# Research Findings

Photo by A.C.C. Bernardi.

## Spatial Variability of Soil Properties and Yield of a Grazed Alfalfa Pasture in Brazil

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### Abstract

Knowledge of the spatial variability of soil properties and of forage yield is needed for informed use of soil inputs such as variable rate technology (VRT) for lime and fertilizers. The objective of this research was to map and evaluate the spatial variability of soil properties, yield, lime and fertilizer needs and economic return of an alfalfa pasture. The study was conducted in a 5.3 ha irrigated alfalfa pasture in Sao Carlos, SP, Brazil that was directly grazed and intensively managed in a 270-paddock rotational system. Alfalfa shoot dry matter yield was evaluated before grazing. Soil samples were collected at 0-0.2 m depth, and each sample represented a group of 2 or 3 paddocks. Apparent soil electrical conductivity (ECa) was measured with a contact sensor. The cost of producing 1 ha of alfalfa was estimated from the amount of lime and fertilizer needed and was then used to estimate the total cost of production for the dairy system. The alfalfa dry matter

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yield was used to simulate the pasture stocking rate, milk yield, gross revenue and net profit. The spatial variability of soil properties and site-specific liming and fertilizer needs were modeled using semi-variograms with VESPER software, the soil fertility information and economic return were modeled with SPRING software. The results showed that geostatistics and GIS were effective tools for revealing soil and pasture spatial variability and supporting management strategies. Soil nutrients were used to classify the soil spatial distribution map and design site-specific lime and fertilizer application maps. Spatial variation in forage and spatial estimates of stocking and milk yield are adequate pasture management tools. Spatial analyses of needs, forage availability and economic return are management tools for avoiding economic problems, as well as potential environmental problems, caused by unbalanced nutrient supplies and over- or under-grazing.

## Introduction

Long-established, properly managed and fertilized pastures are the main source of food for cattle. They also constitute the most practical and least-cost approach to cattle feeding (Camargo *et al.*, 2002). In dairy production systems, intensive pasture grazing increases productivity and allows for higher stocking rates (Corsi and Nussio, 1993; Primavesi *et al.*, 1999).

Among the controllable factors that determine forage yield and quality, soil fertility, including fertilizer use, is one of the most important. Tropical acidic soils are naturally poor in plant nutrients. Therefore, soil liming and a balanced nutrient supply are essential to ensure high yields and high forage quality (Corsi and Nussio 1993; Primavesi *et al.*, 1999; Camargo *et al.*, 2002). Alfalfa is extremely demanding on soil fertility; therefore, an adequate nutrient supply is important for forage production and essential for maintaining high forage quality and profitable yields (Moreira *et al.*, 2008; Bernardi *et al.*, 2013a, 2013b). The application of fertilizer is the main cost of maintenance of permanent pasture (Gillingham, 2001). Fertilization may represent as much as 27 % of the total production cost of alfalfa for intensive dairy cattle production in typical Brazilian systems (Vinholis *et al.*, 2008).

Precision agriculture (PA) contributes to long-term sustainability of agriculture by managing inputs to reduce losses caused by excess fertilizer application or nutrient imbalances (Bongiovanni and Lowenberg-Deboer, 2004). Although all these technologies are available and can be successfully used for pasture management, PA has been developed and applied mostly to annual crops (Schellberg

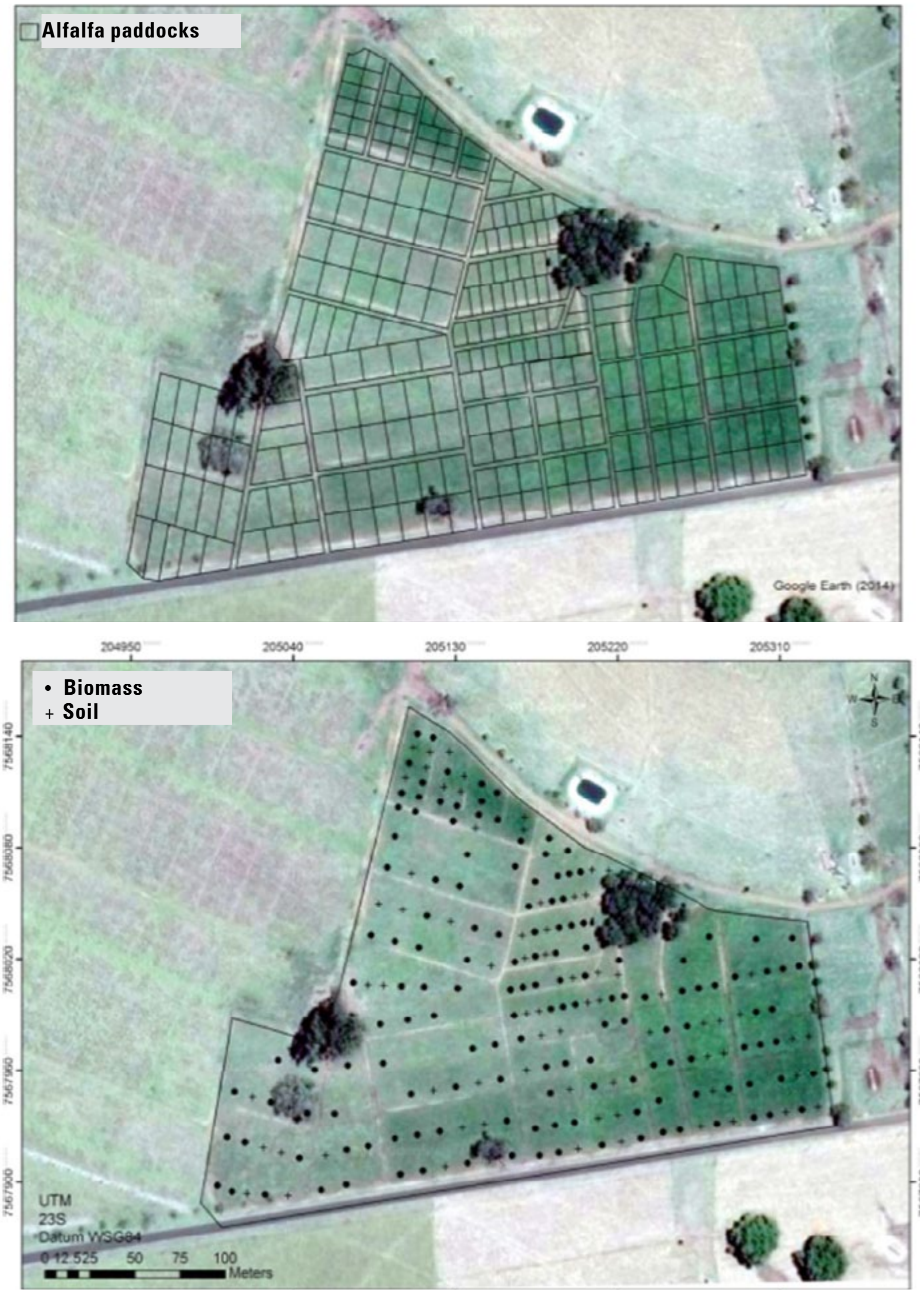


**Fig. 1.** Division of the 270 paddocks of alfalfa pasture under grazing in Brazil. Soil(+) and biomass(•) sampling points.

*et al.*, 2008). The benefits of PA are the precise identification and mapping of small-scale variability, and the development of variable rate technology (VRT, Gillingham 2001). Fu *et al.* (2010) indicated that fertilizer use efficiency and agronomic and environmental management may be improved by adjusting fertilizer inputs based on spatial variability in soil fertility. According to Schellberg *et al.* (2008), detecting spatial variation in pastures is the major challenge; the primary objective of PA is the management of that heterogeneity in the field.

