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Evaluation of Long Term No Tillage Effects on the Spatial Variability of Crop Yield and Soil Properties

Sidney Rosa VIEIRA[1], Sonia Carmela Falci DECHEN[1]; Antonio PAZ GONZALEZ[2]
[1] Research Scientist, Instituto Agronômico (IAC), Centro de Pesquisa e Desenvolvimento de Solos e Recursos Ambientais, Caixa Postal 28, CEP 13020-902, Campinas, SP, Brazil. E-mail: sidney@iac.sp.gov.br; dechen@iac.sp.gov.br.
[2] Universidade da Coruña, A Coruña, Espanha, Email: tucho@udc.es

Abstract: Soil properties vary in space due to many causes. For this reason it is wise to have knowledge of the magnitude and behavior of the variability for adequate data analysis and decision making. Our work on spatial variability of soil properties in São Paulo, Brazil began in 1982 with a very simple soil sampling in a small field. Much progress has been made since then on sampling designs, field equipment and methods, and mostly on computation equipment and softwares. This paper reports the results corresponding to some aspects of this progress, as far as the field, analysis and computation work are concerned. The objective of this study was to illustrate the use of geostatistics in the data analysis for a variety sampling conditions on long term no tillage system. The analysis is done on a wide range of field scales, variables, sampling schemes as well as repeating sampling scheme for the same variable in different years. Semivariograms are compared for the same variables in different scales and samplings as to provide a guide for sampling spacing and number of samples. Normalized crop yield parameters for many years are used in the discussion of time variability and on the use of yield maps to locate management zones. The time of the year in which measurements of soil physical properties are made affected the results both in terms of descriptive statistical and spatial dependence parameters. Crop yields changed (soybean decrease and Maize increase) with time of no tillage but the real cause was not identified. The length of time with no tillage affected the range of dependence for the main crops (increased for soybean, Maize and oats) and therefore increased the size of the homogeneous management zones. The evolution of the sampling grid from 20m with 63 sampling points to 10m with 302 sampling points allowed for a much better knowledge of the spatial variability of crop yields but it had the reverse effect on the spatial variability of soil physical properties.

Key words: geostatistics, semivariogram, kriging, grain crop yield.

INTRODUCTION

It is generally recognized that soils vary widely over a landscape regarding to their physical, chemical and biological nature. Parent materials and soil formation factors can vary due to their inherent characteristics and also due to conditions imposed by human actions. As a consequence soil properties vary across a landscape in such a way as to reach equilibrium with the environmental conditions. The amount of variation over an area depends on many environmental conditions and how they acted on soil properties over time.

Spatial variability of soil properties has been long known to exist and has to be taken into account every time field sampling is performed. BECKETT and WEBSTER (1971) presented a very comprehensive review with deep discussion of soil variability on soil fertility. Soil variability can also occur as a result of cultivation, land use and erosion. SALVIANO et al., (1998) reported spatial variability in soil attributes as a result of land degradation due to erosion. There have been reports of spatial variability of soil properties, mostly affecting crop yield, since the beginning of this century (MONTGOMERY, 1913; WAYNICK, 1918; HARRIS, 1920), but a comprehensive tool to adequately analyse spatial variability was not available until 1971 (MATHERON, 1971). This tool, called geostatistics, contains a very important component called semivariogram which the amount of similarity between neighboring observations. Semivariograms have been widely used in soil science for a number of physical (VIEIRA et al., 1981), chemical (PAZ GONZÁLEZ et al., 2000) and biological (CAMBARDELLA et al., 1994) soil properties at a range of scales and with different sizes of sampling grids. In the past, important contributions have been made to the discussion on general subjects such as optimal spacing of a regular grid for kriging interpolation (WEBSTER, 1985). In general most of the reports show that the adequate evaluation of soil variability depends largely on the intensity of the sampling design with respect to the size of the area under study. When a spatial structure pattern is not evidenced, it means that spatial variability within that particular sampling design is due to heterogeneity at a scale smaller than the distance between adjoining sampling points. If spatial dependence occurs, then using the semivariogram and by means of kriging interpolation method, values can be obtained optimally for the places not sampled and the corresponding kriging estimation variances can be computed (VIEIRA et al., 1983).

At the beginning of the last century there was a large concern on the effects of soil variability over field trials and experiments (HARRIS, 1920). The statistical knowledge available at that time recommended the use of classical statistical methods which requires that the variable under investigation be normally distributed and spatially independent (SNEDECOR and COCHRAN, 1967). As the field equipments and methods got developed, the numerical knowledge of variability became increasingly evident and had to be somehow considered. Soil properties and crop yield components, instead of having random spatial distributions, have been reported to have spatial dependence, meaning that the observations are somehow related to their neighbours (VAUCLIN et al., 1982; VIEIRA et al., 1983; MILLER et al., 1988; SOUZA et al., 1997; MULLA, 1993). It seems obvious that the existence of spatial dependence is scale dependent. VIEIRA (1997) found spatial dependence for soil fertility properties within an experimental plot of 30 by 30 m. On the other hand, the mean annual rainfall in the state of São Paulo, Brazil showed spatial dependence up to 70 km (VIEIRA and LOMBARDI NETO, 1995). The assessment of spatial dependence requires the application of geostatistical procedures such as the analysis of semivariograms (VIEIRA, 2000) using kriging (VIEIRA et al., 1983; VIEIRA and LOMBARDI NETO, 1995; VIEIRA, 1997), cokriging (VAUCLIN et al., 1983) and analysing maps produced with the interpolated values. Geostatistical techniques, including non-parametric models have been further developed in the last years, so that different algorithms producing different error of interpolation are now available (GOOVAERTS, 1997). Nevertheless, ordinary kriging is still the most widely used interpolation method (VIEIRA, 2000).

