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Carbon stocks of a Rhodic Ferralsol under no-tillage in Southern Brazil: spatial variability at a farm scale

P. L. O. A. Machado[A,H], *A. C. C. Bernardi*[B], *L. I. Ortiz Valencia*[C], *M. S. P. Meirelles*[C,D], *C. A. Silva*[E], *L. M. Gimenez*[F], *J. P. Molin*[G], *and B. E. Madari*[A]

[A]Embrapa Rice and Beans, Cx Postal 179, CEP 75375-000 Santo Antonio de Goias, GO, Brazil.
[B]Embrapa Cattle-Southeast, Cx Postal 339, CEP 13560-970 São Carlos, SP, Brazil.
[C]Universidade do Estado do Rio de Janeiro, Departamento de Engenharia de Sistemas e Computação, Rua São Francisco Xavier, 524 Bloco D. CEP 20559-900 Rio de Janeiro, RJ, Brazil.
[D]Embrapa Soils, Rua Jardim Botânico 1024, Jardim Botânico, CEP 22460-000, Rio de Janeiro, RJ, Brazil.
[E]Universidade Federal de Lavras, Dep. de Ciência do Solo, Cx. Postal 3037, CEP 37200-000 Lavras, MG, Brazil.
[F]Fundação ABC, Caixa Postal 1003, CEP 84165-980 Castro, PR, Brazil.
[G]ESALQ-USP, Departamento de Engenharia Rural, Cx. Postal 9, CEP 13418-900 Piracicaba, SP, Brazil.
[H]Corresponding author. Email: pmachado@cnpaf.embrapa.br

Abstract. The objective of this study was to determine, at a farm level, the spatial variability of organic carbon stock (CS) at different depths on a field of 1 soil type in long-term (13-year) crop production under no-tillage. The crop rotation comprised soybean [*Glycine max* (L.) Merr.] alternating with maize (*Zea mays* L.) in the summer season. For the winter season, wheat (*Triticum aestivum* L.) was cropped in rotation with black oat (*Avena sativa* L.), a cover crop. The 12.5-ha field was sampled at a density of 6.25 samples/ha. Within the coarse grid, 2 dense grids with 20-, 10-, and 5-m spacing were established. Soil samples were collected at all grid nodes and analysed for soil organic carbon and bulk density. The CS at 0–0.05, 0.05–0.10, and 0.10–0.20 m was corrected for equal soil mass. Geostatistics was used for the estimation of spatial distribution of CS at 3 soil depths. We found that CS variation was low to medium (CV 6.7–19.4%). The variograms of CS at all depths were best fitted by spherical models and showed ranges of 120 m, except at 0–0.05 m (range 109 m). At 0–0.20 m depth, CS was 15.2–24.5 t/ha (CV 8.2%, range 120 m). The use of geostatistics reveals a powerful tool for the spatial estimation of CS at depth of a Rhodic Ferralsol under no-tillage, and demonstrated CS variation on a 12.5-ha area, even though soil and crop management were the same for >10 years.

Additional keywords: soil organic carbon, soil organic matter, crop rotation, soil texture, geostatistics.

Introduction

The relevance of organic matter to soil functioning and sustained agricultural productivity is widely recognised in both temperate and tropical regions (Coleman *et al.* 1989; Craswell and Lefroy 2001). Additionally, the increase in organic carbon stock (CS) losses raises concern, as it is the largest carbon pool in terrestrial ecosystems and relevant to global climate change (Sabine *et al.* 2004).