Knowledge of the spatial variability of soil properties and forage yield is useful for the informed use of inputs, such as variable rate application (VRA) of lime and fertilizers. To reduce the need for expensive and intensive sampling, PA and forage management require rapid low-cost sensors and methods for revealing spatial variability (McBratney and Pringle, 1999). Measurement of the spatial variability of pasture soil and vegetation is the basis for VRT (Serrano *et al.*, 2010) and grazing management. According to Stefanski and Simpson (2010), VRA is adequate for pasture-based systems, since the irregular distribution of nutrients are a probable cause of irregular biomass productivity. The economic benefits of using VRA instead of using a uniform rate in pasture systems have been demonstrated (Gillingham and Betteridge, 2001). Besides the potential to optimize nutrient use, there has been little research exploring the potential for VRA in pasture systems (Trotter *et al.*, 2014).

Measurements of apparent soil electrical conductivity (ECa) can provide easily measured spatial data for characterizing variation in soil and yield (Kitchen *et al.*, 2003; Serrano *et al.*, 2010). Apparent soil electrical conductivity (ECa) integrates texture and moisture availability, two soil characteristics that affect crop and forage yield, as shown by Kitchen *et al.* (1999), Luchiari *et al.* (2001) and Serrano *et al.* (2010). In Brazil, Machado *et al.* (2006) verified that values of soil ECa reflected spatial variation in soil clay content and were adequate for establishing the limits of management zones.

Evaluating PA tools to determine alfalfa fertilization needs and the resulting economic return to dairy production systems is required for establishing conditions under which the response will be maximized, particularly when pastures have acidic, low-fertility soils.

Hence, the effects of various management practices, including PA, and related issues are important for achieving profitable dairy production.

The objective of this research was to map and evaluate the spatial variability of soil properties, yield, liming and fertilizer need and economic return of an alfalfa pasture.

## Materials and methods

The study was conducted at Embrapa Pecuaria Sudeste, in Sao Carlos (22°01'S and 47°54'W; 856 m above sea level), State of Sao Paulo, Brazil. A 5.3 ha irrigated alfalfa (*Medicago sativa* cv. Crioula) pasture had been intensively managed for 2 years in a rotational system; 270 paddocks were divided by electric fencing into 80, 160 and 240 $m^2$ units. The pastures were managed under an annual rotation system with 1 day of grazing and 30 days between the cycles. Alfalfa shoot dry matter yield was periodically evaluated before grazing, when 10 % of the crop was flowering. All the cuts were made 0.10 m above ground. Alfalfa samples were dried at 65°C for 72 h, for determining the dry matter yield.

Soil samples were collected at 0-0.2 m depth using the zone sampling technique (Fleming *et al.*, 2000). Each zone was established based on alfalfa yield and weed occurrence, since Bernardi *et al.* (2013a) had showed for the same area an inverse correlation between soil fertility level and weed on alfalfa pasture. Each soil sample was a result of at least 10 sub-samples collected at the paddocks at the same zone. Figure 1 illustrates the spatial distribution of soil sampling points. The chemical properties were determined using the methods of Primavesi *et al.* (2005). Soil pH measurements were made in $CaCl_2$, organic carbon was determined by wet combustion and available P was assessed using the resin method. Exchangeable $K^+$, $Ca^{2+}$, $Mg^{2+}$ and H + Al were also measured. Cation exchange capacity (CEC) was measured at the actual soil pH value, and base saturation (V%) was determined. Soil particle size fractions (clay content) were determined by the densimeter method. Soil apparent electrical conductivity was measured using the Veris model 3100 sensor (Veris Technologies, Salina, KS, USA) (Lund *et al.*, 1999).

Liming, P and K fertilization rates were calculated from soil testing. The criteria were those described by Moreira *et al.* (2008) and Bernardi *et al.* (2013a, 2013b): lime to increase basis saturation to 80 %, P fertilizer (super single phosphate, 18 % $P_2O_5$) to increase soil P to 20 mg $dm^{-3}$ and K fertilizer (KCl, 60 % $K_2O$) to increase exchangeable K to 5 % of soil cation exchange capacity.

The amount of liming and fertilizer was used to simulate the cost of producing 1 ha of alfalfa. The cost of alfalfa production as a percentage of total dairy production costs was then estimated. All other fixed and variable costs were based on the data of Vinholis *et al.* (2008) for a Brazilian intensive dairy cattle production system with the following characteristics: cows' diet consisted of 20 % alfalfa pasture and 80% *Panicum maximum* cv. Tanzania (grazed during the rainy season) and maize silage (dry season).

The results obtained for alfalfa dry matter yield in each paddock were used to estimate total dry matter yield in a year and to simulate pasture stocking rate, milk yield and gross revenue. The following data were used in the simulation: (a) average cow live weight (LW) = 550 kg, (b) cow dry matter (DM) consumption = 3.05 % of the LW, corresponding to 16.8 kg day$^{-1}$ of DM, (c) the alfalfa pasture grazing represented 20 % of the forage consumption. The estimates were derived from the following equations:

### Cost of alfalfa production

$$AC = APC + LFC$$

where AC = cost of production of 1 ha of alfalfa, USD ha$^{-1}$ year$^{-1}$; APC = cost of production of 1 ha of alfalfa (Vinholis *et al.*, 2008), includes variable and fixed costs, excluding lime and fertilizer inputs, USD ha$^{-1}$ year$^{-1}$ (AP = USD 1894 ha$^{-1}$ year$^{-1}$); LFC = lime (USD 0.03 kg$^{-1}$) and fertilizer costs (SSP = USD 0.48 kg$^{-1}$ and KCl = USD 0.39 kg$^{-1}$).

### Stocking rate

$$SR = \frac{DM \times GE}{AGN \times GI \times DIFC}$$

where SR = stocking rate in the alfalfa pasture, animal ha$^{-1}$; DM = dry matter yield, kg ha$^{-1}$; GE = grazing efficiency (GE = 0.7); AGN = annual number of grazing events (12 grazing events year$^{-1}$); GI = grazing interval, days (30 days); DIFC = daily individual forage consumption, kg of dry matter cow$^{-1}$ day$^{-1}$.

### Milk yield

$$MY = \frac{SR \times MYd \times 365}{1 + (TPIA + SCIA) \times SR}$$

where MY = annual milk production, l ha$^{-1}$ year$^{-1}$; MYd = daily milk yield, l cow$^{-1}$ day$^{-1}$ (20 l cow$^{-1}$, 4 % fat content); TPIA = tropical pasture individual area, ha cow$^{-1}$ (TPIA = 0.125 ha cow$^{-1}$); SCIA = sugarcane individual area, ha cow$^{-1}$ (SCIA = 0.043 ha cow$^{-1}$); Obs.: TPIA and SCIA are the areas of tropical and sugarcane pastures used for feeding the cows that also graze in 1 ha of alfalfa.

### Gross revenue

$$GR = MY \times MP$$

where GR = gross revenue, USD ha$^{-1}$, MY = annual milk production, l ha$^{-1}$ year$^{-1}$, MP = milk price, USD l$^{-1}$ (MP = USD 0.40 l$^{-1}$).