Long term experiments under tropical conditions using no tillage are rare. Although it is known that the efficiency of the no tillage system in conserving soil and water is climate dependent it is still a very recommended management system mainly because it preserves the soil structure from one year to the next (CASTRO et al., 2005). Therefore, there are reasons to believe that soil physical properties will tend to remain unchanged after the no tillage system has been fully established, if the sampling and measuring tools are appropriate. On the other hand, changes in soil physical properties over time of no tillage adoption may help the understanding of crop yield spatial distribution pattern not repeating over time. Moreover, besides affecting the soil water regime, the no tillage system also requires unique fertilizer management as most of the fertilizer and liming is place at or close to the soil surface (MUZILLI, 1981).

The objective of this study was to illustrate the use of geostatistics in the data analysis for a variety of sampling conditions on long term no tillage system.

MATERIAL AND METHODS

2.1 Study site

The experimental area measuring 3.42ha is located within the Campinas Experimental Center of Instituto Agronômico, Campinas, SP, Brazil, where the parent materials for the soils are dominated by basalt rocks. The soil is a clay texture named Latossolo Vermelho eutroférrico (EMBRAPA, 2006) (Rhodic Eutrudox), located in a field of about 10% slope. A 3.42ha field sampled in three different ways, according to figure 1: a) from 1985 to 1995 the field was sampled at 63 points on a 20m square grid; b) from 1996 to 2002 the field was sampled at 81 points on a 10m square grid; c) from 2003 to 2008 the field was sampled at 302 points on a 10m square grid. Since 1985 this field is being cultivated with grain cereal crops under no tillage. The altitude is about

630m above sea level, in a rolling topography with a slope range between 6 and 10%. The primary reasons for the selection of the site were the apparent natural variability as indicated by the spontaneous vegetation previous to the beginning of the experiment and the representation for other regions with the same soil type. The climate is subtropical with a mean annual rainfall of about 1500 mm, with 5-6 wet months (November to March) although between year variability may be rather large. The field was regularly sampled every harvest time for the summer and winter crops in 2 x 2.5 m subplots, by cutting and weighing all mass above the soil. The cropping history of the site involves the use of no tillage system on grain crops, most of the time with two crops per year, for the last 23 years. In the first months of 1985 the field was cleared with bulldozer then moldboard plowed and disk harrowed and in April 1985 cultivated with Crotalaria juncea, without fertilizer addition or lime amendments. After the flowering of the Crotalaria juncea, 4000 kg/ha of lime was added while tilling the soil. Since then the field has been devoted to no tillage annual crops.

2.2 Samplings and analysis

2.2.1 Soil sampling and field measurements

Soil samples were taken from each one of the 63 sampling points (figure 1) at 0-25cm depth for texture chemical analysis in June 1985 and August 1988. Soil texture was performed using the pipette method for the clay and silt fractions, and sieving for 5 sand fractions according to CAMARGO et al. (1986). One hundred cm3 core samples were collected at each one of the 63 sampling (figure 1) at 0-10 and 10-25cm depth for bulk density and porosity determination in the laboratory, in June 1985 and in August 1989. In April 2002 a sampling was made at 0-10cm depth collecting samples on 10 x 10m grid shown in figure 1 but skipping every other column so that the final sampling was then on 30m spacing in one direction and 10m spacing on the other. Soil samples were collected on the 10m square grid in April 2004 at 10cm depth. Soil cores were collected again at 10cm depth on the 302 points (figure 1) in March 2005. Saturated infiltration rate was measured on the 63 sampling points in 1990, on the 81 sampling points with 5 replicates en 1996, in the 302 sampling points in September 2002, July 2003, September 2003 and July 2008 with the constant head field permeameter (VIEIRA, 1998).

2.2.2 Crop yield components

The crop yield components were measured in plots of 2 x 2.5m, adjacent to the sampling points, measuring the final crop population, the total amount of straw and grain for each one of the crops. Crop yields were measured in 23 harvestings from which, only soybean and maize will be analyzed in this paper as shown in Table 2.

2.2.3 Statistical methods

The statistical analysis used in this study involves an exploratory analysis with the examination of averages, coefficients of variation, extreme values and normal distribution coefficients. The examination of the temporal evolution of descriptive statistical parameters over different sampling intensities may be useful to identify the adequate conditions for future work.

When data are sampled in such a way as to allow for the application of geostatistical analysis, the spatial dependence, according to VIEIRA et al. (1983) can be evaluated by examining the semivariogram, which can be calculated using equation (2),

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

where N(h) is the number of pairs of values Z(xi), Z(xi+h) separated by a vector h. If the semivariogram increases with distance and stabilises at the a priori variance value, it means that the variable under study is spatially correlated and all neighbours within the correlation range can be used to interpolate values where they were not measured. Semivariograms may be scaled by dividing each semivariance value by a constant such as the square of the mean and the variance value, as VIEIRA et al. (1997) suggested.

