Towards accurate measurements of soil organic carbon stock change in agroecosystems

A. J. VandenBygaart[1] and D. A. Angers[2]

[1]Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, KW Neatby Building, 960 Carling Avenue, Ottawa, Ontario, Canada K1A 0C6 (e-mail: vandenbygaarta@agr.gc.ca); [2]Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Blvd., Sainte-Foy, Quebec, Canada G1V 2J3. Received 28 October 2004, accepted 2 May 2005.

VandenBygaart, A. J. and Angers, D. A. 2006. **Towards accurate measurements of soil organic carbon stock change in agroecosystems**. Can. J. Soil Sci. **86**: 465–471. In response to Kyoto Protocol commitments, countries can elect agricultural carbon sinks to offset emissions from other sectors, but they need to verify soil organic carbon (SOC) stock change. We summarize issues we see as barriers to obtaining accurate measures of SOC change, including: soil depth, bulk density and equivalent soil mass, representation of landscape components, experimental design, and the equilibrium status of the SOC. If the entire plow depth is not considered, rates of SOC storage under conservation compared with conventional tillage can be overstated. Bulk density must be measured to report SOC stock on an area basis. More critical still is the need to report SOC stock on an equivalent mass basis to normalize the effects of management on bulk density. Most experiments comparing SOC under differing management have been conducted in small, flat research plots. Although results obtained from these long-term experiments have been useful to develop and validate SOC prediction models, they do not adequately consider landscape effects. Traditional agronomic experimental designs can be inefficient for assessing small changes in SOC stock within large spatial variability. Sampling designs are suggested to improve statistical power and sensitivity in detecting changes in SOC stocks over short time periods.

Key words: Soil organic carbon change, agroecosystems, experimental design, sampling depth

VandenBygaart, A. J. et Angers, D. A. 2006. **Vers une quantification précise des variations de stocks de carbone organique du sol dans les écosystèmes agricoles**. Can. J. Soil Sci. **86**: 465–471. Consécutivement aux engagements pris dans le cadre du Protocole de Kyoto, les pays peuvent choisir des puits de carbone agricoles pour compenser les émissions d'autres secteurs. Auparavant toutefois, ils doivent vérifier l'évolution des stocks de carbone organique du sol (COS). Les auteurs résument les facteurs qui pourraient faire obstacle à une quantification précise des variations de COS, entre autres l'épaisseur du sol, la masse volumique apparente et la masse équivalente de sol, la représentation des composants du relief, la méthode expérimentale et l'état d'équilibre du COS. On pourrait surestimer le taux de stockage du COS lors du travail et du non-travail du sol si on ne tient pas compte de la profondeur de labour. Il faut mesurer la masse volumique apparente pour rapporter les stocks de COS en fonction de la surface. Il est encore plus crucial de rapporter les stocks de COS d'après leur masse équivalente afin de normaliser les effets de la gestion des terres sur la masse volumique apparente. La plupart des expériences où l'on compare le COS résultant de diverses pratiques culturales reposent sur de petites parcelles sans relief. Bien qu'ils aient eu leur utilité pour le développement et la validation des modèles de prévision du COS, les résultats issus de ces travaux de longue durée ne tiennent pas assez compte de l'incidence du relief. Les méthodes expérimentales traditionnelles en agronomie pourraient manquer d'efficacité pour évaluer les petites variations des stocks de COS quand il existe une importante variabilité spatiale. Les auteurs suggèrent des plans d'échantillonnage susceptibles d'améliorer la qualité des statistiques et de permettre une détection plus fine des variations des stocks de COS sur une courte période.

Mots clés: Variation du carbone organique du sol, écosystèmes agricoles, dispositifs expérimentaux, profondeur d'échantillonnage

The Kyoto Protocol gives countries the option of electing agricultural carbon sinks as offsets to greenhouse gas (GHG) emissions from other sectors. However, this is contingent upon adequately verifying that there has been carbon sequestration occurring during the first commitment period. According to the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2004), verification of GHG inventories is required and is defined as "the collection of activities and procedures that can be followed during the planning and development, or after the completion of an inventory, that can help to establish its reliability for the intended application of the inventory". Furthermore it is considered good practice to verify soil organic carbon (SOC) changes using data and methods that are independent of those used to prepare the inventory. Although it is feasible to model SOC stock change at multiple scales (Post et al. 2001), it is still a necessity to monitor it at the plot and field scale in order to obtain the highest accuracy (Ellert et al. 2001, 2002) and to develop and validate SOC prediction models (Falloon and Smith 2003).