### Total cost of production

$$TCP = AC + TCPD$$

where TCP = cost of production, USD ha$^{-1}$ year$^{-1}$; AC = cost of production of 1 ha of alfalfa, USD ha$^{-1}$ year$^{-1}$; TCPD = total production cost of dairy system (Vinholis *et al.*, 2008), USD ha$^{-1}$ year$^{-1}$ (TDC = USD 6,068 ha$^{-1}$ year$^{-1}$).

### Net profit

$$NP = GR - TCP$$

where NP = net profit, USD ha$^{-1}$; GR = gross revenue, USD ha$^{-1}$; TCP = production cost, USD ha$^{-1}$.

Statistical parameters were estimated and geostatistical analyses were conducted for all variables, focusing on the spatial continuity and dependence of soil and forage properties.

Empirical directional semi-variograms were calculated for the x- and y-directions. Semi-variograms were fitted to empirical models using VESPER (Minasny *et al.*, 2005) to estimate the structure of the spatial variation. Contour maps of all variables were estimated using ArcGIS 10.1 (ESRI, 2009). SPRING (Camara *et al.*, 1996), a free object-based georeferenced information system (www.dpi.inpe.br/spring), was used to integrate the soil fertility maps. Using the spatial analyst extension of ArcGIS 10.1, net profit was estimated and mapped by subtracting the production cost from gross revenue.

## Results and discussion

Descriptive statistical parameters of all the analyzed variables are given in Table 1. The parameter mean, variance, coefficient of variation, minimum value, maximum value, skewness and kurtosis were estimated to verify the existence of a central tendency and the dispersion of the data.

The verification of normality is important because kriging performs better when the data are normally distributed (Carvalho *et al.*, 2002). In a data set that approaches the normal distribution, the skewness and kurtosis coefficients must be between 0 and 3 (Carvalho *et al.*, 2002). The skewness and kurtosis of soil P were inconsistent with the normal distribution (Table 1). All other variables were normally distributed.

Using the classification suggested by Pimentel-Gomes (1984), coefficients of variation -CV of soil pH, CEC, base saturation, clay and milk yield displayed low variability, with a CV below 10 %. Soil organic matter (O.M.), Ca, Mg, dry matter yield and stocking rate were the variables with medium variability (CV between 10 and 20 %). Trotter *et al.* (2014) had found CV ranging from 35 to 66 % for P, K and S. All other parameters had high variability. According to Kravchenko (2003), the degree of variability is important in site-specific management because highly variable soil properties are potentially better candidates for site-specific management than are more uniformly distributed soil properties. However, mapping soil properties with higher variability can be less accurate than mapping soil properties with lower variability. Trends in the variation of soil attributes obtained in this study are consistent with those observed by Mulla and McBratney (2000) and Machado *et al.* (2004) for soil parameters.

**Table 1.** Descriptive statistics for variables of a grazed alfalfa pasture in Brazil.

| Variables | μ | σ | Minimum | Maximum | CV (%) | Kurtosis | Skewness | n |
|---|---|---|---|---|---|---|---|---|
| $pH_{CaCl_2}$ | 5.7 | 0.340 | 5.2 | 6.6 | 5.965 | 1.081 | 1.166 | 73 |
| OM (g $kg^{-1}$) | 25.5 | 3.122 | 19.0 | 34.0 | 12.24 | 0.547 | 0.492 | 73 |
| $P_{resin}$ (mg $dm^{-3}$) | 35.0 | 29.82 | 9.0 | 141.0 | 85.20 | 4.298 | 2.096 | 73 |
| K ($mmol_c$ $dm^{-3}$) | 3.5 | 1.345 | 0.6 | 5.4 | 38.43 | -0.783 | -0.571 | 73 |
| Ca ($mmol_c$ $dm^{-3}$) | 37.0 | 5.509 | 26.0 | 55.0 | 14.89 | 2.161 | 0.763 | 73 |
| Mg ($mmol_c$ $dm^{-3}$) | 17.2 | 3.597 | 12.0 | 25.0 | 20.91 | -1.001 | 0.497 | 73 |
| CEC ($mmol_c$ $dm^{-3}$) | 79.6 | 5.401 | 69.0 | 92.0 | 6.785 | -0.387 | -0.137 | 73 |
| Base saturation (%) | 72.4 | 7.105 | 58.0 | 86.0 | 9.814 | -0.889 | 0.109 | 73 |
| Clay (g $kg^{-1}$) | 631.3 | 19.24 | 595 | 674 | 0.03 | -0.258 | 0.245 | 73 |
| $EC_a$ (mS $m^{-1}$) | 7.7 | 4.642 | 0.0 | 42.8 | 60.29 | 1.273 | 0.622 | 4,794 |
| Lime (kg $ha^{-1}$) | 627.8 | 495.9 | 0.0 | 1,584.0 | 78.99 | -1.349 | 0.071 | 73 |
| Single superphosphate (kg $ha^{-1}$) | 408.0 | 414.4 | 0.0 | 1,166.7 | 101.6 | -1.434 | 0.391 | 73 |
| KCl (kg $ha^{-1}$) | 126.8 | 169.1 | 0.0 | 525.0 | 133.4 | -0.182 | 1.096 | |
| Dry matter yield (kg $ha^{-1}$) | 18,540 | 3,279.9 | 9,060 | 28,710 | 17.69 | 0.362 | -0.266 | 153 |
| Stocking rate (cows $ha^{-1}$) | 15 | 2.606 | 7 | 23 | 17.37 | 0.501 | -0.265 | 153 |
| Milk yield (kg $ha^{-1}$ $year^{-1}$) | 30,610 | 1,795.3 | 23,483 | 34,519 | 5.865 | 2.063 | -1.204 | 153 |

*CV* coefficient of variation equals standard deviation (σ) divided by sample mean (μ).

Experimental semi-variograms for all variables were computed, and all fitted models were bounded (Table 2). The plots of semi-variograms are also shown (Fig. 2). Geostatistics is a useful tool for soil fertility because it can be used to estimate and map soil attributes in areas that were not sampled. The results showed that the spatial scale encompassed the full extent of variation of the parameters studied. The spherical model was the best adjusted to experimental variograms of soil pH, Mg, CEC, K fertilization, ECa and milk yield. Trangmar *et al.* (1985) showed that this model best describes the behavior of variograms of soil attributes. For soil O.M., available P, exchangeable K and dry matter yield, the variogram was fitted with a Gaussian model. For soil Ca, base saturation, lime, P fertilizer and stocking rate, an exponential model was used to describe the spatial dependence.

The ratio of nugget to total semi-variance can be used as a criterion for classifying the spatial dependence of variables (Cambardella *et al.*, 1994). Soil pH, O.M., P, Ca, Mg, base saturation, lime, P and K fertilization had weak spatial dependence (>75%). Soil K, CEC, dry matter yield and stocking rate showed moderate spatial dependence, with ratios between 25 and 75 %. Soil ECa and milk yield showed strong spatial dependence, with ratios greater than 75 %. Figure 2 illustrates the semi-variograms of soil properties, with models that are described in Table 2. The

