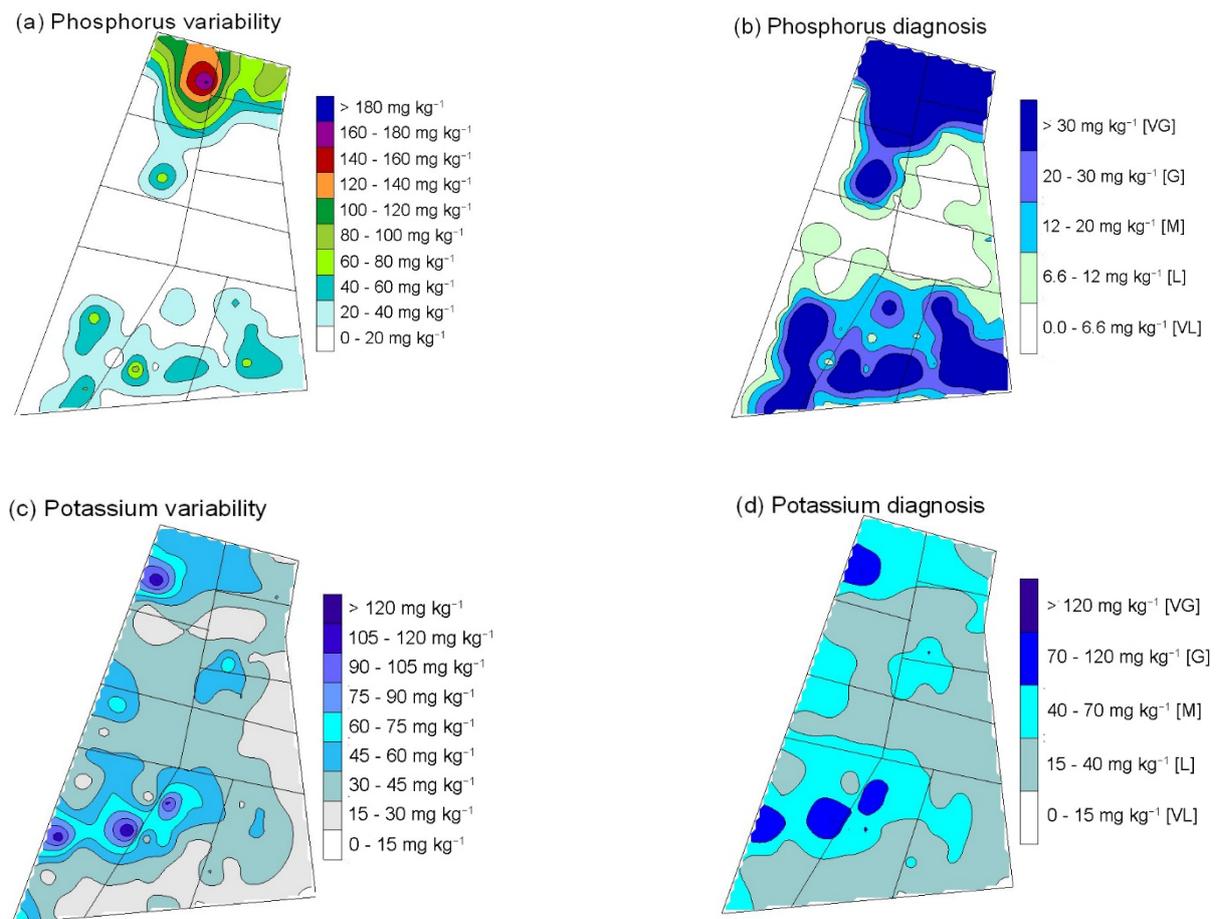
Figure 4. Isoline maps of spatial variability and diagnostic maps of fertility classes for available phosphorus (P) and potassium (K^+) in pastures. VG—Very Good; G—Good; M—Medium; L—Low; VL—Very Low.

Table 4. Cost/benefit analysis of the recommendation of fertilization at a varied rate in comparison with conventional fertilization.

