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QUANTIFYING SOIL CARBON SEQUESTRATION: TEXTURAL EFFECTS
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ABSTRACT

A study of the effects of variations in soil texture within a field on accumulation of soil organic C (SOC) was conducted by removing soil samples from the 0-7.5 cm and 7.5-15 cm depth in a predetermined pattern from selected continuous crop rotations of the Swift Current Old Rotation Experiment. We determined that the rotations receiving N and P fertilizer had significantly more SOC in the surface 7.5 cm than the comparable rotation receiving P alone. Analysis of correlation showed that clay content had little influence in SOC, but that sand or silt could account for 36% of the variability in SOC in the surface 7.5 cm. An examination of distribution of soil texture and SOC over the plot area showed that only in small areas of the field where sand and silt content had extremely high or extremely low values did texture affect SOC. In the majority of the area, where sand and silt content were near average, SOC was influenced mainly by the effects of crop rotations employed. We concluded that there is no need to incorporate additional textural effect functions in SOC process-level models such as CENTURY and EPIC, other than the general functions already built in these models.

INTRODUCTION

The role of CO_2 as one of the greenhouse gases contributing to global warming has now been universally accepted. So too has our need to reduce CO_2 concentrations in the atmosphere by sequestering or storing carbon (C) in the soil. Several countries with large land base areas such as Canada, USA, and Australia were successful in having C sequestered in agricultural soils as result of changes in land management practices included in the Kyoto Agreement as a legitimate offset mechanism. To implement this goal, however, we will need to demonstrate that we can accurately quantify changes in soil C stocks. Although this could be done by making repeated and extensive field measurements, this procedure would be tedious, time consuming, and expensive. Most experts in this area accept that a more feasible solution is to estimate soil C changes through the use of simulation models. However, if computer models are to be used with confidence, we must demonstrate their ability to accurately estimate observed soil C changes.

There are several simulation models (e.g., CENTURY, EPIC) currently in use that provide reasonable estimates of soil C when used to assess 'long-term' changes. However, these models are less reliable when used to assess 'short-term' soil C dynamics. For example, Campbell et al. (1999) demonstrated the inadequacies of the CENTURY and EPIC models when used to simulate results of a 30-yr crop rotation study at Swift Current, Saskatchewan. There are several reasons for the inadequate performance of the current models. One of these is related to the large spatial variability that is associated with taking actual measurements of soil organic C (SOC) from fields or plots (Campbell et al. 2000a). In fact, such variability is commonplace even on fairly level uniform-looking landscapes (Campbell et al. 2000a,b, 1995). For example, Campbell et al. (2000a) in explaining the large spurious variability in SOC over time in some of the rotations at Swift Current, but especially in the Continuous wheat (N+P) treatment, suggested that this variability may have been related to textural differences within the plots.

In his work examining P distribution in the Swift Current Old Rotation Experiment, O'Halloran (1986) determined that a substantial proportion of the variability of the soil P fraction could be attributed to differences in sand content throughout the experimental area, and that sand was the most variable size fraction at the site.

The documented variability in texture at the Swift Current site made this long-term soil management study an ideal substrate to identify short-distance relationships between SOC and soil textural attributes in order to improve our capacity to predict the effects of soil and crop management practices on C sequestration by soils.

MATERIALS AND METHODS

Soil samples were taken from selected plots of the Swift Current Old Rotation long-term experiment. The rotations sampled were continuous wheat fertilized with N and P as required [CW (NP)]; continuous wheat fertilized with P alone [CW (P)]; wheat and lentil phase of continuous cropped wheat-lentil fertilized with N and P (W-Lent). The experiment was laid out as an randomized complete block design with three replicates in plots 10.5 by 40 m (Fig 1). All phases (rotation-year) of each rotation were present every year (Zentner and Campbell 1988). From each plot, 12 cores were taken with a 5 cm diameter sample tube to a depth of 15 cm on a regular grid (Fig. 2). The soil cores were sectioned into 0-7.5, and 7.5-15 cm depths, then they were weighed, crushed by hand, and a sub sample taken for moisture determination. The soil was passed through a 2 mm sieve; all visible plant remains (leaves, stems, crown, and roots) were separated, weighed and saved. Soil was air dried, and a subsample was withdrawn for determination of organic C and total N, which where determined by an automated combustion method (Carlo Erba™, Milan, Italy). Particle size distribution was determined by the pipette method after destroying organic matter and carbonates (McKeague 1978). Results of this analysis are presented as percent sand, silt and clay, and as geometric mean diameter (GMD) (Campbell 1985).