The calculation of the experimental semivariograms was carried out while checking for possible trends in the data sets. Omnidirectional semivariograms were calculated using the program in VIEIRA et al. (2002b). When semivariograms are calculated using equation (2), the result is a set of discrete values of distances along with the corresponding semivariances. Because any geostatistical calculation will require semivariances for any distance within the measured domain, there is a need to fit a mathematical model that would describe the variability. Semivariogram modeling is the foundation for geostatistical analysis, and can also be the most difficult and time consuming portion of the analysis. In part, this is due to the computationally intensive calculations, but it is also due to the difficulty in defining semivariogram models which reasonably honor the experimental semivariograms (McBRATNEY and WEBSTER, 1986). VIEIRA (2000) describes the model fitting process and the cross validation of the fitted models. In this paper, the semivariograms used were fitted to either he spherical model

$$\gamma(h) = C_0 + C_1\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] \qquad 0 < h \le a \tag{3}$$

$$\gamma(h) = C_0 + C_1 \qquad h > a$$

or the exponential model

$$\gamma(h) = C_0 + C_1\left[1 - \exp\left(-3\frac{h}{a}\right)\right] \qquad 0 < h < d \tag{4}$$

where C0 is the nugget effect, C1 is the structural variance, a the range of spatial dependence and d is the maximum distance over the field. These are the three parameters used in the semivariogram model fitting. Models were fit using least squares minimization and judgement of the coefficient of determination. Whenever there was any doubt on the parameters and model fit, the jack knifing procedure was used to validate the model, according to VIEIRA (2000).

The dependence degree (DD) was calculated for all semivariograms that showed spatial dependence according to ZIMBACK (2001).

The graphical representation of semivariogram parameters over time can reveal important changes in soil physical properties as a function of time of using no tillage system. This kind of analysis can help the understanding of the reasons why crop yield maps quite often do not repeat in time.

RESULTS AND DISCUSSION

The descriptive statistical parameters for the soil physical properties under study are shown in table 1. Except for the infiltration data, all other attributes approach a normal distribution as the coefficients of skewness and of kurtosis are very close to zero (0). These coefficients for the infiltration data indicate that they have a great number of small values and a few values really large as to make the distribution to approach a log normal. Infiltration rate values are very well known to have skewed distribution such as this (VIEIRA et al., 1981).

The range of variation for the mean values for clay content (from 540 to 606.2 g/kg) shown in table 1 are not very easily explained since these samples come all from the same soil with only different sampling strategies. One possible explanation for these differences is the laboratory method as the sampling made in 2002 in 102 points was analyzed using the pipette method while the others were all analyzed using the soil hygrometer method. According with CAMARGO et al, (1986) the soil hygrometer method tends to overestimate the clay content for soils situated in the clay texture class or above. On the other hand, the coefficients of variation for clay content are all very low (below 7%) indicating that the variation of this attribute over field of the scale under study is small.

The porosity results are within usual values reported in the literature (VIEIRA et al., 2002a, SIQUEIRA et al. 2008) with very low coefficients of variation (CV) and approaching a normal distribution for all the samplings analyzed.

All of the infiltration rate measurements were made using the same method (VIEIRA, 1998) varying only the number of samples (63, 397, 302 and 299) and the sampling grid (20m grid for the 63 samples, 10m grid in the 81 sampling points with five replications for the 397 points, 10m grid for 302 samples, where the last one had 3 missing values). However, one factor that may have been significant is the month at which the sampling took place both because of the cracks developed in this soil in the dry season (May to September) and also and very importantly the crop present at the time of sampling. The samplings made in 07/2003 and 09/2003, have large mean values because of the effect of cracks but also because it was right after two grass crops (Maize in the summer and Sorghum in the winter season). The grass crop root system seem to have a major effect on soil infiltration rate and so does soil structure cracks VIEIRA et al., 1988). The infiltration measured in 1990 (216.4 mm/h) was done in January on soybean crop, the one in 1996 (109.2 mm/h) was in January in fallow condition, and the one measured in 2002 (207.7 mm/h) was also in January in labelabe (leguminous crop). Obviously the leguminous crop root system does not have the same effect over infiltration as the grass crops.

The statistical parameters for the normalized yields for soybean and maize over the 23 years of no tillage are shown in table 2. In general the mean yields for the large majority are below 0.5, but most of the time the Maize yields are larger than the soybean. Except for maize 1998, the coefficients of variation (CV) for all crops are all above 30%. The irregular rainfall distribution and weed population are the only factors that may heve chaged from one year to the other. It is noticeable the large variation for the same crop in different years, fact that makes it difficult to use yield maps for the delineation of management zones. MULLA (1993) reports on the problem of yield maps not repeating from one year to another for precision agriculture decisions.

The mean values for infiltration, porosity and clay content for the various samplings are shown in figure 2. The error bars were plotted as one standard deviation above and below the mean values for illustration of the variation between samplings. The infiltration values (figure 2a) are the ones that show largest variation from one sampling to the other for the reasons already discussed above, and also have the highest values for the error bars. Notice that the larger infiltration values for the 2003 sampling are also the ones that showed the largest error bars, which means that it also had the largest variability. VIEIRA et al., (1988) reported on a high variability of infiltration measured using the same method used in this study. The porosity mean values (figure 3b) indicate that the no tillage system is reaching some equilibrium with time as far the soil structure. In figure 3c it is better illustrated that the results for clay content for 2002 should not be in this discussion because of the different laboratory method which produced a very different value as compared to the others. We only decided to keep in the analysis to emphasize the point that these data are not comparable with the others. Notice that the Y axis of figures 3b and c do not cross at the zero value. Therefore, there is a graphical illusion of a large difference.