Fertilization Method	Phosphate Fertilization				Potassium Fertilization			
	Quantity (kg) [c]		Cost (USD)		Quantity (kg)		Cost (USD)	
	P_2O_5	SS [a]	Total	Ha *	K_2O	KCl [b]	Total	ha
Fertilization of implantation + maintenance **								
Conventional [d]	6094.9	33,860.6	19,774.1	279.1	3941.5	6569.2	7215.5	101.9
Varied rate [f]	3754.9	20,860.7	12,182.3	172.0	4774.2	7957.0	8739.8	123.4
Balance [e]	2340.0	12,999.9	7591.7	107.2	−832.4	−1387.8	−1524.3	−21.5
Soil analysis [g]								
	Samples				Cost (USD)			
Conventional	10.0				155			
Varied rate	100.0				1550			

(*) ha—hectare; Dollar (USD)—BRL 5.17 (**) Fertilization for medium technological level; [a] SS—Simple Superphosphate (18% P_2O_5) (584.0 USD/ton); [b] KCl—Potassium Chloride (60% K_2O) (1098.4 USD/ton) [30]; [c] Recommended amount for the total area (70.84 ha); [d] Recommendation for the average fertility of each pasture; [e] Higher cost of conventional fertilization (+positive); higher cost of fertilization at a varied rate (-negative); [f] Recommendation by precision agriculture technique; [g] Soil analysis: USD 15.5 (Sellar agricultural analyzes—Laboratory of Agricultural Analysis of Tocantins LTDA ME).
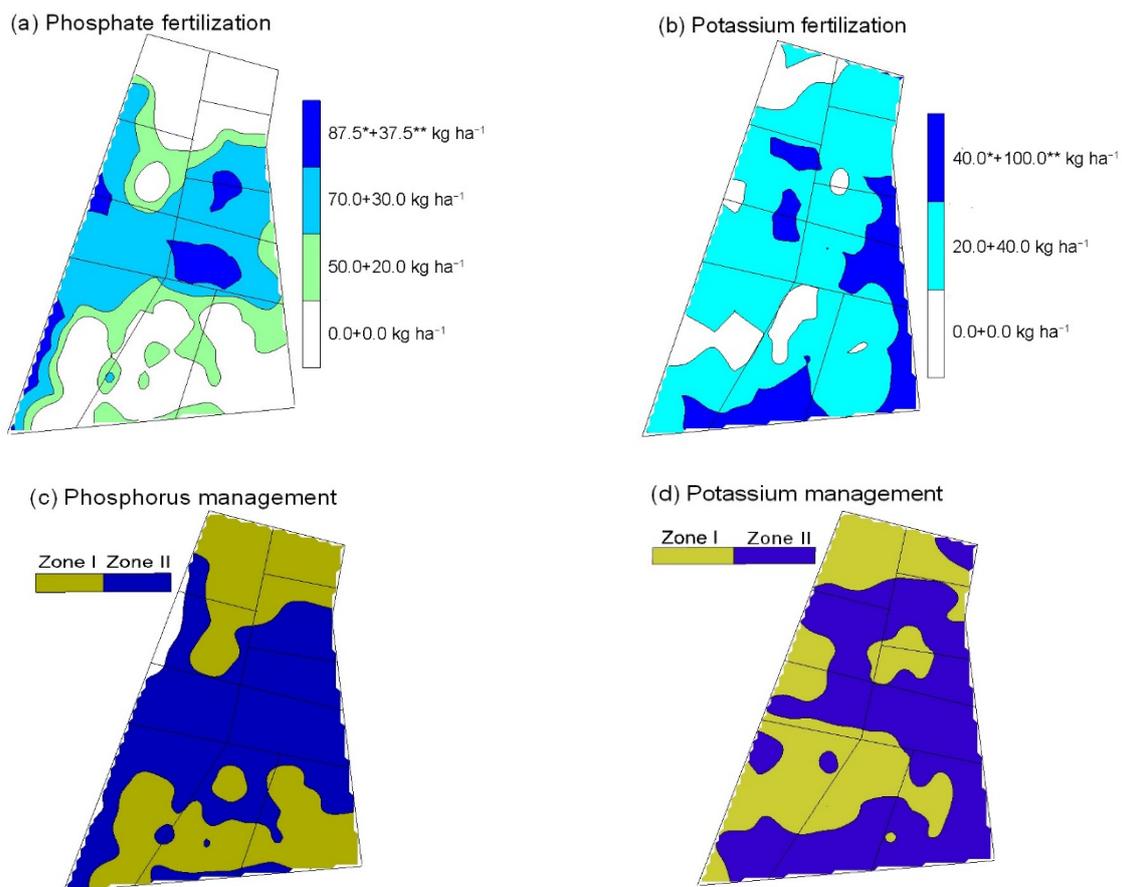
Figure 5. Recommendation maps of phosphate (P$_2$O$_5$) (**a**) and potassium (K$_2$O) fertilization (**b**) application for (*) implantation and (**) maintenance and management zones (**c**) and (**d**) of grass *Megathyrsus maximus* cv. Mombasa considering the technological level available.