A large amount of literature reports a decrease of organic matter after the conversion of Brazilian tropical forest into agriculture based on ploughing and several disc harrowings (Sidiras and Pavan 1986; Machado and Gerzabek 1993; Klink and Moreira 2002). Further work, however, has indicated that the use of appropriate physical management of soils of tropical and subtropical regions enables the amounts of carbon entering the soil to exceed that lost to the atmosphere and that more plant residues, particularly cover crops, can be retained on the soil surface (Castro Filho *et al.* 1991; Franzluebbers 2005). Adoption of no-tillage (NT) in Brazil began in the southern States in the 1970s and was rapidly adopted by farmers in the centre-west region (*Cerrado* biome**).** Nationwide, the area under NT in Brazil is 25.5 Mha, making it the second largest adopter of conservation agriculture in the world (Febrapdp 2004). The area data are a compilation of anecdotal information provided by extension services and no-tillage associations in individual Brazilian States, and may include areas where cover-crop seeds are broadcast and incorporated at ~0.10 m by a light disc harrow (Bolliger *et al.* 2006). The use of cover crops (e.g. black oat, millet) in rotation with cash crops (e.g. soybean, maize, beans) is key for the successful implementation of NT in Ferralsols and Acrisols, as cover crop residues are the main driving force of soil surface mulching (Machado and Silva 2001). Recently, the adoption of an integrated crop livestock system, a hybrid production system that includes a crop phase and a pasture phase in rotation under NT, has shown strong potential for sustainable beef and grain crop production while increasing soil C accumulation by deep rooting *Brachiaria* spp. (Bell and Shellman 2006).

The benefits of NT for crop production with simultaneous soil organic matter aggradation are well documented (Machado

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and Freitas 2004; Sisti *et al.* 2004). No-tillage also allows improvements of soil aggregation and aggregate stability (Madari *et al.* 2005*a*), water infiltration rate (Roth *et al.* 1986), and efficacious erosion control (Muzilli 1994). No-tillage is increasingly being promoted as an option to diminish the impact of human activities on the climate system or for a carbon credit trading program usually planned by non-governmental organisations (Caldeira *et al.* 2004; Mendis and Openshaw 2004). However, in Brazil, there are few data for evaluating the spatial variability of CS at farm scale, although this information is crucial to assess changes in soil carbon. In an area of 0.36 ha, after 5 years of grain crop production, the variation in organic matter content of a Ferralsol under NT, showing 7.5% at 0–0.10 m and 8.9% at 0.20–0.30 m, was higher than under disc-plough tillage only in the topsoil layer showing, 4.7% at 0–0.10 m and 9.5% at 0.20–0.30 m (Souza *et al.* 1998). Those authors concluded that, in contrast to NT, disc ploughing resulted in more homogenisation, thus diminishing soil organic matter variability.

Several studies on CS of NT soils have been evaluated in small plots of homogeneous soils measuring 15 by 20 m (Bayer *et al.* 2000), 8 by 14 m (Leite *et al.* 2003), 8 by 25 m (Machado *et al.* 2003), and 4 by 10 m (Sisti *et al.* 2004). However, as observed by Bergstrom *et al.* (2001), the effects of management must also be assessed at larger scales, comparable to on-farm practices and encompassing changes in topography. Also of interest in this regard are data reported by Parton *et al.* (1987) on factors controlling soil organic matter levels in the Great Plains Grasslands. Climate, soil texture, and plant lignin are the major controls over organic matter dynamics.

The objective of this study was to evaluate, at farm level, the spatial variability of CS at different depths of a Rhodic Ferralsol in long-term crop production under NT.

Material and methods

Site characteristics

The study site is located on a 12.5-ha soybean field of Fazenda Tabatinga (Tabatinga Farm), 870 m ASL, in Carambeí, State of Paraná, Brazil (24°51′45″S, 50°15′58″W; Fig. 1). The climate is Cfb (Köppen 1931) with mean annual temperature of 17.6°C and mean annual precipitation of 1560 mm, falling mostly in summer. The deep, well-drained soil is classified as a clayey, kaolinitic Rhodic Ferralsol in the FAO System (FAO 2006) and as Latosssolo Vermelho distroférrico in the Brazilian Soil Classification System (EMBRAPA 2006). Soil properties of the study site are: pH(water) 5.40, Ca 3.6 $\text{cmol}_c/\text{dm}^3$, Mg 2.1 $\text{cmol}_c/\text{dm}^3$, K 104 mg/dm^3, P 16.7 mg/dm^3, clay 555 mg/kg.