Tables 3 and 4 show the parameters for the models fitted to semivariograms for the soil physical properties and for the yield data. From 23 semivariograms, twelve were fitted with exponential models and eleven with spherical. McBRATNEY and WEBSTER (1986) pointed out that the spherical model is the one that occurs for most of the situations. The dependence degree values calculated according to ZIMBACK (2001) (last column in tables 3 and 4) are in general high indicating enough spatial dependence in order to use kriging interpolation. VIEIRA (2000) recommends that kriging interpolation will not have any advantage to other interpolation procedures if the dependence degree is below 10%. The smallest dependence degree values are for infiltration, a variable that has a very high random variation owing to its nature of being dependent of many other variables such as root and worm canals and soil cracks (VIEIRA et al., 1981). The range of spatial dependence found for most variables indicates that the present sampling strategy with 302 sampling points on a 10m square grid is enough for most geostatistical evaluations in this field.

The temporal evolution of the dependence degree for clay content, porosity and infiltration are shown in figure 3. For all the variables, in general, there was a decrease in the above parameters with the time with no tillage. The most noticeable of this is the decrease in the dependence degree for porosity (figure 3b) reaching a value just below 20% for the 2005 sampling. It is possible that this values are also reaching a stable situation with the time of no tillage developing the soil structure. It is also noticeable the decrease in dependence degree for clay content (figure 3c). GREGO e VIERA (2005) found spatial dependence for clay content in a small experimental plot.

The temporal evolution of the mean values for yield for soybean and maize and the corresponding coefficients of variation (CV) is shown in figure 4. A linear trend line was added to illustrate the temporal evolution. In figure 4a are the mean yields of soybean as a function of time. The soybean yield showed a significant yield decrease with time and the maize yield, on the other hand showed a slight increase. It is believed that the dispersion fromone year to another may be due to climatical conditions and weed population competition. Conversely, the coefficients of variation for soybean increased and for maize decreased with time of no tillage (figure 4).

Figure 5 shows the temporal evolution of some semivariogram parameters for soybean. Figure 5a shows the nugget effect values as a function of the time of no tillage. The spatial continuity for soybean increased significantly with time as the nugget effect values drastically decreased. The dependence degree remained somewhat stable over time of no tillage and the range of dependence showed a slight increase with time. That means that the soybean yield is progressively becoming more uniform over time.

The time evolution for the semivariogram parameters for maize yield (figure 6) reveals results completely reverse to the ones found for soybean (figure 5). While soybean showed an increase in spatial continuity as shown by the decrease in nugget effect values (figure 5) the maize crop showed a very pronounced increase. Therefore, as the time with no tillage progresses the maize crop yield becomes more discontinuous over space. The way these two crops interact with the soil condition may have been the main factor for these results. The range of dependence for maize showed a very high decrease with time, meaning the size of uniform regions for this crop decrease with time, a result that may be of high relevance for site specific management. It should be remembered that at about 10 years (1995) was also when there a change in sampling spacing from 20m square grid to 10m square grid. That means that the shorter spacing improved the assessment of the spatial variability for crop yields and allowed for enough information in order to suggest some management zone establishing in the field.

Long term and frequently monitored no tillage experiments are rare mostly within tropical conditions. VIEIRA et al., (2002a) report on some changes in soil physical properties under no tillage and crop rotation and concluded that both bolk density and saturated hydraulic conductivity are significantly affected by the changes in organic matter content. CARVALHO et al, (2002) investigated the effect of soil tillage on the spatial variability of soil chemical properties and concluded that the no tillage promoted a significant increase in the organic matter content

CONCLUSIONS

The time of the year in which measurements of soil physical properties are made affected the results both in terms of descriptive statistical and spatial dependence parameters.

Crop yields changed (soybean decrease and Maize increase) with time of no tillage but the real cause was not identified.

The length of time with no tillage affected the range of dependence (increased for soybean and decreased for maize) and therefore changed the size of the homogeneous management zones.

The evolution of the sampling grid from 20m with 63 sampling points to 10m with 302 sampling points allowed for a much better knowledge of the spatial variability of crop yields but it had the reverse effect on the spatial variability of soil physical properties.