Organic C concentration in the soil was evaluated using a randomized complete block design with split-plots. Rotations were main plots; depth and its interaction with rotations were subplots. Cores, nested within rotations and depths, were subsamples. In this model subsamples do not contribute to the experimental error, but determine a subsampling error that provides a measure of uniformity within experimental units, or observational differences (Steel and Torrie 1980). Additionally, differences among experimental units were assessed using a Tukey-Kramer HSD test (Kramer 1956).

To assess the effect of texture on SOC we conducted simple linear regressions between SOC and sand, silt, and clay content, and with geometric mean diameter (GMD)of soil separates. In addition, analyses of covariance (ANCOVA) for SOC using the model described in the previous paragraph and with either sand, silt, clay, or GMD as covariates were conducted to assess SOC corrected to a common value of the covariates.

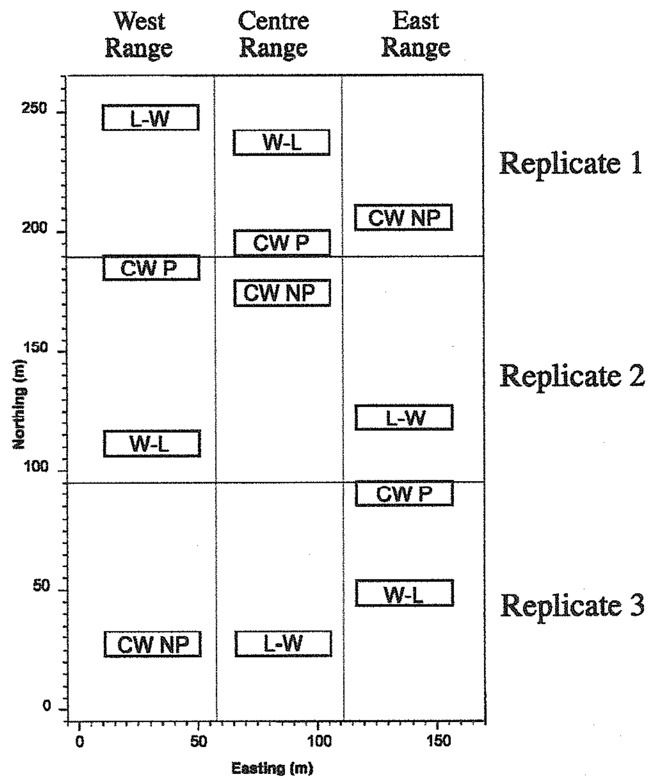

Figure 1. Distribution of plots in the field (only plots sampled shown).

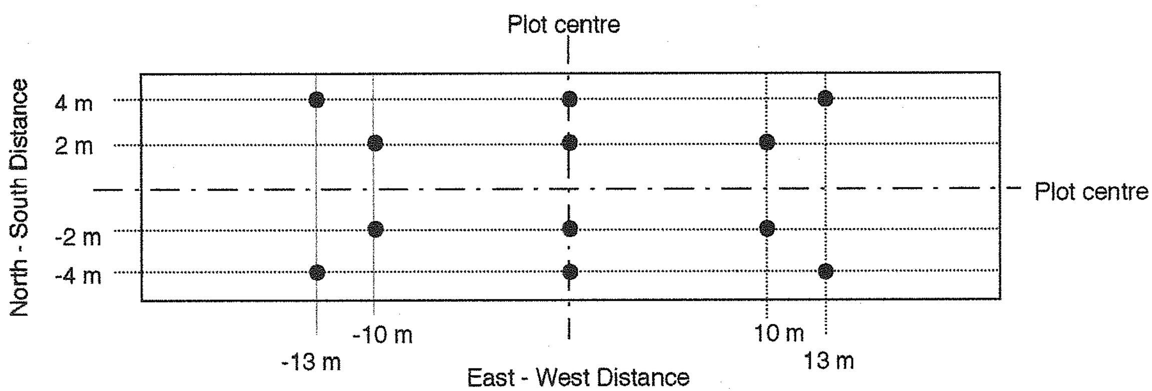

Figure 2. Location of soil cores taken within the rotation plots

Semivariograms of the various soil attributes were calculated for the entire experimental area. Semivariograms indicate the spatial dependency of the variance of the variables analyzed. Finally, we estimated the distribution of these soil attributes over the entire experimental area using a 4x4 block kriging procedure (Clark 1979).