The scientific literature suggests that improved management of agricultural soils can result in increases in SOC stock (Six et al. 2002; VandenBygaart et al. 2003). However, it is acknowledged by many that it is very difficult to adequately detect a small change in SOC stocks over time periods of less than 5 yr (Post et al. 2001; Ellert et al. 2001). This is due to a number of factors including the dif-

Abbreviations: **CT**, conventional; **GHG**, greenhouse gas; **NT**, no-tillage; **PET**, potential evapotranspiration; **SOC**, soil organic carbon ficulty in observing a small change against a large background in SOC, large spatial variability in SOC stocks at multiple scales, and inadequate experimental designs, which may yield Type II statistical errors in comparison testing (observing no difference when there really is one). The purpose of this paper is twofold: (1) to outline some deficiencies in the existing methods, and consequently the interpretation of data, to monitor SOC change, and (2) to identify areas in which we may be able to improve our ability to accurately observe small changes in SOC over short time periods.

SOIL DEPTH AND TILLAGE

A number of studies have derived rates of SOC sequestration based on no-tillage trials from long-term experiments (Six et al. 2002; VandenBygaart et al. 2003). West and Post (2002) collated data from experimental trials comparing SOC from conventional (CT) and no-tillage (NT). Their analysis showed that relationships between CT and NT SOC stocks were:

$$SOC_{NT} = 1.20(SOC_{CT}) + 255.12, \text{ and}$$
$$SOC_{NT} = 0.93\ (SOC_{CT}) + 181.36$$

when the data were normalized to the 0–7 cm and the 7–15 cm depths, respectively. These findings imply that there was a loss of SOC in the 7–15 cm depth increment under no-till. This suggests that insufficient consideration of the entire plowing layer may result in overstating the rates of SOC storage under no-till (Royal Society 2001, p. 26–27).

To further emphasize the necessary consideration of soil depth, Fig. 1 shows the rate of SOC storage at successive depths for a 25-yr no-till period compared with a spring moldboard plow in southern Ontario (Deen and Kataki 2003). When the top 10 cm of the profile is considered there is clearly a considerable gain of SOC of 135 kg ha^{-1} yr^{-1} after accounting for bulk density. However, if the soil beyond the depth of tillage is included (about 18 cm), the rate of sequestration is inverted resulting in a net loss of SOC at a rate of about 120 kg ha^{-1} yr^{-1} to 20 cm. In this case there was an actual gain of SOC after 25 yr when just the top 10 cm was considered, yet when the entire depth of tillage was considered there was an overall loss of SOC.

The exercise in Fig. 1 emphasizes that the entire plow depth should be considered, particularly if differences in SOC stratification develop among the management practices. In other words, the SOC may simply be redistributed through the plow layer, and could yield no net change over time, or could even yield a net loss.

An analysis of the United States Department of Agriculture Pedon Database (USDA 1997) indicates that a large proportion (about 66%) of Ap horizons are greater than or equal to 15 cm. If many of these soils had been moldboard plowed and subsequently converted to no-till, an inversion of the SOC profile (as demonstrated in Fig. 1) is possible. If no consideration is made for soils with plow depths greater than 15 cm, there could be a very large overestimation of the true rates of sequestration when they are tallied to a national scale. The dynamics of the organic matter that had been placed at this depth under the moldboard plow would not be considered if only the top portion of the plow layer was sampled. A rapid change can occur at depths approaching the previous plowing depth when soils are converted to no-till. When a long-term no-till sandy loam in southern Ontario was plowed once, there was a significant decrease in SOC storage of about 3 Mg ha^{-1} near the topsoil-subsoil interface after only two cropping seasons (VandenBygaart and Kay 2004).

BULK DENSITY AND EQUIVALENT SOIL MASS

In addition to SOC concentration and soil depth, calculation of SOC storage requires determination of the bulk density. If the soil is stony, the mass and volume of large rock fragments must also be taken into consideration. Large physical changes often occur with change in soil tillage practice. The data presented in Fig. 2 show the temporal variation in bulk density after plowing a silty clay loam soil that had been under no-till for 22 yr (VandenBygaart and Kay 2004). If these changes in bulk density are not accounted for in the calculation of SOC storage, there can be errors in interpretation (Post et al. 2001; VandenBygaart and Kay 2004).