**Table 2.** Parameters for semi-variograms models of characteristics of a grazed alfalfa pasture in Brazil.

| Variable | $C_0$ | $C_1$ | A(m) | Model | Nugget/sill $100[C_0(C_0+C_1)^{-1}]$ | Spatial dependence |
|---|---|---|---|---|---|---|
| $pH_{CaCl_2}$ | 0.003285 | 5.81 | 10,000 | Spherical | 99.9 | Weak |
| OM (g $kg^{-1}$) | 2.664 | 9.34 | 84.81 | Gaussian | 77.8 | Weak |
| $P_{resin}$ (mg $dm^{-3}$) | 62.66 | 959.1 | 66.29 | Gaussian | 93.9 | Weak |
| K ($mmol_c$ $dm^{-3}$) | 0.963 | 2.013 | 165 | Gaussian | 67.6 | Moderate |
| Ca ($mmol_c$ $dm^{-3}$) | 3 | 39 | 71 | Exponential | 92.9 | Weak |
| Mg ($mmol_c$ $dm^{-3}$) | 2 | 11.17 | 62.2 | Spherical | 84.8 | Weak |
| CEC ($mmol_c$ $dm^{-3}$) | 9.33 | 20.7 | 64.57 | Spherical | 68.9 | Moderate |
| Base saturation (%) | 1 | 81 | 102 | Exponential | 98.8 | Weak |
| Clay (g $kg^{-1}$) | 9.63 | 535.9 | 208.8 | Spherical | 98.24 | Weak |
| $EC_a$ (mS $m^{-1}$) | 17.22 | 5.75 | 184.6 | Spherical | 25.0 | Strong |
| Lime (kg $ha^{-1}$) | 8,363 | 244,748 | 97 | Exponential | 96.7 | Weak |
| Single superphosphate (kg $ha^{-1}$) | 13,209 | 213,942 | 107 | Exponential | 94.2 | Weak |
| KCl (kg $ha^{-1}$) | 4,415 | 18,997 | 90 | Spherical | 81.1 | Weak |
| Dry matter yield (kg $ha^{-1}$) | 7,725,788 | 4,380,353 | 19.77 | Gaussian | 36.2 | Moderate |
| Stocking rate (cows $ha^{-1}$) | 4.543 | 3.026 | 36.33 | Exponential | 40.0 | Moderate |
| Milk yield (kg $ha^{-1}$ $year^{-1}$) | 2,790,218 | 780,683 | 63.57 | Spherical | 21.9 | Strong |

The parameters are: $C_0$ the nugget variance; $C_1$ the sill of the autocorrelated variance; *A* the range of the spatial dependence.

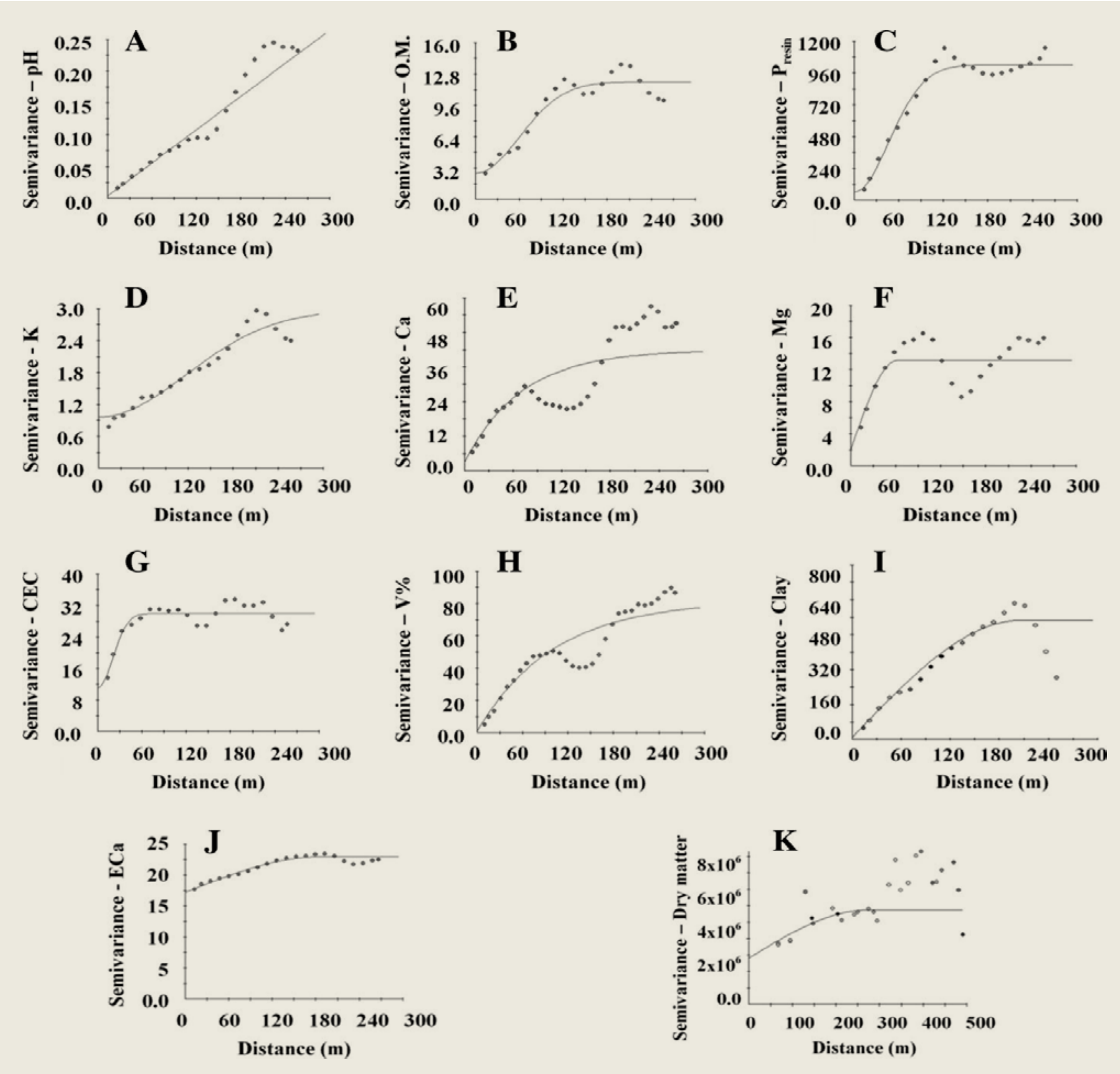

**Fig. 2.** Semi-variograms of pH (A); organic matter (B); available P (C); exchangeable K (D); Ca (E); Mg (F); cation exchange capacity (CEC) (G); base saturation-V% (H); clay (I); soil apparent electrical conductivity (ECa) (J); and dry matter yield (K) of a grazed alfalfa pasture in Brazil.

spatial variability of soil properties may be affected by intrinsic and extrinsic factors, such as soil formation factors and soil management practices, respectively (Cambardella *et al.*, 1994). The ranges for the soil parameters were between 62 and 10,000 m (Table 2). These results indicate that a grid spacing of 62 m would be adequate for characterizing the spatial variability of the soil characteristics at this site. Therefore, 2.6 samples ha$^{-1}$ could adequately represent soil spatial variation at this site.

Figure 3 shows the spatial patterns of the soil parameters generated by kriging from the semi-variograms. The range values for soil organic matter (from 19 to 34 g kg$^{-1}$) and cation exchange capacity (from 69 to 92 mmol$_c$ dm$^{-3}$) are considered medium and high, respectively, according to Alvarez Venegas *et al.* (1999) to Brazilian tropical soils.