RESULTS AND DISCUSSION

General distribution of soil properties

Soil textural class in both sampling depths varied between Silt Loam (SiL) and Loam (L). In the surface 7.5 cm, 63% of the samples were classified as SiL, with the rest classified as L. In the 7.5 to 15 cm depth the samples were evenly split between SiL and L. Sand and silt were more variable than clay, and had similar ranges of values within each depth (Table 1). Clay was relatively uniform throughout the site and had a range of values less than one-half of those exhibited by the coarser fractions. Indeed the observations between the 10^{th} and 90^{th} percentiles (80% of the observations) had a total range of just 2.25% clay. The uniformity in clay content observed throughout the site had important implications for the effect of textural variation on SOC concentration. It is interesting to note that the range of the sand and silt fractions were similar in the 0 to 7.5 cm depth and also they were very close in the 7.5 to15 cm depth.

Table1. Mean and range of values observed for textural parameters and soil organic C

Variable	0 – 7.5 cm				7.5 – 15 cm			
	Mean	Min	Max	Range	Mean	Min	Max	Range
Organic C (mg kg^{-1})	24.4	19.0	31.9	12.9	19.3	10.5	29.2	16.7
Sand (%)	27.6	21.8	38.9	17.1	27.5	22.4	41.0	18.6
Silt (%)	49.7	38.7	56.3	17.6	48.6	34.0	54.2	20.2
Clay (%)	22.7	19.2	25.0	5.8	23.9	20.8	27.6	6.8
GMD^z (mm)	0.035	0.027	0.053	0.026	0.033	0.027	0.058	0.031

^{z} Geometric mean diameter of soil separates

Soil organic C averaged 24.4 mg kg^{-1} in the surface 7.5 cm depth and 19.3 mg kg^{-1} in the 7.5 to 15 cm depth. The range of values, however, was much larger in the subsurface than at the surface layer (Table 1).

Although over the entire plot area the range of the variables were somewhat large, within each experimental unit the variation was much narrower (data not shown), indicating that the values of the various soil attributes, even when variable, did not change abruptly, but changed gradually with distance.

Relationships between soil organic C and soil separates

The regression between SOC and GMD (Table 2) indicated that as the mean diameter of the soil separates becomes smaller, SOC concentration increased in both depth segments, although the slope of the regression line was significantly steeper in the surface 7.5 cm than deeper in the profile (Table 2). The proportion of variability in SOC explained by GMD, sand and silt was much higher in the surface 7.5 cm of the soil than in the next layer.

The regressions of SOC with each of the soil separates (sand, silt, and clay) indicated that the bulk of the variability in SOC was associated with the variability of the sand and silt fractions (Table 2). The clay fraction in general had a weak association with SOC and if anything, an inverse relationship with SOC, contrary to the generally accepted positive association often cited in the literature (Parton et al. 1987). Although the regression of SOC on clay was statistically significant for the surface layer, in practice the effects of clay were negligible as this regression explained only 3% of the variability in SOC. In the 7.5 to 15 cm layer the clay fraction explained 10% of the variability in SOC. The low coefficients of determination for the regressions of SOC on clay were due, at least partially, to the narrow ranges of clay content observed throughout the experimental site.

Table 2. Simple linear regression between SOC and geometric mean diameter, sand, silt, and clay content.

Variable	Intercept	Slope	R^2	Prob > F^z
0 –7.5 cm				
GMD[y]	38 (3)	-389 (99)	0.29	< 0.0001
Sand	40.42 (3.49)	-0.58 (0.12)	0.36	< 0.0001
Silt	-1.80 (5.72)	0.53 (0.11)	0.36	< 0.0001
Clay	38.64 (12.44)	-0.62 (0.14)	0.03	0.03
7.5 – 15 cm				
GMD[y]	25 (3)	-204 (90)	0.12	< 0.0001
Sand	28.37 (3.32)	-0.34 (0.12)	0.18	< 0.0001
Silt	0.83 (5.35)	0.37 (0.11)	0.24	< 0.0001
Clay	41.34 (10.76)	-0.93 (0.45)	0.10	< 0.0001

[z] Probability of obtaining a larger value of F by chance alone.
[y] Geometric mean diameter of soil separates.

Because of the negligible contribution of the clay fraction to the variability in SOC, most of the explainable variability in this study was related to the soil fractions coarser than 0.002 mm. Since the coarser fraction of the soil is a binary mixture of sand and silt, it follows that their proportions in the mixture are inversely related; that is when the proportion of sand increases, the proportion of silt must decrease, and vice-versa. As a result, one expects that the relations between SOC and sand or silt would be equal but opposite. Indeed this is what we observed, the absolute value of the slope of these regressions were the same (Table 2), but with opposite signs. In the 0-7.5 cm depth, where the effect of clay was nearly zero, sand and silt each explained 36% of the variability in SOC, while in the second depth where clay had a slightly larger role, sand and silt explained 18% and 24% of the variability, respectively.