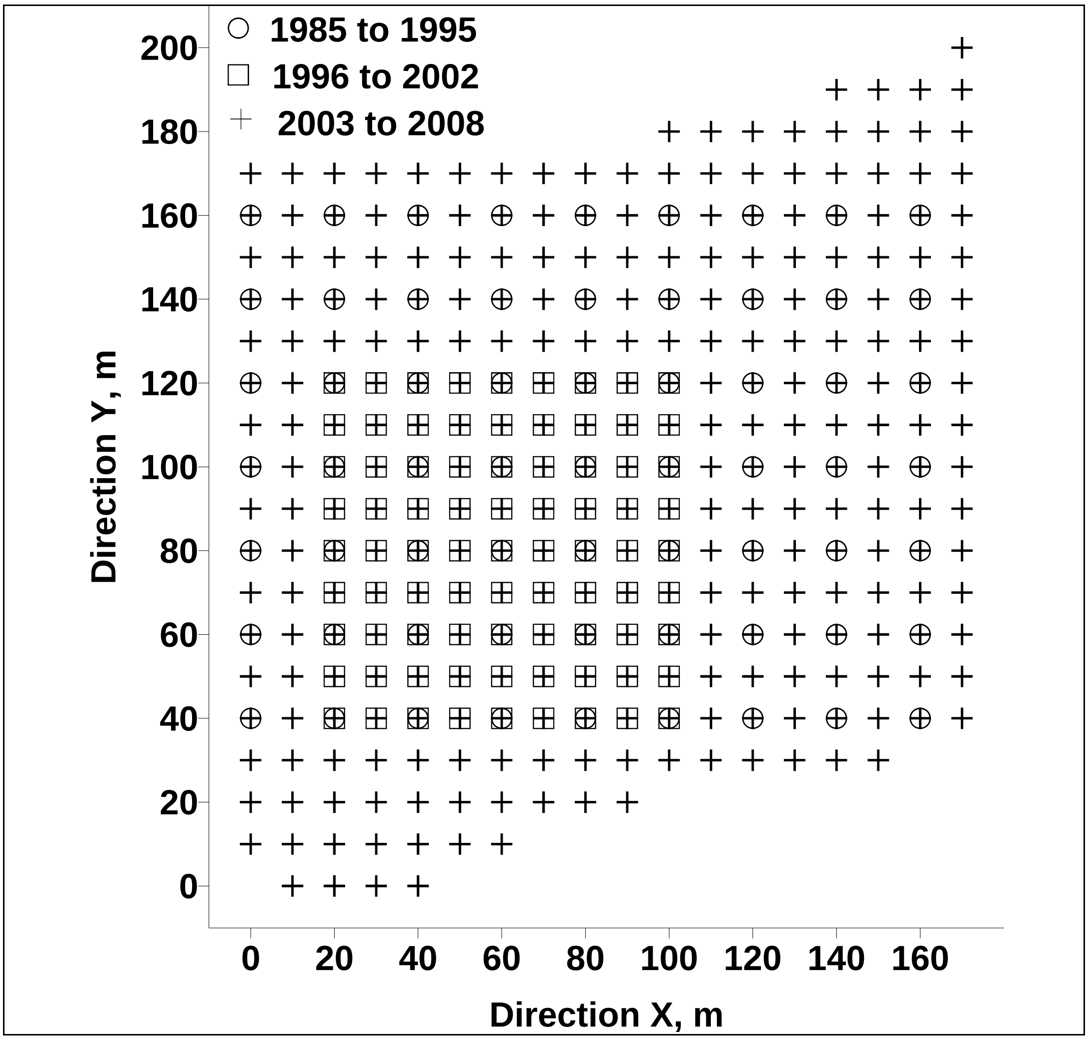

Figure 1. Sampling lay outused from 1985 to 2008 according to the legend in the map.

Table 1. Descriptive statistical parameters for soil properties analyzed.

Variable	Unit	N	Mean	S.D.	C.V.	Min	Max	Skew	Kurt
Clay 63 25cm 1985	g/kg	63	584.1	29.93	5.12	490	640	-0.869	0.842
Clay 63 25cm 1988	g/kg	63	580.5	27.44	4.73	500	640	-0.704	0.689
Clay 102 10cm 2002	g/kg	102	540.0	34.95	6.47	413	613	-0.253	0.695
Clay 302 10cm 2004	g/kg	302	606.2	34.13	5.63	500	700	-0.125	0.015
Porosity 63 1985	cm^3/cm^3	63	0.54	0.04	6.50	0.46	0.62	-0.275	-0.245
Porosity 63 1989	cm^3/cm^3	63	0.55	0.02	4.03	0.50	0.60	-0.029	-0.177
Porosity 302 2005	cm^3/cm^3	302	0.54	0.03	5.33	0.44	0.65	0.028	0.618
Infiltration 63 1990	mm/h	63	216.4	211.6	97.78	10.7	966	1.631	2.908
Infiltration 397 1996	mm/h	397	109.2	123.5	113.1	3.477	1613	6.145	60.37
Infiltration 302 2002	mm/h	302	207.7	152.1	73.22	24.56	923.3	2.043	5.108
Infiltration 302 07/2003	mm/h	302	523.7	375.6	71.72	73.87	2650	2.091	5.722
Infiltration 302 09/2003	mm/h	302	454.0	350.2	77.13	36.93	2216	1.908	4.333
Infiltration 299 07/2008	mm/h	299	147.2	93.16	63.31	8.364	518.6	1.365	2.120

Table 2. Descriptive statistical parameters for crop yields.

Name	Mean	S.D.	C.V.	Min	Max	Skew	Kurt
			Soybean				
1985	1149.0	308.5	26.8	342.4	1952.0	0.115	0.456
1987	3135.0	605.9	19.3	1917.0	4500.0	0.224	-0.476
1988	2851.0	498.4	17.5	1389.0	3918.0	-0.360	0.403
1990	4478.0	1106.0	24.7	2201.0	8462.0	0.978	2.505
1991	1353.0	371.3	27.4	536.8	2768.0	1.074	2.743
1994	2719.0	653.6	24.0	1170.0	3970.0	-0.287	-0.152
2007	1238.0	283.9	22.9	560.0	2080.0	0.441	0.047
2008	1303.0	412.7	31.7	356.0	2578.0	0.638	-0.090
			Maize				
1986	5686.0	1273.0	22.4	2400.0	7650.0	-0.443	-0.547
1993	2083.0	510.0	24.5	1093.0	3663.0	0.430	0.393
1997	3087.0	190.1	6.2	2560.0	3665.0	0.207	1.144
1998	5434.0	380.3	7.0	3980.0	6040.0	-1.545	4.007
2003	7896.0	1891.0	24.0	1604.0	13100.0	-0.604	1.698