The minimum values of soil Ca and Mg (26 and 12 mmol$_c$ dm$^{-3}$)

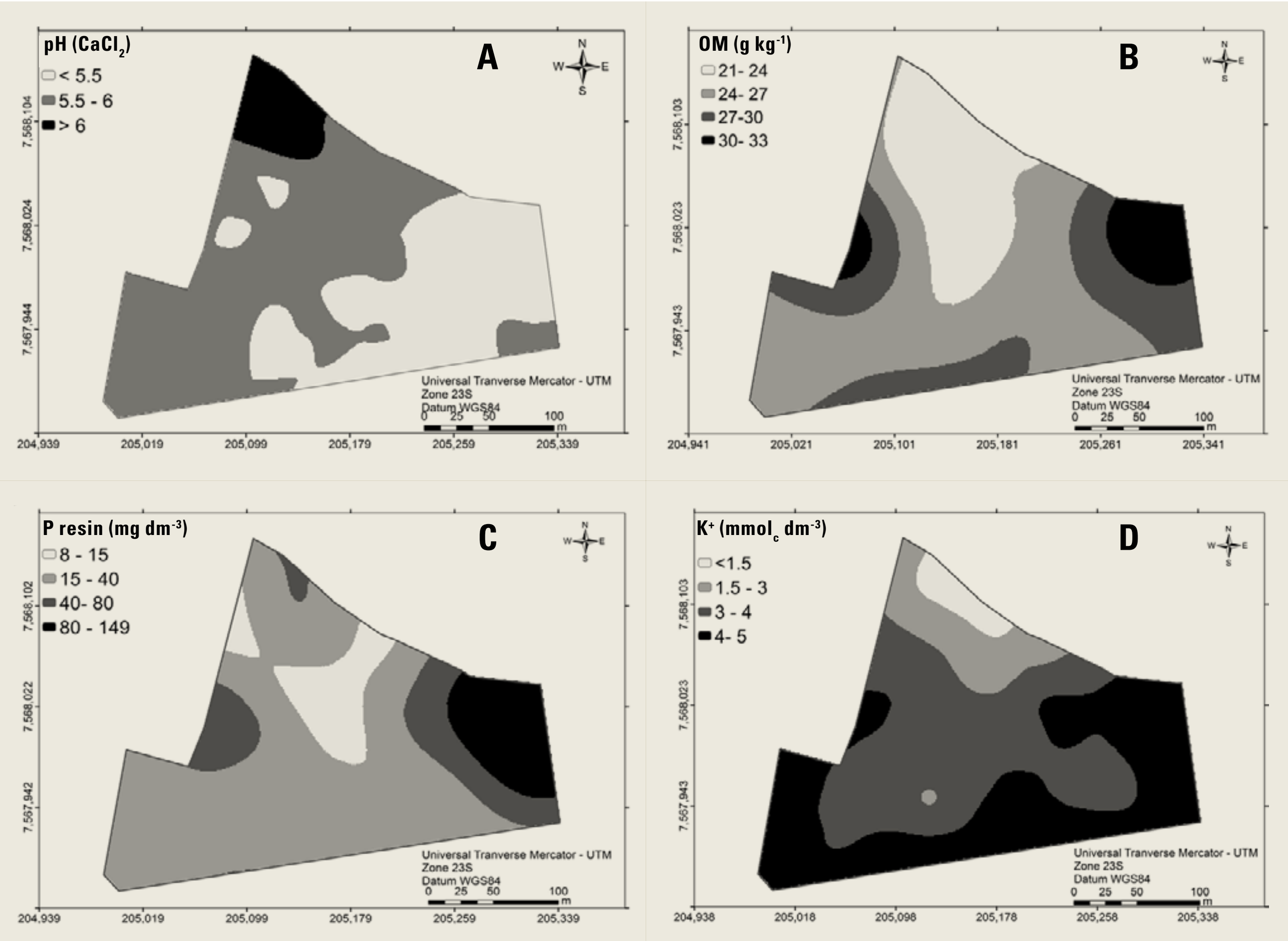


**Fig. 3A-D.** Kriged maps for pH (A); organic matter (B); available P (C); exchangeable K (D); of a grazed alfalfa pasture in Brazil.

were higher than 7 and 8 $mmol_c\ dm^{-3}$, which is considered high (Raij *et al.*, 1997). These results could indicate that the soil Ca and Mg were sufficient, but the requirement for lime is also determined by the base saturation.

There is a direct relationship between soil pH and base saturation because negative charge formation is dependent on the pH of the soil solution. The pH values were considered low (up to 6.0) to very low (over 6.0), and base saturation ranged from medium (51–70 %) to high (71–90 %) (Raij *et al.*, 1997).

The most variable classifications were obtained for soil P and K. Soil P levels (Fig. 3C) were classified into four groups (Raij *et al.*, 1997): low (6-12 mg $dm^{-3}$), medium (13-30 mg $dm^{-3}$), high (31-60 mg $dm^{-3}$) and very high (>60 mg $dm^{-3}$). The class considered medium represented 65 % of total area, and the high and very high levels represented 25 %. Soil K levels also were classified into four groups: low (0.8-1.5 $mmol_c\ dm^{-3}$), medium (1.6–3.0 $mmol_c\ dm^{-3}$), high (3.1-6.0 $mmol_c\ dm^{-3}$) and very high (>6.0 $mmol_c\ dm^{-3}$). The higher K levels included 84% of the total area. These levels will affect the fertilizer needs, the productivity standards (Stefanski and Simpson, 2010) and production costs.

Kriged estimates for soil texture and ECa were contoured and mapped, and their patterns of variation in the field are shown in Fig. 4. The soil texture was clay and very homogenous, and less than 2 % of the studied area had less than 600 g $kg^{-1}$ of clay content. ECa values ranged from 2 to 11 mS $m^{-1}$.

The soil fertility maps (Fig. 3) obtained from VESPER (Minasny *et al.*, 2005) in the raster mode were converted to vector mode in ArcGIS [Environmental Systems Research Institute (ESRI)] Inc., 2009). Vector polygons were then created for each soil fertility class. Numerical values were assigned to the classifications: 1 for low, 2 for medium, 3 for high and 4 for very high. Using SPRING