Because this soil developed from eolic materials (Ayres et al. 1985), it is likely that the association of SOC with sand and silt observed in this study is purely an incidental association resulting from short-range transport and sorting of soil and organic particles by wind, rather than a functional association resulting from physical interaction between SOC and soil separates. This hypothesis is further supported by the fact that the associations between SOC and sand or silt were much stronger at the surface of the soil (where these transport processes are active until today) than in the 7.5 to 15 cm layer. Previous work carried out at the field level provides evidence that short-distance transport-deposition processes active during the process of soil formation and exacerbated by cultivation can affect the distribution of organic matter within a field (Selles et al. 1999).

Particle size distribution

Applying a t-test to particle size distribution in the surface 7.5 cm for each individual plot, measured as GMD, revealed that there were differences in GMD among plots assigned to the same rotation, except for CW (NP). Plots assigned to CW (NP) had similar GMD values (P > 0.05) (Table 3). But plots assigned to CW (P) in replicates two and three had significantly larger GMD than in replicate one. There were six plots assigned to W-Lent since it was a two-crop rotation. For this rotation, four of the plots had similar GMD of about 0.032 mm, but plot 70 in replicate three, and especially plot 14 in replicate one had much larger GMDs. This last plot had the largest GMD of all plots sampled in this study and eliminating it from the analysis would have produced a substantially smaller average GMD for the W-Lent rotation.

Table 3. Soil organic C and GMD of individual plots.

Rotation	Replicate	Plot No	SOC	GMD	Sand	Silt	Clay
			(mg kg^{-1})	(mm)	(%)		
CW (NP)	1	26	24.6^{cd}	0.032^{ab}	26.3^{abc}	49.0^{d}	24.7^{c}
	2	38	27.1^{e}	0.033^{ab}	25.8^{abc}	51.2^{ef}	23.0^{ab}
	3	61	23.9^{c}	0.034^{ab}	27.4^{c}	49.0^{d}	23.6^{ab}
CW (P)	1	18	24.5^{c}	0.034^{ab}	27.0^{bc}	50.4^{de}	22.7^{a}
	2	28	19.7^{a}	0.037^{cd}	30.2^{d}	46.4^{ab}	23.4^{ab}
	3	73	20.8^{ab}	0.039^{d}	32.8^{e}	43.3^{a}	23.9^{bc}
W-L	1	4	28.0^{e}	0.031^{a}	24.6^{a}	52.6^{ef}	22.8^{a}
	1	14	23.1^{bc}	0.044^{e}	33.6^{e}	43.7^{b}	22.6^{a}
	2	35	27.4^{e}	0.032^{a}	25.3^{a}	51.5^{ef}	23.2^{ab}
	2	52	27.0^{de}	0.031^{a}	24.6^{ab}	52.7^{f}	22.7^{ab}
	3	70	23.3^{bc}	0.035^{bc}	27.7^{c}	49.1^{d}	23.2^{ab}
	3	77	24.1^{c}	0.032^{ab}	25.7^{abc}	50.8^{def}	23.5^{ab}

Numbers followed by the same letter are not significantly different ($P > 0.05$) based on Tukey-Kramer HSD test.

Despite these differences among experimental units treated alike, and contrary to the results of previous work (O'Halloran et al. 1985), analysis of variance revealed that particle size distribution was generally uniform across all rotations studied as evidenced by the non significant rotation term ($P > 0.10$) (data not shown). Also, this analysis showed that particle size distribution within a rotation was uniform, as indicated by the non-significant sub-sampling term (data not shown). These results indicate that the blocking used in the design of this field experiment was successful in removing the textural variability observed among the experimental.

This analysis of variance further showed that particle size distribution was uniform with depth, which is consistent with the nature and depth of the eolian deposits from which this soil developed (Ayres et al. 1985)

Soil organic carbon

Consistent with the results of other studies (Campbell et al. 2000a), the effect of crop rotations on SOC was restricted to the surface layer of the soil; consequently, the remaining discussion will be restricted to our findings for the 0 to 7.5 cm sampling depth.

Analysis of variance showed that rotations had a significant effect on SOC (Table 4), and that within a single rotation SOC was relatively uniform as shown by the non-significant sub-sampling term.

Table 4. Results of analysis of variance (ANOVA) and analysis of covariance (ANCOVA) for SOC at the 0-7.5 cm depth.