According to Bognola *et al.* (2004), these soils were developed both from Devonian sedimentary rocks (Ponta Grossa Formation) and from Precambrian rocks such as subalcaline granites, syenites, and migmatites. The terrain is gently sloping to undulating, with slopes mostly <6%. The region is part of the Atlantic Forest biome and the original formation in the study site is a steppe vegetation with patches of mixed ombrofila forest characterised by *Araucaria angustifolia* (Bertol.) Kunze and *Ocotea porosa* (Mez.) Barroso Rodriguésia (Nanuncio and Moro 2008). The native vegetation of the study site was replaced with agriculture for rainfed upland rice production in 1960. Disc ploughing followed by light disc harrowing in a soybean–wheat rotation was first introduced in 1973. Since 1988, cropping during the summer season involved soybean [*Glycine max* (L.) Merr.] alternating with maize (*Zea mays* L.). During the winter season, wheat (*Triticum aestivum* L.) was cultivated in rotation with black oat (*Avena sativa* L.). Black oat was grown as a cover crop. Fertiliser rates for soybean were 62.5 kg P_2O_5 and 62.5 kg K_2O/ha.

Sampling and measurements

Sampling was conducted with a procedure similar to that suggested by Bergstrom *et al.* (2001); a 40 by 40 m grid was established over the field, resulting in 107 sampling points. The sampling grid covered a rectangular area measuring 120 m (*x*-axis) by 1040 m (*y*-axis), with the long side aligned in the direction of plant line.

Previous observations of the field identified 2 contrasting zones with regard to soil texture, ranging from 362 to 667 g clay/kg (Machado *et al.* 2006). Hence, within the coarse grid, dense grids with 20-, 10-, and 5-m spacing were laid out for each area, and the soil was sampled at all grid nodes (Fig. 1). Each node of the sampling grid was geographically referenced using a GPS Trimble Geoexplorer 3C (Sunnyvale, CA).

In January 1999, at the flowering time, sampling for CS analysis was done at all grid nodes to a depth of 0–0.05, 0.05–0.10, and 0.10–0.20 m in pits dug to a depth of 0.30 m. From each depth a slice of soil material (thickness 0.05–0.10 m depending on the layer) was collected using a bricklayer's trowel. All samples were placed in plastic bags and transferred to the laboratory of Embrapa Soils, Rio de Janeiro. Upon arrival at the laboratory, the samples were air-dried and ground to pass a 2-mm sieve. Soil organic carbon was determined using an acid dichromate oxidation with 5-min external heating (EMBRAPA 1997).

The soil bulk density was measured using the core (0.04 by 0.04 m) method (EMBRAPA 1997), in which samples at 0–0.05 m were collected at all positions in the grid, and in deeper soil layers (0.05–0.10 and 0.10–0.20 m) at intervals of 80 m. For the surface layer (0–0.05 m), 14 samples were not analysed due to material losses during transportation. Soil bulk density estimation of the missing samples was done using the average bulk density values of neighbouring points. Although wheel tracks on this farm were fixed, care was taken with those soil samples collected near the tracks. Thus, unrealistically large bulk densities due to compaction of tractor wheel were excluded.

Each sample of field-moist soil was transferred to a container, and placed in an oven at 105°C until constant weight. The soil bulk density determined by the oven-dry mass of the soil sample divided by the sample volume. Stones were not present in the soil.

Soil organic carbon and the values of soil density were used to compute total CS on a unit area basis to all depths. Stocks of soil organic carbon were corrected for equal soil mass in the profile as described by Sisti *et al.* (2004) for the same soil type and biome.