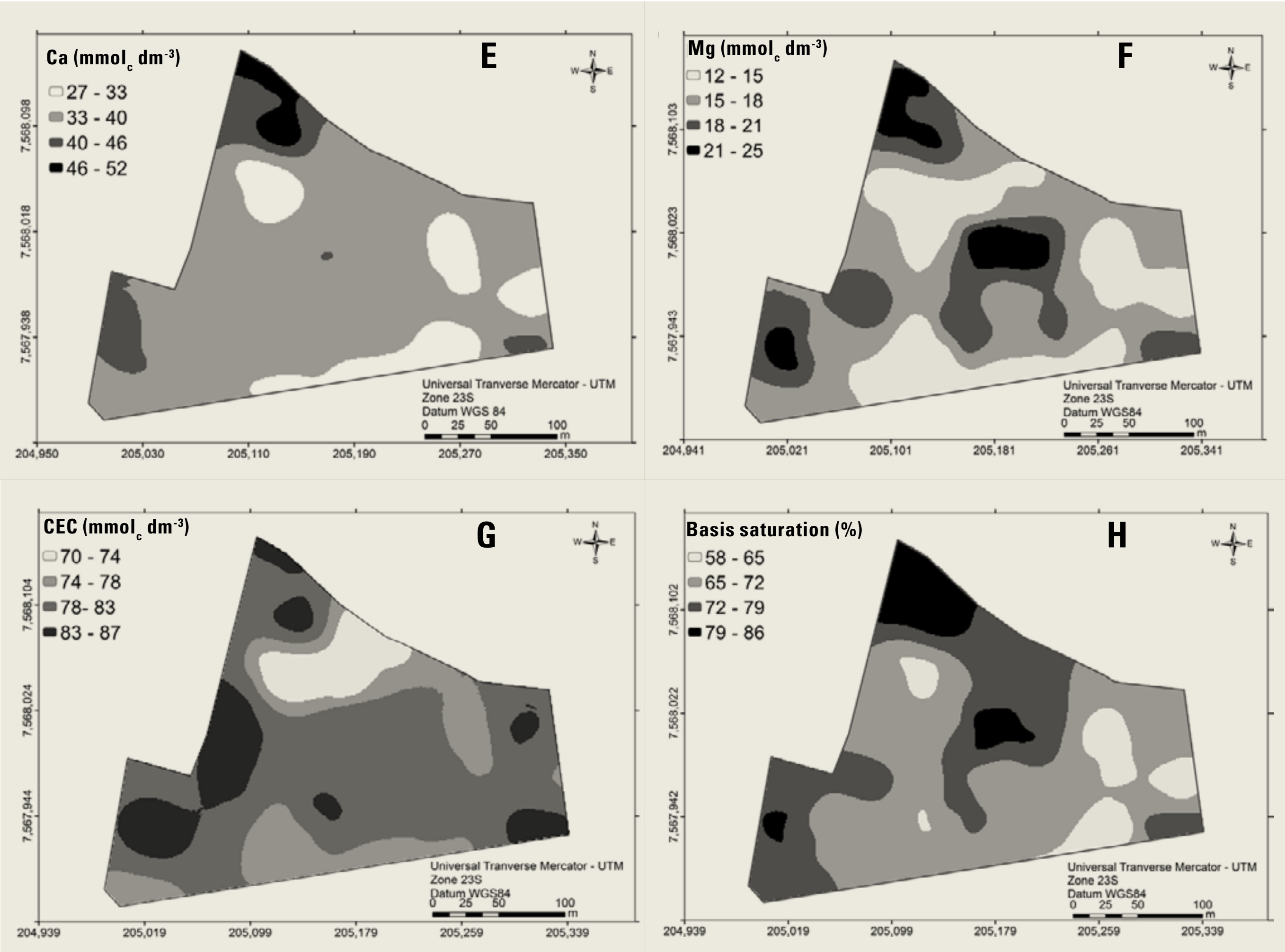


**Fig. 3E-H.** Kriged maps for Ca (E); Mg (F); cation exchange capacity (CEC) (G); and base saturation-V% (H) of a grazed alfalfa pasture in Brazil; of a grazed alfalfa pasture in Brazil.

(Camara *et al.*, 1996), all the vector polygons were converted to matrix mode and compared in a soil fertility classification map (Fig. 4C) that represented the average of all polygons. Two soil fertility classes, medium and high, were established. Because soil ECa integrates soil properties such as soil texture, soil organic matter, cation exchange capacity and exchangeable basis, the regions with lower values are the same as the regions classified as ''medium soil fertility''. One aspect that can affect the correlation of ECa with other soil properties is the different soil layer assessed. Serrano *et al.* (2010) had observed positive correlations of ECa with soil pH and pasture dry matter yield, but there were no significant correlations between the EC and parameters such as clay and soil organic matter.

Liming and fertilizer site-specific recommendations for alfalfa pasture were based mainly on soil analysis (Moreira *et al.*, 2008). Limestone rates are calculated to raise soil base saturation (V%) as a percentage of the soil cation exchange capacity (CEC) at pH 7.0. In alfalfa pastures, V% should be increased to 80 % (Moreira *et al.*, 2008) for the best results. Liming is the lower cost and more efficient way to neutralize soil acidity, reducing Al and Mn toxicity, improving P, Ca and Mg availability, increasing CEC, promoting $N_2$ fixation and improving soil structure (Moreira *et al.*, 2008). The amount of liming in Fig. 5A was calculated to reach V = 80 %. The liming recommendation map indicated that the application rate should be up to 1.2 t ha$^{-1}$ in 44 % of the area (2.4 ha) and up to 1.6 t ha$^{-1}$ in 9 % of the area. Twenty-two percent of the area needs less than 360 kg ha$^{-1}$, and 25 % should receive up to 770 kg ha$^{-1}$.

The P recommendation was based on ion exchange resin-extractable P availability and the amount needed to reach 20 mg dm$^{-3}$ (Moreira *et al.*, 2008). The site-specific map (Fig. 5B indicated that 68 % of the area should receive up to 500 kg ha$^{-1}$

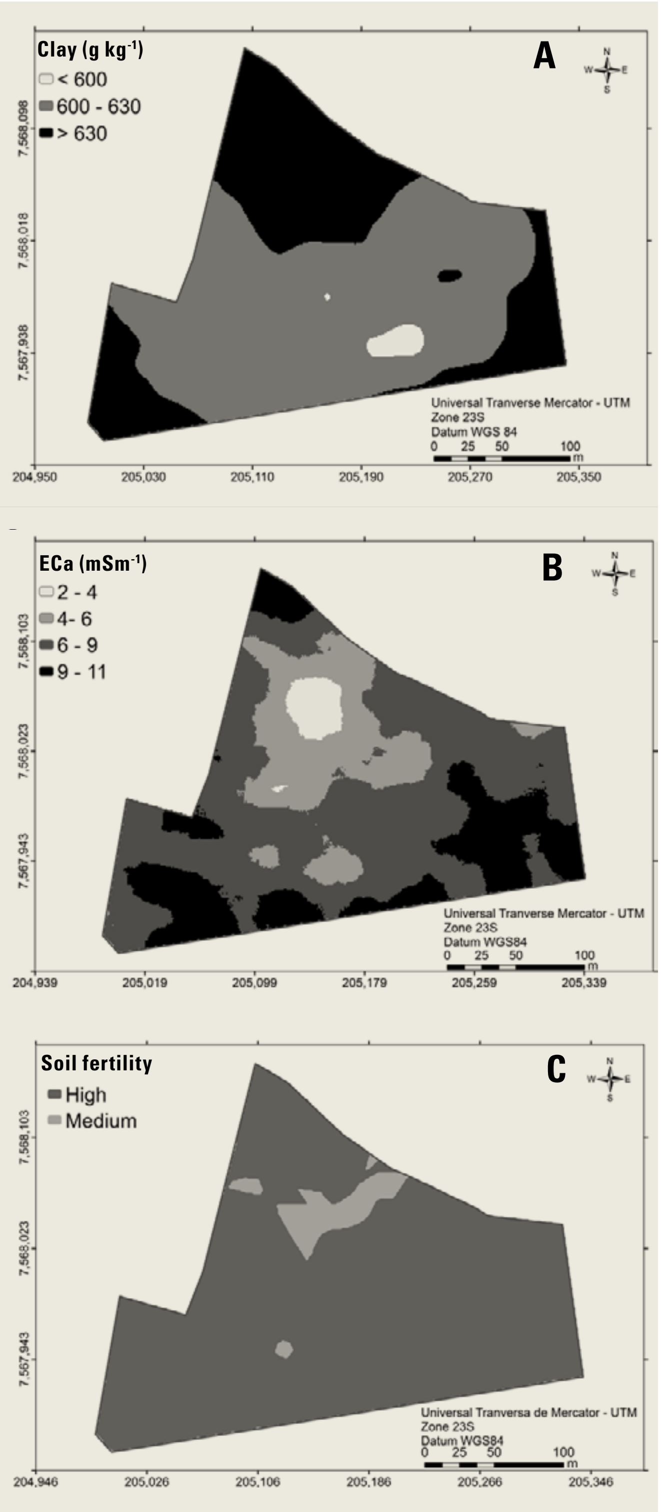


**Fig. 4.** Kriged maps for clay (A), soil apparent electrical conductivity ECa (B) and fertility (C) of a grazed alfalfa pasture in Brazil.