Table 3. Parameters of the models fitted to the semivariograms

Variables	Modelo	C_0	C_1	A	r^2	RMSE	DD
Clay 63 25cm 1985	Spherical	302.48	564.44	80	0.5832	7.401	65.11
Clay 63 25cm 1988	Exponential	36.34	727.25	85	0.6038	5.884	95.24
Clay 102 10cm 2002	Exponential	380.08	780.47	70	0.3700	5.113	67.25
Clay 302 10cm 2004	Spherical	645.98	546.64	80	0.7917	2.602	45.84
Porosity 63 1985	Exponential	0.000516	0.000961	60	0.1880	0.000	65.07
Porosity 63 1989	Exponential	0.000354	0.00015	60	0.0883	0.000	29.79
Porosity 302 2005	Exponential	0.00062	0.00013	90	0.1884	0.000	17.12
Infiltration 63 1990	Exponential	9613	45928	80	0.7292	253.581	82.69
Infiltration 397 1996	Exponential	0	6037	26	0.3800	82369	100.00
Infiltration 302 2002	Spherical	15000	5900	84	0.7076	196.252	28.23
Infiltration 302 07/2003	Exponential	83942	33680	30	0.4491	1692.326	28.63
Infiltration 302 09/2003	Exponential	72583	47705	56	0.7664	985.559	39.66
Infiltration 299 07/2008	Exponential	6067	3067	17	0.6701	86.712	33.58

Table 4. Parameters of the models fitted to the semivariograms of normalized yield data

Variable	Model	C_0	C_1	a	r^2	RMSE	DD
			Soybean				
1985	Spherical	40962.4	45957.4	37.7	0.1038	575.13	52.87
1987	Spherical	158794.7	258810.1	77.3	0.8599	1355.99	61.97
1988	Spherical	153295.2	94504.4	22.9	0.0003	2081.77	38.14
1990	Spherical	480186.8	701769.9	80.0	0.5192	6569.72	59.37
1991	Spherical	74823.4	55672.6	80.0	0.3967	909.20	42.66
1994	Spherical	121351.2	348425.1	68.8	0.7187	2253.45	74.17
2007	Spherical	42683.7	32539.1	80.0	0.7748	252.15	43.26
2008	Spherical	59493.3	99896.5	61.5	0.9943	738.79	62.67
			Maize				
1986	Spherical	67891.7	1669581.1	80.0	0.6130	12975.46	96.09
1993	Spherical	157791.8	97769.6	40.3	0.0618	1648.17	38.26
1997	Spherical	32188.2	5202.1	59.4	0.1340	170.30	13.91
1998	Spherical	114323.8	28650.9	60.0	0.1307	974.68	20.04
2003	Spherical	368880.6	2066519.3	32.4	0.8201	57491.28	84.85

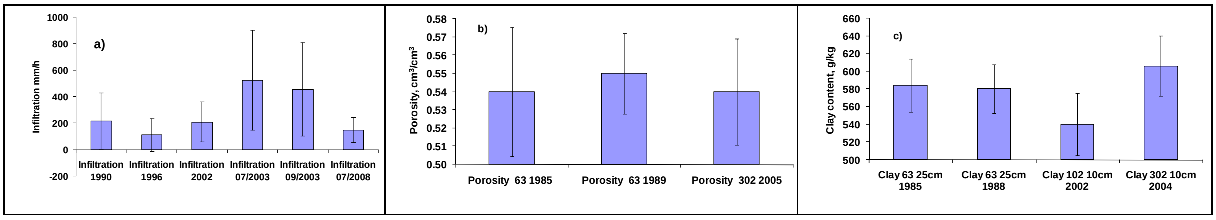

Figure 2. Mean soil physical properties and errors with different samplings over the same soil.

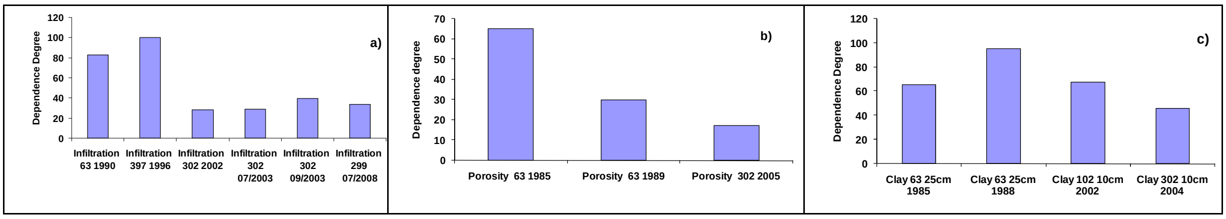

Figure 3. Temporal evolution of some semivariogram parameters for soil physical properties.

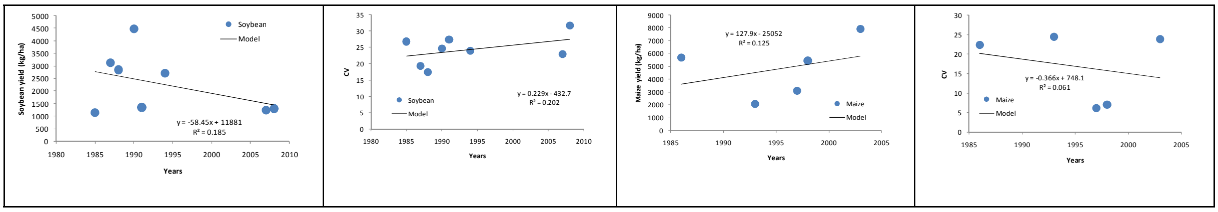

Figure 4. Temporal evolution of soybean and maize yield and the corresponding CVs.