There are still other cautions with respect to bulk density. For example, when soils are converted from CT to NT there is generally an increase in bulk density when the entire plow layer is considered (Kay and VandenBygaart 2002). As a result, there will be a relative drop of the soil surface after conversion to no-till (Fig. 3). Thus, if samples are taken to the same depth within the plow layer, more mass of soil will be taken from the no-till soil (Fig. 3). This could increase the mass of SOC in the no-till and could widen the difference between the two systems if there is significant SOC beneath the maximum depth of sampling. To circumvent this problem, Balesdent et al. (1990) and Ellert and Bettany (1995) described methods to make comparisons based on equivalent soil mass. Ellert and Bettany (1995) also re-computed data from a previous study of comparing SOC stocks between NT and CT. For all six comparisons made in the study, they showed a decrease in SOC accumulation with no-till using the equivalent soil mass procedure.

In this paper, we evaluated studies published since Ellert and Bettany's (1995) paper, which compared SOC storage on an equivalent mass basis in replicated NT and CT experimental plots in temperate agroecosystems. In the seven studies considered, only four of the 21 comparisons yielded a significantly ($P < 0.05$) larger SOC storage with no-tillage (Table 1). Although this data set is small and represents a sporadic representation of climate-soil situations, one should be cautious in interpreting the rates of sequestration quoted in studies not considering comparisons based on equivalent soil masses between treatments.

It should further be noted, however, that consideration for equivalent mass in calculating SOC storage is only critical when the entire topsoil is not sampled, when there is significant amounts of SOC situated beneath the lowest sampling depth. If standard depth measurements are made in which the entire topsoil is contained within the complete profile sampled, and there is little SOC below, any changes in bulk density affecting SOC storage calculations are accounted

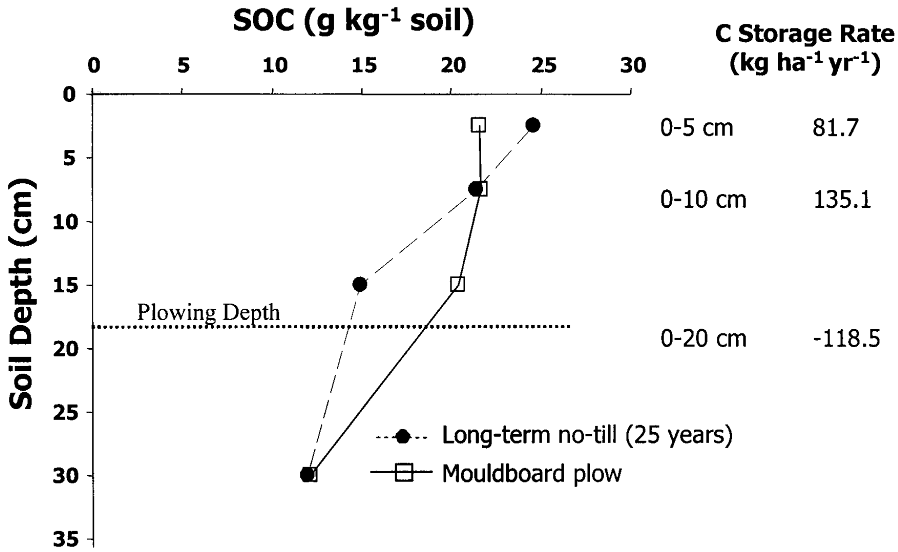

Fig. 1. Comparison of rates of SOC change when different depths are considered 25 yr after conversion to no-till from conventional tillage (Deen and Kataki 2003).

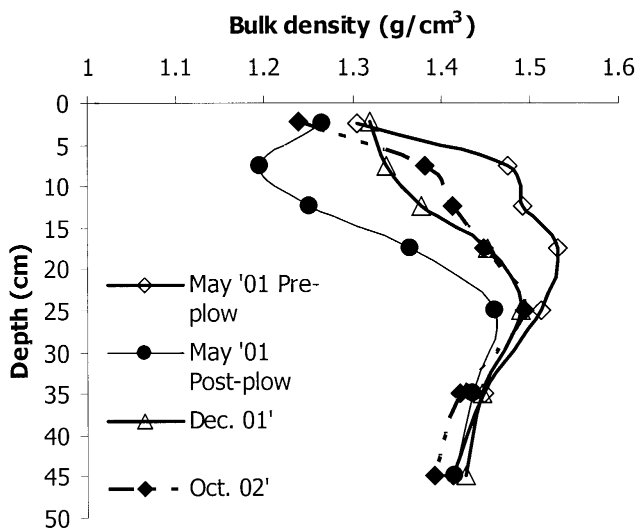

Fig. 2. Changes in mean bulk density with depth (n = 30 per soil depth increment) after plowing a long-term no-till soil in southern Ontario.

for, and equivalent mass calculations should not be necessary.

We cannot discount the possibility that the small number of studies exhibiting a significant increase of SOC in no-till with equivalent mass measures could be due to inadequate experimental plot and statistical designs. The inherent spatial variability in SOC could result in differences not being detected when there really were differences.