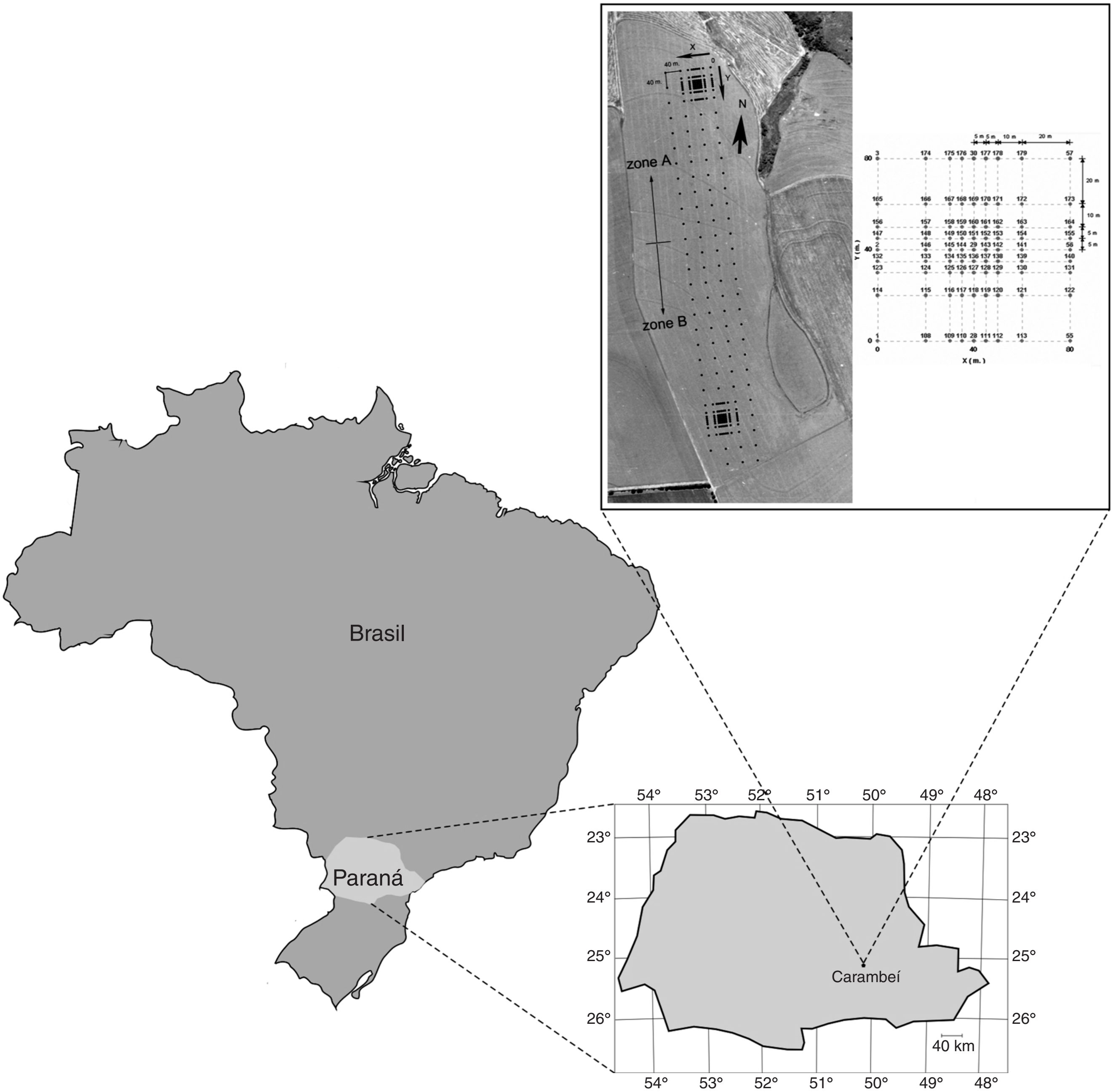

Fig. 1. Location of the study site on Tabatinga Farm, Parana State, Brazil, with sampling grid and details of dense grid with 20-, 10-, and 5-m spacing. Zone A and B indicate sandy and clayey soil, respectively.