The management of soil fertilization by the conventional method of sampling and recommendation generated a cost of approximately USD 27,144.6. For precision agriculture techniques with fertilization at a variable rate, of the cost was approximately USD 22,472.2, representing savings of USD 4672.4 (17.2%).

Phosphate and potassium fertilization by the conventional method from the mean soil fertility promoted a cost 38.4% higher and 21.1% lower, respectively, in relation to the costs of the amount of this fertilizer needed for application at varied rates.

4. Discussion

4.1. Diagnosis of the Pastures Stage of Degradation

In general, the increase in pasture degradation is related to the reduction of soil fertility [3,6]. However, it was found that pastures implanted in sites with medium to good levels of available P and K$^+$ showed an advanced stage of degradation. The management factor was probably the most responsible for the degradation state of these pastures, which had a low forage population and high density of weeds (Figure 2).

According to Pires [24], pastures in quadrant 1 include new pastures with few weeds, well-formed and distributed grasses and good soil fertility. In this category, there is a need for little investment to achieve the maximum production of the forage, being an area for maintenance, which is more economical than recovery. Pastures in quadrant 2 represent pastures in the initial deterioration stage, with an infestation of weeds but with a high forage population and the fertility of easy handling to reach adequate levels.

In quadrant 3, the pastures are under an advanced stage of degradation, with low grass population and low fertility, the fertilization and replanting of the area being necessary

for its recovery. Pastures classified in quadrant 4 are considered condemned pastures and totally degraded, with low grass population and high weed infestation (>50%). This last scenario would only improve after pasture reform.

4.2. Descriptive Statistical Analysis of Available P and K+

The descriptive statistics of available P and K+ data in the studied area allowed the verification that the average values of these attributes presented levels below critical for K+ and above critical for P for the good development of most cultures [29] (Table 3).

The data of available P and K+ did not present normal distribution; however, the normality of the data is not an issue for the geostatistical analyses when evaluating all data together [31]. Therefore, it did not preclude the application of these techniques in soil variability studies. The absence of normal distribution of available P and K+ under the studied pastures is probably due to the differential management practices adopted in each evaluated pasture. Both the application of fertilizers, and the grazing and export of nutrients by the plants ingested by the cattle, can make the study area more heterogeneous.

The soil had a medium and high coefficient of variation for the availability of K+ and P, respectively. Thus, the large coefficient of variation (CV) is probably due to the irregular application of tanned cattle manure, which only took place in some of the studied areas. The changes in soil chemical properties are consequences of complex interactions of their formation, due to long-term weathering–leaching processes, in addition to management practices [18,32].

Since K+ is easily leached, its available content in soil showed a lower CV. It might have been caused due to its easy loss within the soil profile, which prevents K+ accumulation in high concentrations in areas where manure was applied, contrary to phosphorus, which is less mobile in soil. This is also verified as a function of the larger amplitude of data for P in relation to K+, corroborating the greater variation of P contents.

The data of available P and K+ presented a positive asymmetric distribution. The asymmetry coefficient (Cs) is used to characterize how the frequency distribution moves away from the symmetry. If the value found for this coefficient is zero, the distribution is symmetric, if positive, the distribution is asymmetric on the right and if negative, it is asymmetric on the left [33].

The kurtosis coefficients (Ck) can also be used to evaluate if the data follow a normal distribution, which should preferably be null, with accepted values between −2.00 and +2.00 [31,34]. It is observed in Table 3 that the values of Ck for both the evaluated attributes were outside the acceptable limits. Silva Neto et al. [17] verified the normal distribution of available P and K+ in areas under different management practices. They also observed that the Ck for P did not fit within the limit indicated by Negreiros Neto et al. [31], presenting both positive asymmetries, which indicates a higher amount of data above average values.

4.3. Geostatistical and Spatial Analyses of Available P and K+ in Soils

The range (A_0) of P was higher than K+ (Figure 3). The range corresponds to the radius of the areas considered homogeneous for each studied variable [35,36]. Ranged values are influenced by agronomic practices, mainly by the application of amendments and fertilizers, since the objective is to homogenize the cultivated area in terms of soil properties. The more homogeneous the cultivation area, the greater the radius of the spatial correlation of the evaluated attributes, that is, the greater the range. The adoption of precision agriculture by treating each need in a timely manner tends to standardize soil fertility, reducing spatial variability and increasing the geostatistical range [34].