Sources of variation	df	ANOVA	ANCOVA			
			Sand	Silt	Clay	GMD[z]
			Prob > F[y]			
Block	2	0.23	0.50	0.54	0.28	0.41
Rotation	2	0.04	0.12	0.11	0.03	0.12
Error	4	--	--	--	--	--
Core[Rotation][x]		0.99	0.11	0.08	0.96	0.12
Covariate	1	--	<0.0001	<0.0001	0.04	<0.0001
R^2	--	0.66	0.86	0.85	0.68	0.84
CV (%)[w]	--	8.4	5.5	5.6	8.3	5.8

[z] Geometric mean diameter of soil separates
[y] Probability of obtaining a larger value of F by change alone
[x] Core nested within rotations; sub-sampling error
[w] Model coefficient of variability

Table 5. Least squares means for SOC at the 0-7.5 cm depth as estimated by analysis of variance (ANOVA) and analysis of covariance (ANCOVA).

Rotation	ANOVA	ANCOVA			
		Sand	Silt	Clay	GMD
			(mg kg^{-1})		
CW (N+P)	25.3[b]	24.8[b]	25.1[b]	25.5[b]	24.6[b]
CW (P)	21.1[a]	22.0[a]	22.0[a]	21.1[a]	22.0[a]
W-Lent	25.6[b]	25.3[b]	25.3[b]	25.3[b]	25.5[b]
$LSD_{0.05}$	3.4	3.6	3.6	3.3	3.8

Numbers followed by the same letter are not significantly different ($P > 0.05$) based on Tukey-Kramer HSD test.

Fertilization of continuous wheat with adequate amounts of N produced a significant increase in SOC in the surface 7.5 cm of the soil when compared to continuous wheat fertilized with P alone (Table 5). Attempting to use sand, silt, or clay content, or GMD as covariates to express SOC at a common value of these independent variables did not influence the least squares means of SOC (Table 5). However, with the exception of clay content, these variables increased the R^2 and decreased the CV of the model, and rendered the overall effect of rotation non significant (Table 4). This agrees with the analysis of variance of particle size distribution, which indicated that soil texture was uniform across rotations.

Similar to the findings for particle size distribution, a t-test comparison showed that there were differences in SOC among plots of the same rotation (Table 3). However, the results of the analysis of variance showed that blocking was relatively successful in removing some of this unwanted variability. This explains, at least partially, the reason why analysis of covariance did not change the results obtained with the ANOVA, although the covariates were significant.

Spatial variability

Semivariograms computed for sand, silt, clay and GMD revealed that the variance of these attributes were well structured, with the semivariograms accounting for over 99% of the variance of sand, silt and GMD, and for 81% of the variance of clay (Fig. 3). The range of the semivariogram, or distance over which samples are related to each other, ranged between 34 and 36 m, suggesting that soil texture within experimental plots were relatively homogeneous, which agrees with the results obtained earlier using analysis of variance. Further, the range suggests that among three neighboring experimental plots, textural characteristics will tend to be more similar than among plots located farther apart.

The experimental semivariogram for textural characteristics displays a distinct wave structure suggesting that samples separated 75 or 175 m from each other are more alike than samples separated by 40 to 50 m. This is clear evidence of a cyclic variation of soil texture within the field. Sand and silt show a marked cyclic variation with a period centered at 100 m, clay shows a less distinct cyclic pattern with a period of 40 m. The semivariogram of GMD showed a distinct cyclic pattern with a period of approximately 80 m, which was intermediate between those observed for sand, silt, and clay (Fig. 3).

We estimated the distribution of sand, silt, clay, and GMD throughout the experimental area using a 4x4 bock kriging technique (Clark 1979). Given the good spatial structure of the variance of these properties, goodness of fit test for kriging produced jackknifing R^2 of 0.87 for sand, 0.85 for silt, 0.42 for clay, and 0.82 for GMD. Jackknifing is a cross validation procedure where each point sampled is estimated based only on neighboring points, and the estimated values are compared to their original values by simple linear regression (Selles et al. 1999).

Maps of the distribution of these variables in the experimental area (Fig. 4) indicate that, with the exception of localized areas of extreme values (fish eyes) the majority of the study area has relatively uniform particle size distribution. Kriged estimates indicate that 80% of the plot area would have a sand content between 24 and 28% sand, 87% of the area would have a silt content between 46 and 52% silt, and 85% would have a clay content ranging from 22 to 23% clay.