Considering that soil organic carbon often increases with increasing clay values due to physico-chemical protection against decomposition (Lepsch *et al*. 1994; Watts *et al*. 2006), data on clay content of the study site published by Machado *et al*. (2006) were used to relate the spatial dependence of CS to clay content collected from the same grid nodes and determined by the pipette method.

Geostatistical analysis

Geostatistical analysis was performed for all depths, separately focusing on the spatial dependence of CS. Empirical directional semi-variograms were calculated for *x*- and y-directions. A semi-variogram model was fitted to empirical semi-variograms using Variowin semi-automatic fitting (Pannatier 1996). A test of goodness-of-fit was also performed, which consisted of a weighted mean square fit, standardised by the variance of the data and weighted by the number of pairs in each lag and the inverse of the mean distance of the lag. Values of goodness-of-fit closer to zero indicate that the semi-variogram model fits better than empirical semi-variogram. Using S-PLUS 2000 (Insightful Corp., Seattle, WA), the box-plot representation method (Sokal and Rohlf 1995) was

Table 1. Summary statistics of the total soil organic carbon (CS) and soil bulk density at 3 depths of a Ferralsol under no-tillage in southern Brazil

For bulk density, there were 93, 47, and 46 observations at 0–0.05, 0.05–0.10, and 0.10–0.20 m, respectively

Soil depth (m)	CS (t/ha) Mean	Min.	Max.	CV (%)	Soil bulk density (g/cm^3) Mean	Min.	Max.	CV (%)
0–0.05	10.5	4.2	13.6	16.7	0.90	0.71	1.45	15.3
0.05–0.10	9.8	4.2	12.5	17.5	1.09	0.83	1.46	11.3
0.10–0.20	17.7	6.6	22.9	19.4	1.12	0.82	1.60	12.7
0–0.20	38.0	15.2	48.0	6.7	–	–	–	–

applied to get a comparative picture of the CS stock distribution on the field.

Soil organic carbon stocks were estimated by ordinary kriging in a 10-m-squared grid and GSLIB software was used for geostatistical analysis (Deutsch and Journel 1992). Contour maps of soil kriging estimates were prepared using Surfer 8.05 (Golden Software Co., Golden, CO). Cross-validation was conducted to evaluate the performance of the interpolation (Webster and Oliver 2001). For validation a separate independent set of data is recommended (Voltz *et al.* 1997), but in this study, due to the lack of a separate independent dataset, the kriging process was evaluated using the same observed dataset. Mean error (ME), mean squared error (MSE), and root mean squared error (RMSE) were chosen to measure the bias and the precision of kriging process. They are defined by:

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}\{z(x_i) - \hat{z}(x_i)\}$$

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\{z(x_i) - \hat{z}(x_i)\}^2$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\{z(x_i) - \hat{z}(x_i)\}^2}$$

where N is the number of observations, z and $\hat{z}$ are observed and predicted values, respectively at location x_i, the kriged estimate of z, and $\hat{\sigma}^2$ is the variance.

Results and discussion

As Table 1 shows that the average CS varied between 9.8 t C/ha at 0.05–0.10 m and 17.7 t C/ha at 0.10–0.20 m. Organic carbon stocks at 0–0.05 m were not in good agreement with those reported for experimental plots on Ferralsols by Machado *et al.* (2003) with a 21-year-old wheat–soybean rotation (14.1 t C/ha at 0–0.05 m) and Sisti *et al.* (2004) with the same crop rotations after 13 years (14.9 t C/ha at 0–0.05 m). A comparison of results of soil carbon accumulation is difficult because of different time of adoption of NT and soil properties.

Coefficient of variation for CS across the sampling design was low to medium, with a range of 6.7–19.4% and was similar to that observed by Souza *et al.* (2004) in a study of the spatial variability of organic matter in a clayey Ferralsol from São Paulo State. Soil bulk density increased at depth and the values were typical for Ferralsols under grain crop production, as also found by Cardoso *et al.* (2006) in southern Brazil.