The attributes presented adjustments to the linear (P) and exponential (K+) models. The adjustment to the exponential model for the K+ data presented better quality of the predictions at not sampled points through kriging, which can be verified by cross-validation coefficient (K+ = 0.90 and P = 0.28). The linear model (adjusted for P data) resembles the pure nugget effect but allows variographic analysis. The pure nugget effect is characteristic of phenomena with high randomness with unexplained or random variance,

considering that there is a marked discontinuity in the origin of the semivariogram [37,38]. There is a difference in values of nearby points, indicating that there may be a lower regionalization of the sample mesh and/or spurious variations associated with sample collection and measurement. This difference may be due to undetected measurement errors or microvariations considering the sampling distance used [38,39]. Therefore, shorter distances between the sampling points would be necessary to detect the dependence [40].

The data showed a very low spatial dependence degree (SDD < 20%) for P and medium ($60\% \leq$ SDD < 80%) for K^+. Diagnostic maps of available P and K^+ levels in the studied area were developed by classifying the levels as very low, medium, good or very good, according to criteria used by Carneiro et al. [18,34].

Through the isoline maps, it was verified their respective variations in the evaluated area. The areas with available P considered very good do not coincide with the areas of very good K^+, showing the imbalance in the fertility of the area. However, this imbalance can be corrected by the adoption of precision agriculture techniques and correct fertilization practices at a varied rate according to the requirements of each region. The spatial variability maps of soil properties are fundamental in the evaluation of soil fertility, which allows the visualization of areas where divergent management practices must be performed. Furthermore, such information is important for increasing precision in agriculture and livestock and allows the application of inputs with varied rates, aiming at the homogenization of soil fertility.

According to Carneiro et al. [18,34], maps of spatial variability of soil properties and diagnosis of the degradation stage of pastures allow adequate management of the area and indicate priority areas of intervention, such as those that have nutritional deficiencies that may hinder reaching high agricultural production.

4.4. Recommendation of Fertilization, Management Zones and Evaluation of Cost/Benefit

The application of the inputs with the adoption of precision agriculture, in addition to homogenizing soil fertility, allows an economy regarding the acquisition of inputs since there is better control in the distribution and the number of fertilizers required [18,34].

The use of spatial variability and management zone maps favors the adequate management of pastures. Using the maps, it is observed that it is necessary to increase available P and K^+ levels in most parts of the area in order to produce the Mombasa grass with quality. Note that the management zones for available P and K^+ are different, showing the imbalance between these two nutrients. This makes the use of precision farming techniques even more reusable to homogenize the fertility of this area and to ensure not only increased fertility but also nutritional balance.

Phosphate fertilization by the conventional method promoted an increase in the cost because this method of application of fertilizer would occur in places where there is no need for it. As for potassium fertilization, the application by the conventional method has a lower cost in relation to the varied rates.

The lowest cost obtained with the conventional application of potassium fertilizer is due to the fact that the fertility of the area is considered average. Therefore, it was made a homogeneous application with the same dose in the whole area ($20 \, kg \, ha^{-1}$ at implantation and $40 \, kg \, ha^{-1}$ in maintenance). However, the area presented low fertility sites, requiring the application of potassium fertilizer in higher quantities ($40 \, kg \, ha^{-1}$ at the implantation and $100 \, kg \, ha^{-1}$ in maintenance). This variation is one of the main problems of fertilization by the average level of nutrients, causing loss of production due to nutrient deficiency in some areas. In contrast, with an average application, excessive amounts may be applied in places where the nutrient level is already adequate, which may cause environmental problems, such as groundwater contamination or eutrophication of nearby water bodies.

Carneiro et al. [18] found that the use of precision agriculture using geostatistical tools reduces fertilizer application costs by 20.5% compared with a recommendation based on average soil fertility. The recommendation at a variable rate by the mapping of areas using geostatistical or other techniques is the principle to increase crop productivity and improve

soil management efficiency [18]. Furthermore, it promotes the economy through the correct application of amendments and fertilizers [18]. Thus, the adoption of practices that lead to greater precision in agriculture becomes essential for increasing soil fertility, which can contribute to improved production of implanted crops, ensuring better management of the production system.

5. Conclusions

The degradation stage of the studied pastures was mostly explained by the heterogeneity of soil fertility in the area, mainly regarding available phosphorus and potassium contents, which reflected inadequate management and degradation of the majority of the pastures.

Geostatistical and precision agriculture techniques were important for the diagnosis and determination of the appropriate management of areas under pastures.

The use of geostatistical techniques was efficient in detecting and mapping the spatial variability of nutrient availability in the soil and defining the management zones.

Application at a variable rate favors the proper use of fertilizers, with the application of the appropriate quantity of each fertilizer, according to the necessity of each place of application within the area of interest. Furthermore, the use of geostatistical and precision agriculture techniques allowed the reduction of costs and the optimization of management of soil fertility in the area.

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