Similar spatial analyses were conducted for SOC. The semivariogram of SOC, as with those for particle size distribution, showed good spatial structure and accounted for 99% of the variance of SOC. The range of the semivariogram was 36 m, similar to those determined for soil separates and GMD. The experimental semivariogram also showed evidence of a cyclic process operating in the experimental area. However, while the cyclic process verified for particle size distribution had a single period, SOC exhibited a complex process consisting of two superimposed processes, one with a period of 40 m and another with a period of 130 m (Fig. 3).

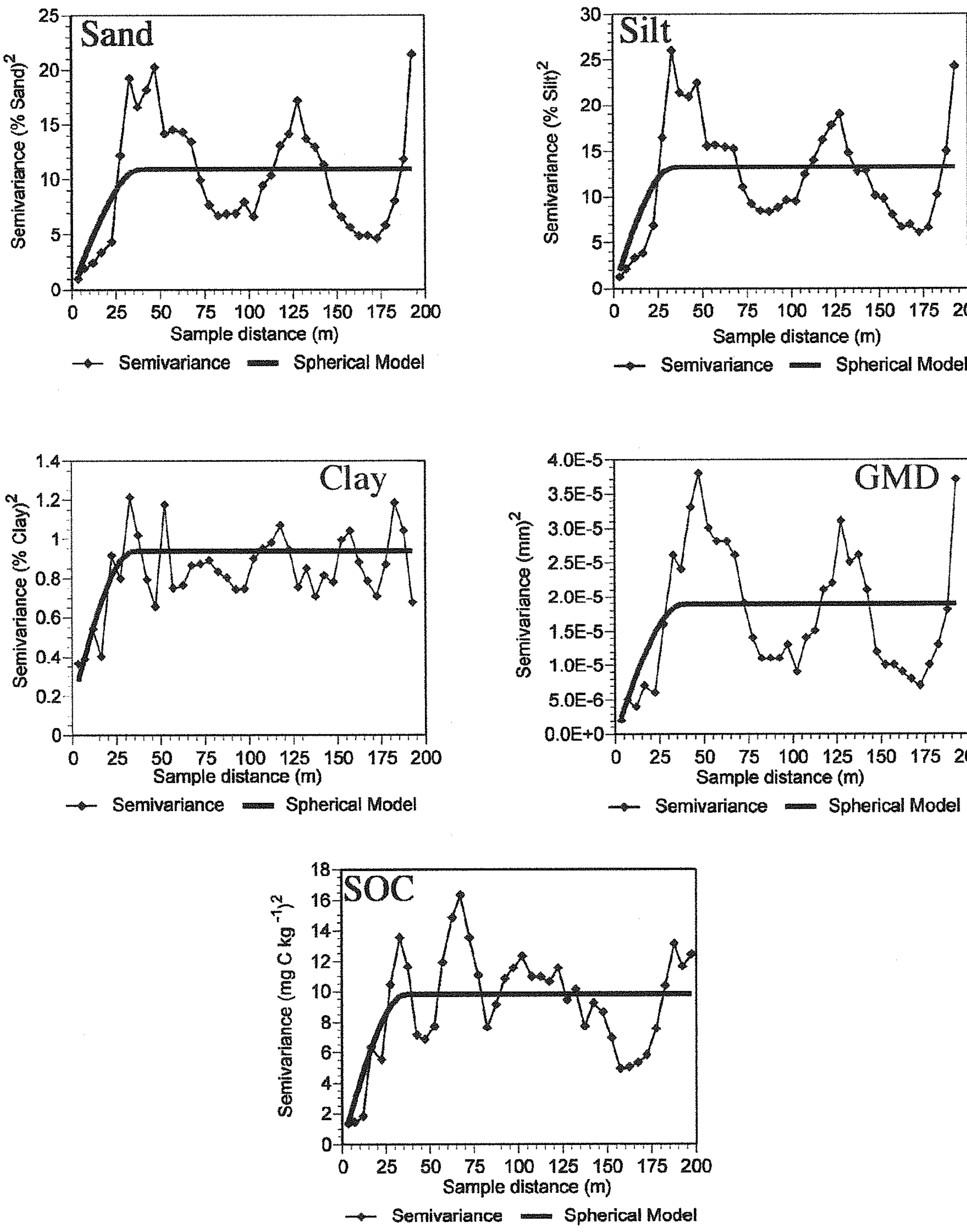

Figure 3. Semivariograms for sand, silt, and clay content, geometric mean diameter (GMD), and soil organic C concentration (SOC), showing experimental semivariogram and fitted spherical model.