Experimental semi-variograms for CS were computed for all depths, and all fitted models were bounded, showing that the full extent of the variation had been encountered at the spatial scale of this study. The models are given in Table 2.

Spherical models best fitted the CS, with goodness-of-fit values 0.0006–0.0042 at all depths. Spherical models also fitted experimental semi-variograms of CS in a 63-ha area with 5 different soil types from western Brazilian Amazon (Cerri *et al.* 2004*a*, 2004*b*).

The ranges of the semi-variogram models for CS at different depths show similar orders of magnitude. For 0–0.05 m they are 135 m, for 0.05–0.10 m they are 148 m, and for 0.10–0.20 m they are 125 m. This indicates that a grid spacing of up to 125 m (0.64 samples/ha) would be adequate for the characterisation of the spatial variability of soil CS at all depths for this site.

Kriged estimates for CS were contoured and mapped so that their patterns of variation on the field could be examined (Fig. 2). The patterns of variation in CS are slightly different among depths. At 0–0.05 m, the pattern has a larger scale of variation than at 0.05–0.10 and 0.10–0.20 m. Under NT, large amounts of crop residue are kept at the soil surface and are key sources of soil carbon (Bayer *et al.* 2000). All maps, however, have a similar distribution of CS in the field, in which soil in the southern area showed greater CS than in the northern area (Fig. 3).

The RMSE values were 1.06–4.46 t C/ha and indicate a small map bias (Table 3). Mapping CS in Mollisols from Nebraska, USA, Simbahan *et al.* (2006) found RMSE values ranging from 10.8 to 12.5 t C/ha, which was considered small for CS at 0–0.30 m depth ranging from 17.7 to 126.7 t C/ha. In our study, CS at 0–0.20 m depth ranged from 15.2 to 48.0 t C/ha.

Table 2. Model parameters for the fitted semi-variogram models for total soil organic carbon (t C/ha) at different depths of a Ferralsol under no-tillage in southern Brazil

C_0, Nugget variance; C, contribution; Sill, $C_0 + C$

Soil depth (m)	Model	Range (m)	C_0	C	Sill	Goodness of fit
0–0.05	Spherical	109	0.15	1.5	1.6	0.0006
0.05–0.10	Spherical	120	0.00	1.3	1.3	0.0042
0.10–0.20	Spherical	120	0.12	4.2	4.3	0.0013
0.00–0.20	Spherical	120	0.00	18.8	18.9	0.0024