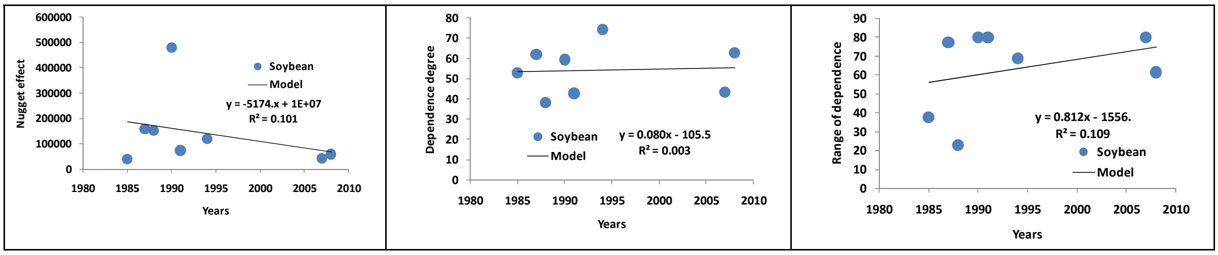

Figure 5. Temporal evolution of some semivariogram parameters for soybean normalized yield.

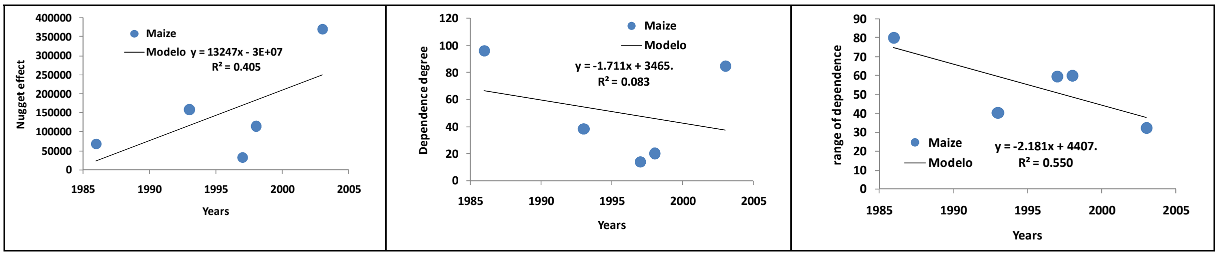

Figure 6. Temporal evolution of some semivariogram parameters for maize normalized yield.

REFERENCES

BECKETT, P.H.T.; WEBSTER, R. Soil variability: a review. Soil Fertility, v.31, p.1-15, 1971.

CAMARGO, O.A.; MONIZ, A.C; JORGE, J.A.; VALADARES, J.M.A.S. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Campinas: Instituto Agronômico, 1986. 94 p. (Boletim técnico, 106)

CARVALHO, J.R.P.; SILVEIRA, P.M.; VIEIRA, S.R. Geoestatística na determinação da variabilidade espacial de características químicas do solo sob diferentes preparos. Pesquisa Agropecuária Brasileira, v.37, p.1151-1159, 2002.

GOOVAERTS, P. Geostatistics for natural resources evaluation. Applied Geostatistics Series, Oxford University Press, 1997.

CASTRO, O. M., MBAGWU, J. S. C., VIEIRA, S. R., Kanthack, R., DECHEN, S. C. F., De MARIA, I. C., BRAGA, N. R. Effect of no-tillage crop rotation systems on nutrient status of a rhodic ferralsol in southern Brazil. Agro-Science Journal of Tropical Agriculture, Food, Environment and Extension. , v.4, p.8 - 14, 2005.

CAMBARDELLA, C.A. et al. Field scale variability of soil properties in central Iowa soil. Soil Science of America Journal, Madison, v.47, p.1501-1511, 1994.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA-EMBRAPA. Centro Nacional de Pesquisa de Solos. Sistema Brasileiro de Classificação de Solos. 2° ed. Rio de Janeiro, 2006.306p.

GOOVAERTS, P., Geostatistics for natural resources evaluation; Applied Geostatistics Series, Oxford University Press, New York, 500 pp, 1997.

GREGO, C.R.; VIEIRA, S.R. Variabilidade espacial de propiedades físicas do solo em uma parcela experimental. Revista Brasileira de Ciência do Solo, Viçosa, v.29, p.169-177, 2005.

HARRIS, J.A. Practical universality of field heterogeneity as a factor influencing plot yields. Journal of Agricultural Research, Washington, v. XIX, n.7, p. 279-314, 1920.

MATHERON, G. The theory of regionalized variables and its application. Fontainebleau: Les Cahiers du Centre de Morphologie Mathematique, 1971. 56 p. (Fascicule 5)

McBRATNEY, A. B.; WEBSTER, R. Choosing functions for semi-variograms of soil properties and fitting them to sampling estimates. Journal of Soil Science, v.37, p.617-639, 1986.

MILLER, M.P.; SINGER, M.J.; NIELSEN, D.R. Spatial variability of wheat yield and soil properties on complex hills. Soil Science Society of America Journal, Madison, v.52, p.1133-1141, 1988.

MONTGOMERY, E.G. Experiments in wheat breeding: experimental error in the nursery and variation in nitrogen and yield. Washington: United States Department of Agriculture/Bureau of Plant Industry, 1913. p. 5-61. (USDA Bulletin, 269)

MULLA, D.J. Mapping and managing spatial patterns in soil fertility and crop yield. In: Soil specific crop management. Madison: Soil Science Society of America, 1993. p. 15-26.