EXPERIMENTAL DESIGN

Many studies that have been conducted to measure SOC stock change over time have done so within existing long-term agronomic experiments. Agronomic experiments are often block designs, and were developed, and thus optimized, to assess management effects on crop production, not for changes in SOC over time. In this respect, researchers studying SOC stock change have usually used comparisons between treatments as a surrogate for time. Also, many of these long-term agronomic research sites did not have adequate measures of SOC at the initiation of the experiments. Ideally, assessing changes in SOC should be done over time, but should also be compared with a baseline treatment such that there is confidence that any changes that do occur are due to the actual management differences, and not other confounding factors such as climate (Campbell et al. 2000).

Due to the inherently large spatial variability in SOC stocks, small differences in SOC stocks among treatments are often masked by large variations in SOC across field plots. These differences in SOC may be due to pedologic or geomorphologic differences and can mask any true changes in SOC due to treatment. Not considering this effect may result in Type II statistical errors in comparison testing (observing no differences when there really are differences). One solution to this problem for future initiation of monitoring projects is for soil scientists to consider more appropriate plot designs when initiating experiments for monitoring changes in SOC over time.

Ellert et al. (2002) simulated changes of SOC stock by applying a known amount of carbon as recalcitrant coal to assess the ability to detect a change due to management. They situated "microsites" at locations within the landscape in which six soil cores were sampled in a systematic grid, while subsequent cores samples were taken, nested within the initial core locations (Fig. 4a). They applied a known amount of 3.64 Mg ha^{-1} of carbon as coal and determined the statistical power of the microsite approach. When comparing the differences after applying the coal, Ellert et al. (2002) showed that using the side-by-side spatial approach the statistical power was less than if the comparisons were

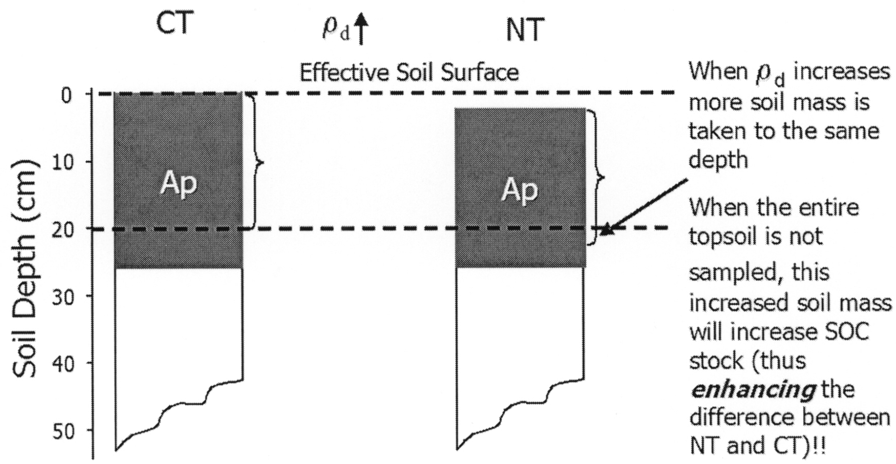

Fig. 3. Schematic illustrating that sampling to fixed depths in no-till and conventional tillage could inflate rates of SOC change in favor of the no-till system.

made temporally within the same plots. They could confidently detect the added carbon ($P < 0.01$) for equivalent masses exceeding 60-cm depths when comparisons were made in the same plots after applying the coal.

VandenBygaart and Kay (2004) set out to determine the permanence of SOC that had been stored after 22 yr of no-till in a field in southern Ontario. They devised a plot design in which cores were sampled in a regular systematic grid similar to Ellert et al. (2002), but with greater intensity of sampling (Fig. 4b). However, subsequent soil cores were taken at positions within 5 cm of the initial core locations that further minimized the effect of inherent SOC variability on statistical power (see VandenBygaart 2006). Using paired-core statistical testing, VandenBygaart and Kay (2004) were able to observe differences as small as 700 kg ha^{-1} over a period of three growing seasons at a 95% level of confidence. These designs could be very useful for monitoring SOC stock change at varying positions in the landscape in order to accurately observe small changes over short time periods such as 4 or 5 yr.

REPRESENTATION OF LANDSCAPE COMPONENTS

Experimental plots in which SOC stock change has been assessed over time are generally situated in level positions of the landscape. This is a consequence of the purpose of most agronomic experiments, which is to minimize the effects of external confounding factors. But there is evidence that the response of changing crop and soil management practices to SOC change varies across a variable landscape.