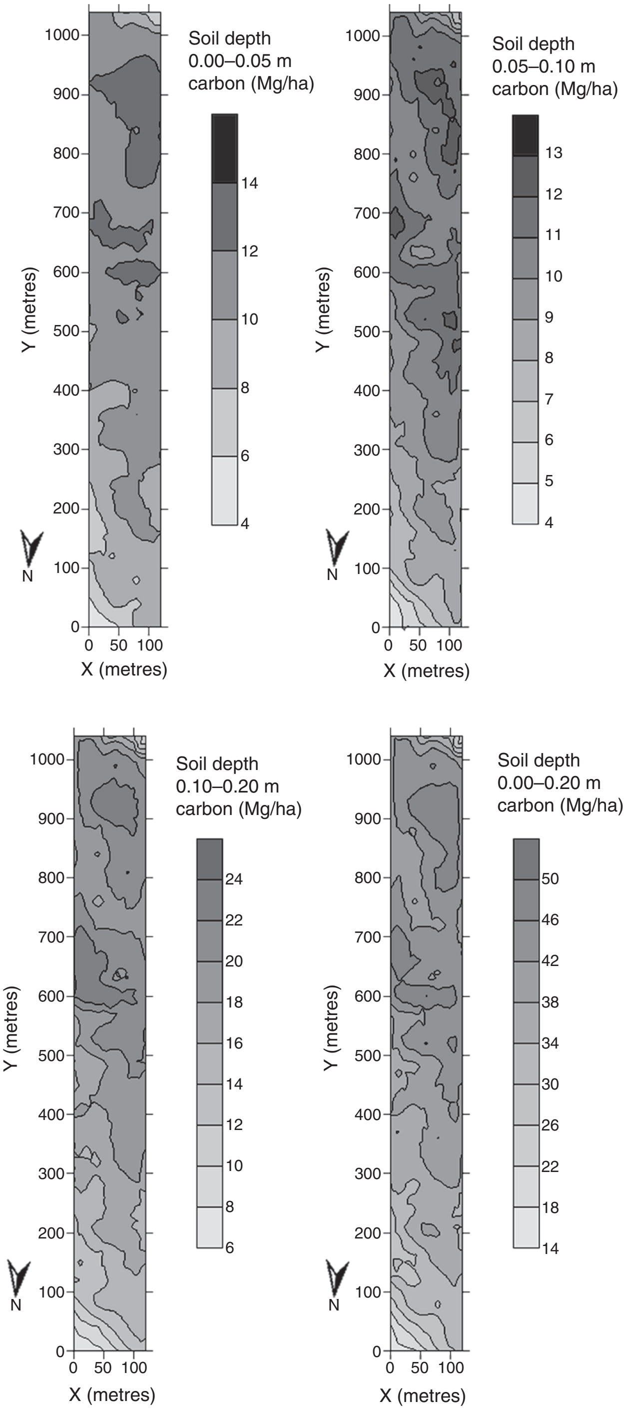

Fig. 2. Maps of the kriged estimates for soil organic carbon stocks of the study site at 0–0.05, 0.05–0.10, 0.10–0.20, and 0–0.20 m.

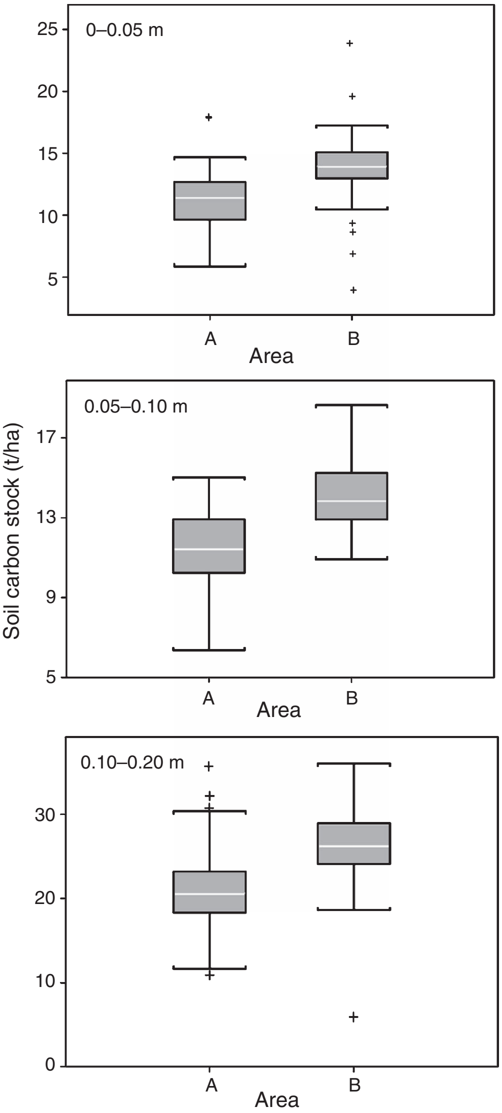

Fig. 3. Box and whisker plots of soil carbon stocks in 2 zones of the study site (Zone A, sandy soil; Zone B, clayey soil). The middle horizontal line is the median value, the extent of the upper box is the first quartile, the extent of the lower box is the third quartile, and 50% of the data lie within the 2 boxes (the interquartile range). The extent of the whiskers is the last data point or 1.5 times the distance of the interquartile range if there are outliers. Outliers are marked with a plus sign in the plot.