MUZILLI, O. O. Manejo da Fertilidade do Solo, In: IAPAR, Plantio Direto no Estado do Paraná. Londrina: IAPAR, 1981. p.43-58 (Circular n° 23).

PAZ GONZÁLEZ, VIEIRA, S. R. & TABOADA CASTRO, M. T. The effect of cultivation on the spatial variability of selected properties of an umbric horizon. Geoderma. 97: 273-292, 2000.

SALVIANO, A. A. C.; VIEIRA, S. R.; SPAROVEK, G. Variabilidade espacial de atributos de solo e de Crotalaria juncea (L.) em área severamente erodida. Revista Brasileira de Ciência do Solo, v. 22, n. 1, p.115-122, 1998.

SIQUEIRA, G.M.; VIEIRA, S.R.; CEDDIA, M.B. variabilidade de atributos físicos do solo determinados por métodos diversos. Bragantia, v.67, n.1, p.693-699, 2008

SNEDECOR, G.W.; COCHRAN, W.G. Statistical methods. 6th Edition. Ames, Iowa State University Press, 1967. 593 p.

SOUZA, L. S.; COGO, N. P.; VIEIRA, S. R. Variabilidade de propriedades físicas e químicas do solo em um pomar cítrico. Revista Brasileira de Ciência do Solo, Viçosa, v. 21, n. 3, p. 367-372, 1997.

VAUCLIN, M.; VIEIRA, S.R.; BERNARD, R.; HATFIELD, J.L. Spatial variability of two transects of a bare soil. Water Resources Research, Washington, v.18, n.6, p.1677-1686, 1982.

VAUCLIN, M.; VIEIRA, S.R.; VACHAUD, G.; NIELSEN, D.R. The use of cokriging with limited field soil observations. Soil Science Society of America Journal, Madison, v.47, p.175-184, 1983.

VIEIRA, S. R. ; MBAGWU, J. S. C. ; CASTRO, Orlando Melo de ; ALVES, M. C. ; DECHEN, Sonia Carmela Falci ; MARIA, Isabella Clerici de . Changes in some physical properties of a typic haplorthox in southern Brazil under no-tillage crop rotation systems. Agro-Science Journal of Agriculture, Food, Environment and Extension, v. 3, p. 1-12, 2002a.

VIEIRA, S.R. Permeâmetro: novo aliado na avaliação de manejo do solo. O Agronômico, Campinas, v 47-050, p. 32-33, 1998.

VIEIRA, S.R. Uso de geoestatística em estudos de variabilidade espacial de propriedades do solo. In: NOVAIS, R.F. (Ed.). Tópicos em Ciência do Solo. Viçosa: Sociedade Brasileira de Ciência do Solo, 2000. p.1-54.

VIEIRA, S.R. Variabilidade espacial de argila, silte e atributos químicos em uma parcela experimental em um Latossolo Roxo de Campinas (SP). Bragantia, Campinas, v. 57, n. 1, p.181-190, 1997.

VIEIRA, S.R.; HATFIELD, J.L.; NIELSEN, D.R.; BIGGAR, J.W. Geostatistical theory and application to variability of some agronomical properties. Hilgardia, Berkeley, v. 51, n. 3, p.1-75, 1983.

VIEIRA, S.R.; LOMBARDI NETO, F. Variabilidade espacial de potencial de erosão das chuvas do Estado de São Paulo. Bragantia, Campinas, v. 54, n.2, p. 405-412, 1995.

VIEIRA, S.R.; MILLETE, J.; TOPP, G.C.; REYNOLDS, W.D. Handbook for geostatistical analysis of variability in soil and climate data. In: ALVAREZ V., V.H.; SCHAEFER, C.E.G.R.; BARROS, N.F.; MELLO, J.W.V.; COSTA, L.M., eds. Tópicos em ciência do solo. Viçosa, Sociedade Brasileira de Ciência do Solo, 2002b. v.2, p.1-45.

VIEIRA, S.R.; NIELSEN, D.R.; BIGGAR, J.W. Spatial variability of field-measured infiltration rate. Soil Science Society of America Journal, Madison, v.45, p.1040-1048, 1981.

VIEIRA, S.R.; NIELSEN, D.R.; BIGGAR, J.W.; TILLOTSON, P.M. The scaling of semivariograms and the kriging estimation. Revista Brasileira de Ciência do Solo, Viçosa, v. 21, p.525-533, 1997.

VIEIRA, S.R.; REYNOLDS, W.D.; TOPP, G.C. Spatial variability of hydraulic properties in a highly structured clay soil. In: WIERENGA, P.J.; BACHELET, D. (Eds.). VALIDATION OF FLOW AND TRANSPORT MODELS FOR THE UNSATURATED ZONE, 1988, Las Cruces. Proceedings... Las Cruces: Department of Agronomy and Horticulture, New Mexico State University, 1988, p. 471-483 (Research Report 88—SS-04)

WAYNICK, D.D. Variability in soils and its significance to past and future soil investigations. I. Statistical study of nitrification in soils. Agricultural Sciences, Davis, v.3, n.9, p.243-270, 1918.

WEBSTER, R. Quantitative spatial analysis of soil in field. Advances in Soil Science, v. 3, n. 1, p. 2-56, 1985.

ZIMBACK, C.R.L. Analise espacial de atributos químicos de solos para fins de mapeamento da fertilidade do solo. 2001. 114f. Tese (Tese de Livre Docência) – Faculdade de Ciências Agronômicas-UNESP, Botucatu.