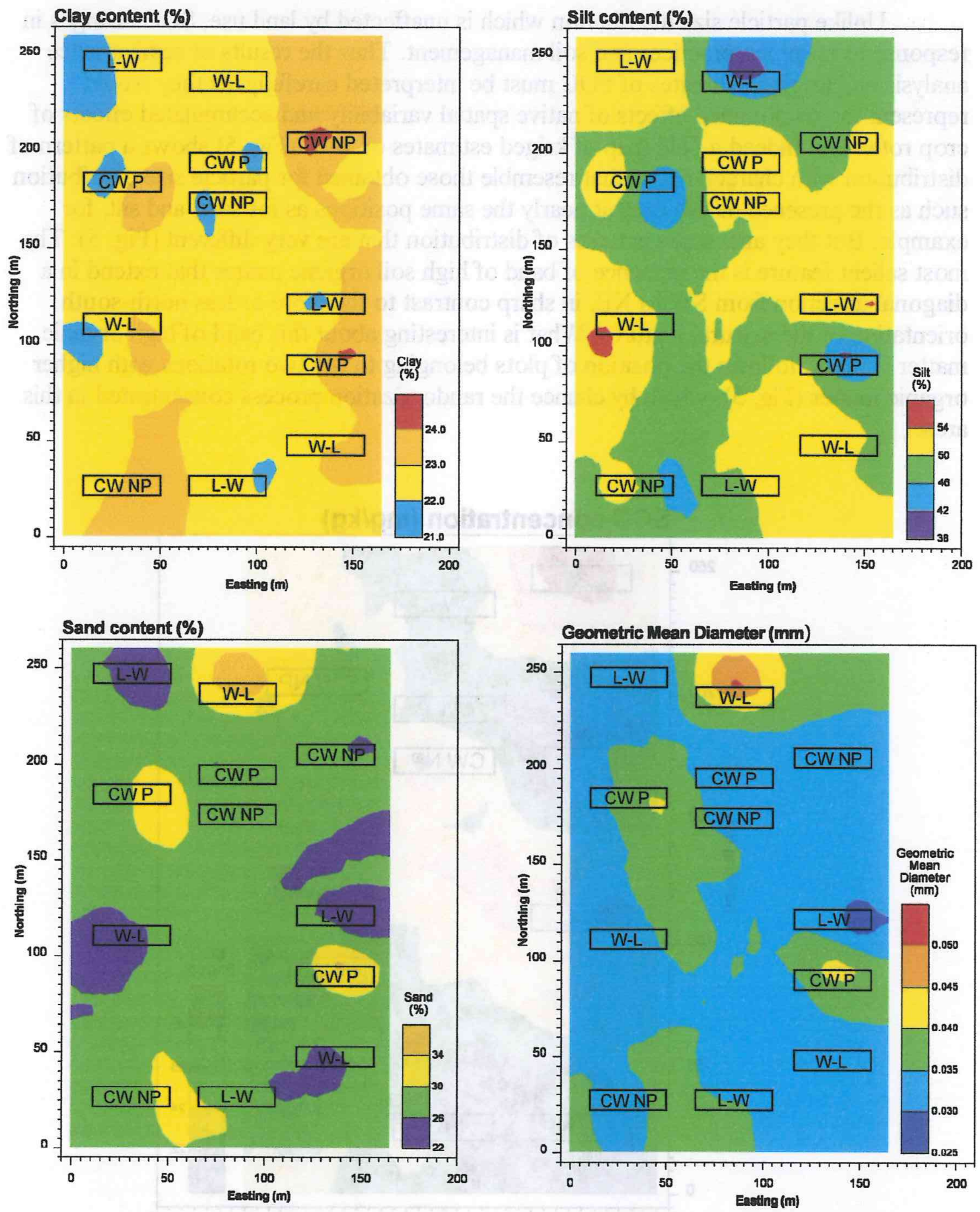

Figure 4. Distribution of clay, silt, sand and geometric mean diameter in the 0 to 7.5 cm depth estimated by block kriging. Rectangles show position of experimental plots in the field. CW NP: continuous wheat fertilized with N and P, CW P: continuous wheat fertilized with P alone, L-W and W-L: the two phases of the wheat-lentil rotation.