Table 3. Mean error (ME), mean squared error (MSE) and root mean squared error (RMSE) for kriging total soil organic carbon (t C/ha) using spherical model

Soil depth (m)	ME	MSE	RMSE
0–0.05	–0.33	1.93	1.39
0.05–0.10	0.18	1.13	1.06
0.10–0.20	0.20	4.77	2.18
0.00–0.20	1.22	19.91	4.46

Spatial variability of soil clay content was also examined for this same field (Machado *et al*. 2006). At 0–0.20 m depth, average clay contents ranged from 362 to 442 g/kg in Zone A, and from 612 to 667 g/kg in Zone B. The patterns of variation in clay content reported by Machado *et al*. (2006) and CS in this study are very similar, although the proportion of the variance in

CS associated with the variance of clay content at all depths was very low (R^2 0.34–0.37). The validity of the relationship between soil carbon and clay content has been already questioned (Lugo and Brown 1993; Percival *et al.* 2000). Additionally, the textural effect on soil carbon of surface layers is controversial because of higher carbon variability due to management and higher proportion of particulate organic matter, which adds variability and masks the interaction of soil carbon in humified organic matter and the mineral matrix (Zinn *et al.* 2005). We did not study the topographical effects on CS variability, but even in relatively flat terrains as observed in this study site, topography is known to operate as one of the main factors of soil formation that may also influence spatial patterns of soil C distribution (Kravchenko *et al.* 2006).

As a practical implication of this study, the data suggest that despite 11 years of homogeneous tillage, fertiliser, and plant management of this 12.5-ha field, the area shows contrasting values of CS that can hardly be assessed by the recommended (Oliveira *et al.* 1996) composite soil sample of ~12 subsamples collected in a zigzag pattern and summarised by mean values. In a study of spatial variability of soil properties of an Acrudox (pH 5.95) in the western Brazilian Amazon, Cerri *et al.* (2004*a*) found that organic carbon at 0–0.10 m depth ranged from 4.7 to 53.7 g C/kg soil (CV 29.5%) and clay content ranged from 61 to 574 g clay/kg soil (CV 19.5%) in a 63-ha field for 20 years under pasture. Properties of the soil, including CS, vary at many different scales of spatial resolution in the landscape and even within a single field (Bergstrom *et al.* 2001). Our results also provide a good example of potential difficulties faced when trying to demonstrate CS of NT soils at the farm level. Grid sampling, transportation to the laboratory, and sample preparation for soil carbon and density analysis are tedious and hardly affordable. Only for CS laboratory analysis, the total cost for 12.5 ha reached US$1159.00, while a CS evaluation by composite soil sampling would cost US$4.54. Costs and labour are even higher if a total CN analyser (dry combustion) and soil sampling down to 1 m were adopted. Baker *et al.* (2007) reported that shallow soil sampling (0–0.30 m) employed in studies comparing NT with ploughed soils introduces a bias; in contrast to Six *et al.* (2002), Sisti *et al.* (2004) and Diekow *et al.* (2005) showed that in Ferralsols from southern Brazil, increased CS is found below 0.50 m depth. Apparently, in combination with pedotransfer functions for soil density estimates at depth (Benites *et al.* 2007), the use of rapid, accurate, and less expensive analysis than dry combustion, such as infrared spectroscopy, may acquire large amounts of good quality soil data for soil carbon monitoring in NT systems at the farm level (Madari *et al.* 2005*b*; Viscarra Rossel *et al.* 2006).

Conclusions

After 12 years of no-tillage under crop rotation involving cover crops, the coefficient of variation of CS of a Rhodic Ferralsol was medium, with CS at 0–0.20 m depth ranging from 15.2 to 48.0 t/ha. The sampling grid of up to 125 m established over the 12.5 ha (6.25 samples/ha), followed by a map of kriged estimates, was adequate to reflect the spatial variability of CS of this Ferralsol under no-tillage system.

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