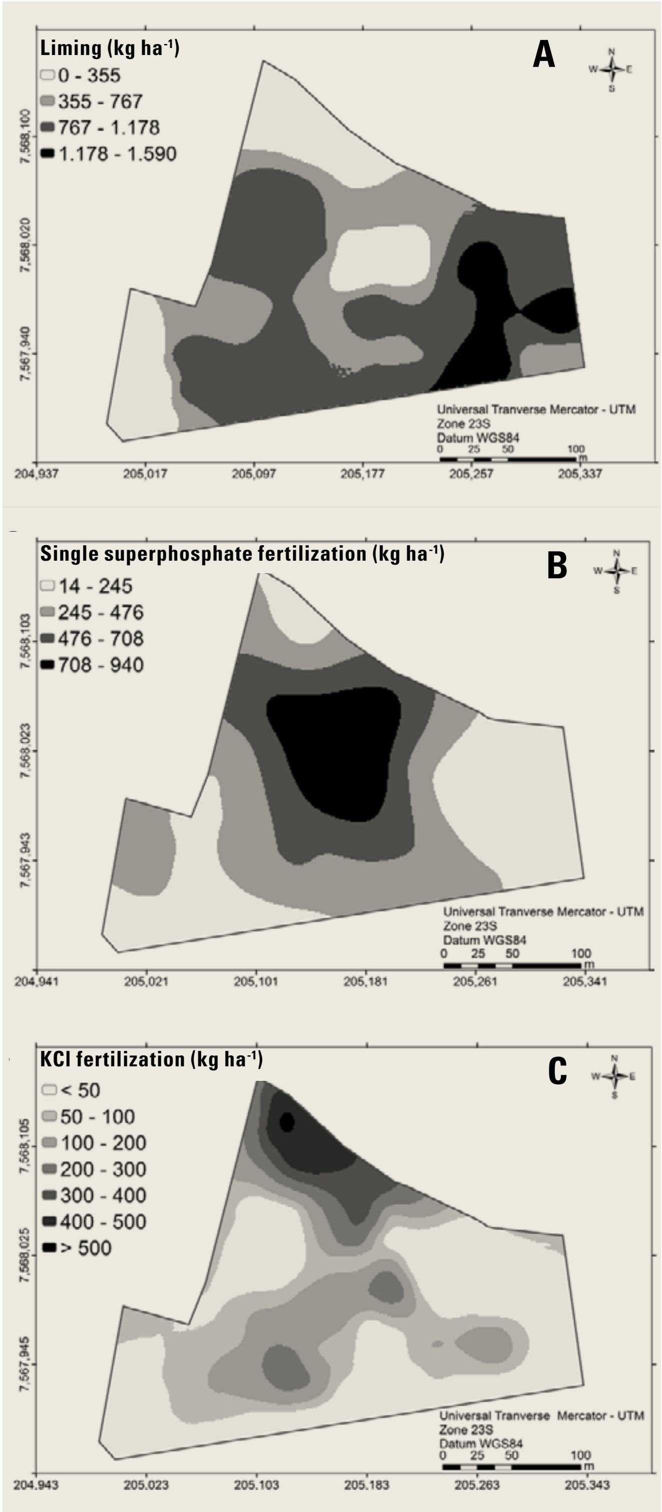


**Fig. 5.** Kriged maps for liming (A), single superphosphate fertilization (B), and KCl fertilization (C) of a grazed alfalfa pasture in Brazil.

of single superphosphate. Single superphosphate is needed to increase soil P levels and improve the N-fixing capacity of alfalfa pasture. Gillingham (2001), McCormick *et al.* (2009) and Serrano *et al.* (2010) also reported great differences in P levels of pasture soils. Higher amounts were recommended for the rest of the area (42 %). Potassium rates were recommended based on the values of soil exchangeable K needed to reach 5 % of the cation exchange capacity (CEC), according to the recommendation of Bernardi *et al.* (2013b). Most of the area (85 %) should receive up to 200 kg $ha^{-1}$ of KCl (Fig. 5C). The results of this study suggest that lime and fertilizers VRA could provide improvements in biomass yield and optimization in nutrient use. McCormick *et al.* (2009), Fu *et al.* (2010) and Trotter *et al.* (2014) also successfully established site-specific nutrient fertilizer maps based on soil nutrient availability for grazing systems. However, a proper diagnosis of the limiting factors of pastures have to be implemented, since increasing nutrient application rates where pasture growth is constrained by factors other than soil fertility may not lead to increased yields (Gillingham, 2001).

Stocking rate is a key management variable for determining productivity and profitability of grazing systems. This rate determines the quality of forage, forage use efficiency, animal performance and milk production per area (Fales *et al.*, 1995). Figure 6 illustrates that the simulation based on dry matter yield allowed estimation of stocking rates and milk yield within the area. Maps of this type may be used to avoid over- or under-grazing. Gillingham and Betteridge (2001) already had shown the variability in production within dairy farm paddocks on dairy farms.

Milk yield determines gross revenues. The results of this simulation have shown that an alfalfa pasture adequately supplied with lime and fertilizer can support high stocking rates that result in high milk production per hectare. Therefore, as shown by Fales *et al.* (1995), the optimal stocking rate for a given dairy farm depends on individual farm resources (e.g., land, buildings, cows, etc.). The rate can be adjusted according to local resource constraints, thus avoiding or minimizing significant adverse economic impacts. This approach can help farm managers predict future scenarios and support their management decisions.

The challenges for alfalfa pasture in Brazil are persistent unbalanced soil nutrients that may lead to low forage and milk yields. Research data (Bernardi *et al.*, 2013a; 2013b) showed that large gains in pasture productivity and nutrient maintenance are possible when soil fertility constraints are overcome. Precision agriculture tools help reveal nutrient heterogeneity (Gillingham and Betteridge, 2001; Schellberg *et al.*, 2008; Trotter *et al.*, 2014) and indicate where to implement PA in a competitive and cost-efficient manner.