Unlike particle size distribution which is unaffected by land use, SOC changes in response to cropping practices and soil management. Thus the results of semivariance analysis and kriging estimates of SOC must be interpreted carefully, as they would represent the confounded effects of native spatial variability and accumulated effects of crop rotations. Indeed a field map of kriged estimates of SOC (Fig. 5) shows a pattern of distribution with characteristics that resemble those obtained for particle size distribution such as the presence of fish eyes at nearly the same positions as for sand and silt, for example. But they also show patterns of distribution that are very different (Fig. 5). The most salient feature is the presence of band of high soil organic matter that extend in a diagonal direction from SW to NE, in sharp contrast to the more or less north-south orientation of the textural features. What is interesting about this band of high organic matter is that it follows the position of plots belonging to the two rotations with higher organic matter (Fig. 5), which by chance the randomization process concentrated in this area.

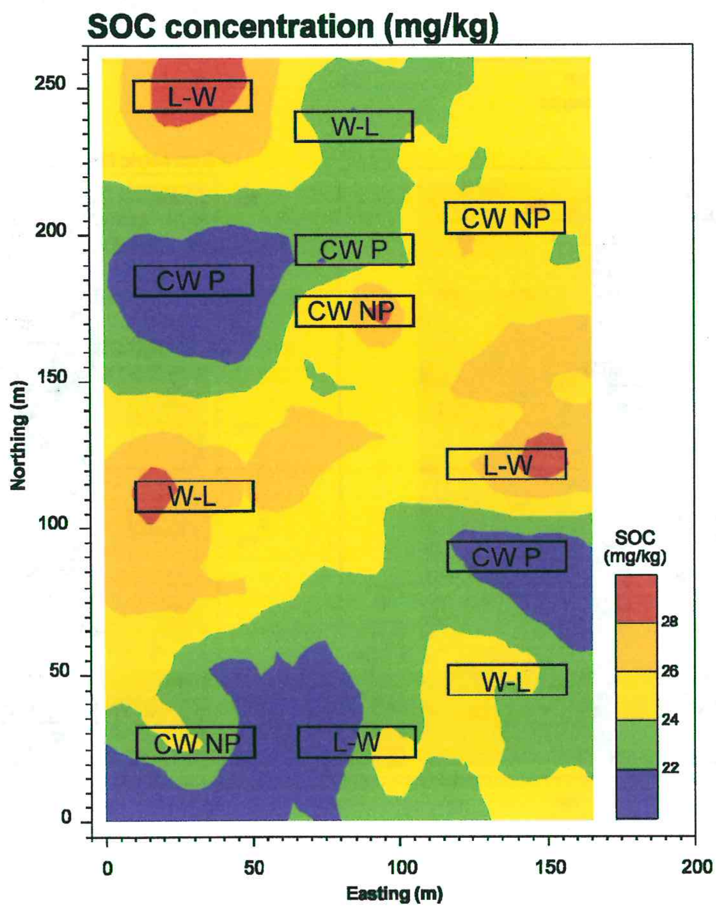

Figure 5. Distribution of soil organic C in the 0 to 7.5 cm depth estimated by block kriging. Rectangles show position of experimental plots in the field. CW NP: continuous wheat fertilized with N and P, CW P: continuous wheat fertilized with P alone, L-W and W-L: the two phases of the wheat-lentil rotation.

These results suggest that in areas of near average sand or silt content, which was in the majority of the experimental area, SOC was influenced by crop rotations. Only in areas where sand and silt had extremely high or low values was there evidence of texture affecting SOC concentration. This is reinforced by the fact that neither analysis of covariance nor cokriging with sand or silt as covariates affected the means of SOC by rotation or the distribution of SOC in the field.

CONCLUSIONS

We determined, using simple regressions, that there was an association between particle size distribution (especially sand and silt), or soil texture, and SOC. Further, results from our geostatistical analysis showed that there was a certain degree of association between SOC and texture, but only in a few discrete areas of the field where sand and silt had extremely large or small values. In the majority of the field, however, where sand and silt varied within relatively narrow limits, SOC distribution in the field indicates that soil texture did not have an effect on SOC. Results from our study indicate that the experimental design of the rotation experiment provided appropriate protection, against biasing the estimates of SOC by textural variations. Further, at this site the relationships between SOC and texture appear to be of a circumstantial nature arising from the presence of short distance transport and deposition processes rather that one of physical or physicochemical interaction between soil organic matter and clay. Consequently, these results do not explain the previously noted marked variability in SOC observed when the CW (NP) were plots measured over time, and the apparent lower variability observed for SOC over time in the W-Lent plots. Thus, based on these findings there is no need to incorporate additional textural effect functions in SOC process-level models such as CENTURY and EPIC, other than the general functions already built in these models. The nature of the short-distance effects of soil texture in SOC appear to be site specific, and related to soil forming factors. Thus no generalized functional relationship could be developed for inclusion in process-level SOC models.

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