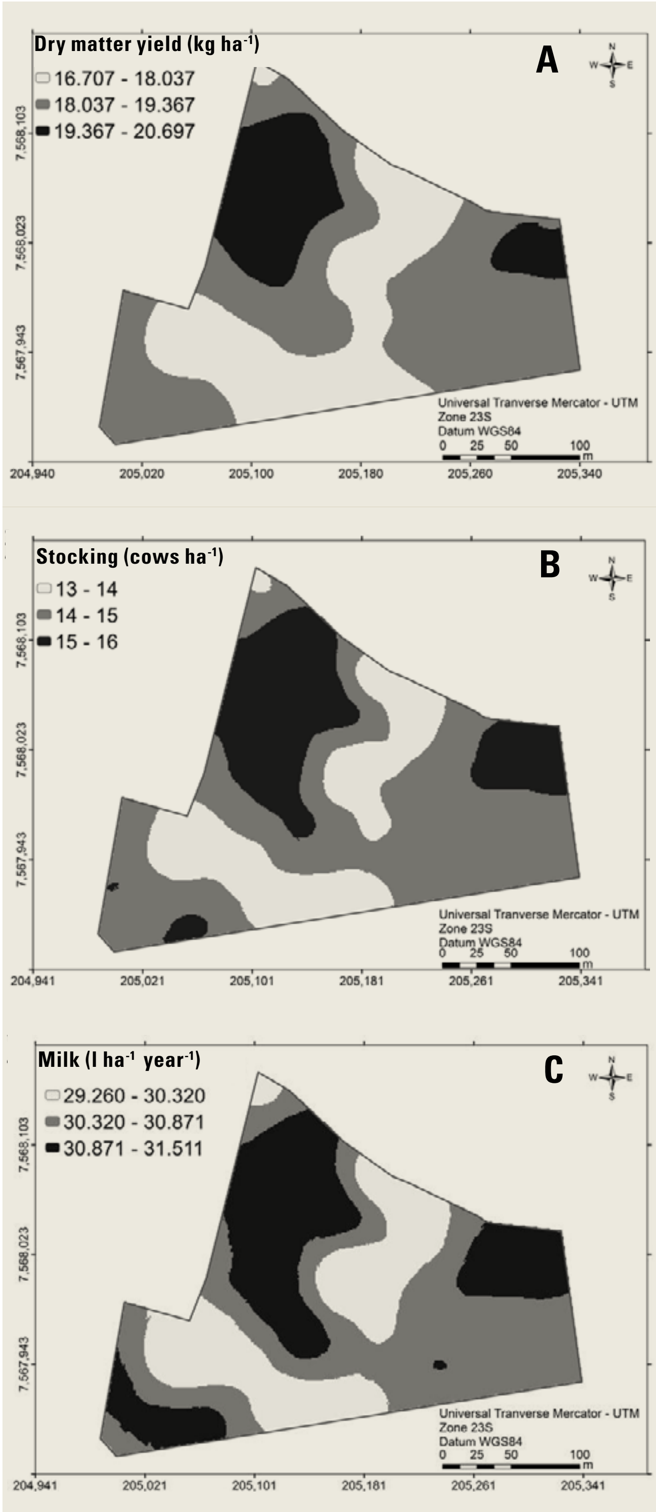

**Fig. 6.** Kriged maps for dry matter yield (A), stocking rate (B), and milk yield (C) of a grazed alfalfa pasture in Brazil.

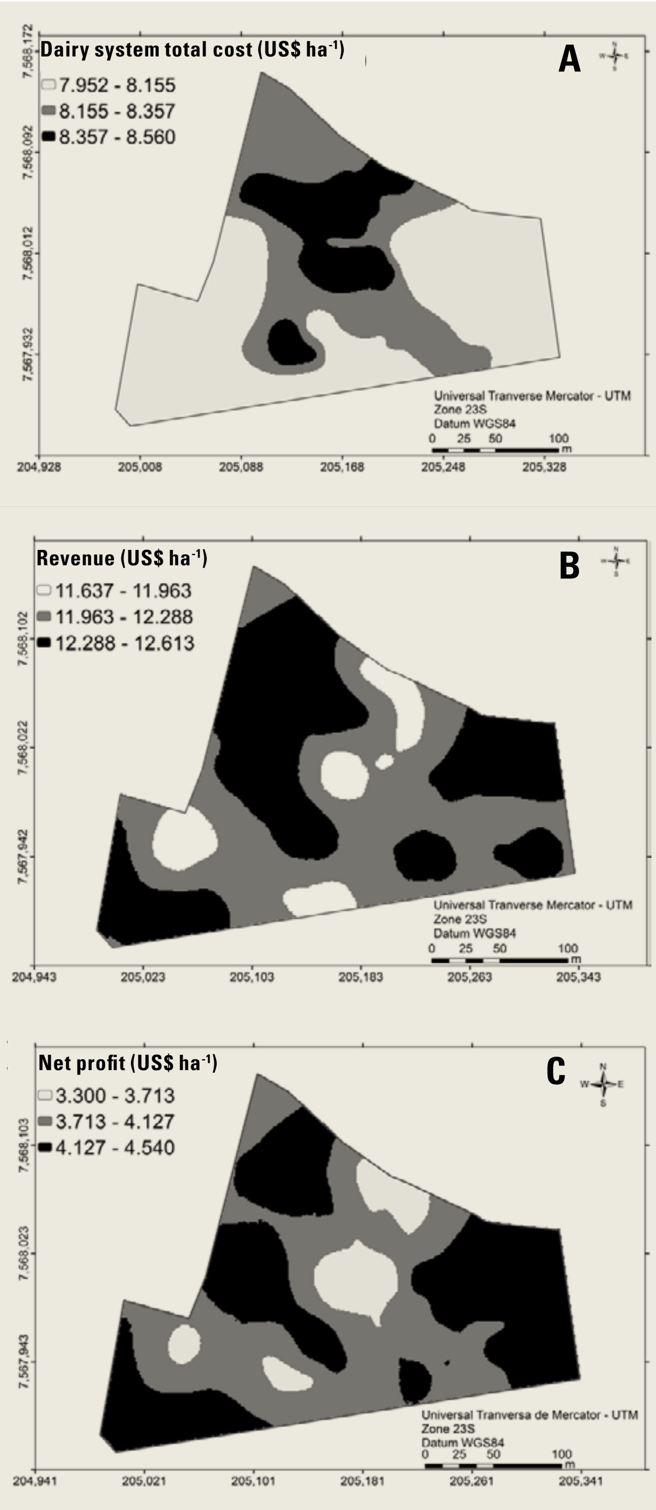


**Fig. 7.** Kriged maps for production cost (A), gross revenue (B), and net profit (C) of a grazed alfalfa pasture in Brazil.

In a dairy system, low economic returns may reduce farm investment and pasture productivity. This is particularly true when alfalfa is grown on tropical soils, where the constant replenishment of nutrients is a major constraint. Economic profitability of this dairy system was estimated based on the cost of production, including the VRT application of lime and P and K fertilizer, and the revenue from milk yield. The maps in Fig. 7 illustrate the spatial heterogeneity of costs (a), revenue (b) and net profit (c). Almost 10 % of the alfalfa pasture area is approximately 19 % less profitable than the best area. The cost of P fertilizer may be a decisive factor in the economic balance of the system as Fu *et al.* (2010), Serrano *et al.* (2011) had also demonstrated. The results obtained in this research confirm the advantages of using PA tools to support management decisions in pasture systems. Results of Gillingham and Betteridge (2001) also had shown that within a 2 ha paddock with three management zones and the VRT recommendation could save about one-third of the usual fertilizer applied without reducing pasture production. According to Gillingham (2001), Fu *et al.* (2010), Serrano *et al.* (2011) and Trotter *et al.* (2014) these kind of maps provide useful information for agronomic and also for environmental management.

The results from this study showed the advantages of the methodology that allows the identification of areas for differentiated paddocks management, instead of homogeneous fertilizer application. So the situation can be further complicated when cattle are involved, since the implementation of precision agriculture in pasture is difficult for the associated temporal variability (Schellberg *et al.*, 2008). Grazing animals are a remarkable source of variability of nutrients in the soil as a result of the heterogeneous deposition of excreta (McCormick *et al.*, 2009). Nevertheless, results from Serrano *et al.* (2011) had shown that temporal stability changes over time and pasture fields should be managed according to the current year's conditions.

## Conclusions

The results showed that geostatistics and GIS were effective tools for revealing soil and pasture spatial variability and supporting management strategies. Soil nutrients were used to classify the soil spatial distribution map and design site-specific lime and fertilizer application maps. Spatial variation in forage and spatial estimates of stocking and milk yield are adequate pasture management tools. Spatial analyses of needs, forage availability and economic return are management tools for avoiding economic problems, as well as potential environmental problems, caused by unbalanced nutrient supplies and over- or under-grazing.

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