VandenBygaart et al. (2002) monitored the change in SOC stock after converting four farmer's fields to no-till from moldboard plow tillage. They situated soil coring locations at varying positions in the landscapes, which each had a history of soil redistribution such that shoulder slopes profiles were generally shallow with low SOC stock, while foot and toeslope landscape positions generally had thick soil profiles due to deposition of soil from upslope. After 15 yr, the shoulder-slope landscape positions generally showed sharp increases in SOC stock. However, this was countered by most depositional landscape positions showing declines in SOC after initiating no-tillage. At all four sites the response of SOC stock to converting to no-tillage was a linear function of the SOC stock at the time of conversion; landscape positions that had a low SOC stock due to past erosion generally showed gains in SOC, while positions with large SOC stocks due to deposition showed losses after 15 yr of no-till.

In the central Great Plains of the United States, Sherrod et al. (2003) evaluated the effects of cropping frequency on SOC stocks over a 12-yr period. At three locations differing in potential evapotranspiration (PET), they situated sampling locations at summit, sideslope and toeslope positions. At toeslope landscape positions, the only site that showed an increase in SOC in the top 20 cm after the 12 yr was the low PET site (Sterling) but only if cropping intensity was 100%. The other two sites with medium and high PET (Stratton and Walsh, respectively) showed losses of SOC at toeslope positions even if continuously cropped. This is even though crop inputs were greatest at toeslope landscape positions, and suggests that enhanced mineralization due to increased moisture in the toeslope positions overrides any crop carbon input benefits (Campbell et al. 2005). Each of the sideslope and summit landscape locations showed at least equal or larger SOC storage when continuously cropped over the 12-yr period. Clearly there is a need to represent landscape position when assessing SOC stock changes. In particular acquiring data on rates of change of SOC at different landscape positions is critical when upscaling is necessary for the purposes of a country's GHG inventory.

EQUILIBRIUM STATUS OF SOC

Before plots are sampled, there should be sufficient knowledge of the land-use and management history of the site. This becomes particularly important for confidence that the SOC stock is in an equilibrium state when the management or land-use change is implemented at the start of the exper-

Table 1. Replicated studies comparing SOC in no-till (NT) versus conventional tillage (CT) in which comparisons were made on an equivalent mass basis as per Ellert and Bettany (1995)

Study	Location	Treatments[y]	Duration (yr)	Depth of sampling (cm)	NT-CT (Mg ha^{-1})	P level or statistic	Significance
Deen and Kataki (2003)[z]	Elora, Ontario, Canada	NT vs. Spring MP, Fall MP	25	40	–10.1	$P > 0.05$	NS
	Elora, Ontario, Canada	NT vs. Spring MP + secondary tillage	25	40	–11.8	$P > 0.05$	NS
	Elora, Ontario, Canada	NT vs. Fall MP	25	40	–6.9	$P > 0.05$	NS
	Elora, Ontario, Canada	NT vs. Fall MP + secondary tillage	25	40	–3.2	$P > 0.05$	NS
McConkey el al. (2003)	Elstow, Sask. Canada	NT vs. CT^1	16	20	4.4	$P < 0.05$	*
	Indian Head, Sask. Canada	NT vs. CT^2	8	20	12	$P < 0.05$	*
	Melfort, Sask. Canada	NT vs. CT^2	25	20	4.1	$P < 0.05$	*
Needelman et al. (1999)	36 fields in Illinois, USA	NT vs. CT^3	variable but > 5	30	Not listed	$P = 0.43$	NS
Yang and Wander (1999)	Urbana, Illinois, USA	NT vs. MP	8–9	30	4.7	$P > 0.05$	NS
Wander et al. (1998)	Perry, Illinois, USA	NT vs. MP/CP	10–11	30	$<0^{\dagger}$	$P > 0.05$	NS
	Monmouth, Illinois, USA	NT vs. MP/CP	10–11	30	$<0^{\dagger}$	$P < 0.05$	*
	DeKaulb, Illinois, USA	NT vs. MP/CP	10–11	30	$<0^{\dagger}$	$P > 0.05$	NS
Cambell et al. (1998)	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat)	6	15	–2.31	$P = 0.14$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat N + P)	6	15	–0.37	$P = 0.84$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat-Wheat)	6	15	–1.57	$P = 0.38$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat-Wheat N + P)	6	15	1.27	$P = 0.47$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat-Wheat N + P - straw)	6	15	0.48	$P = 0.78$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Green Manure-Wheat-Wheat)	6	15	–3.31	$P = 0.07$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Fallow-Wheat-Wheat-Hay-Hay-Hay)	6	15	–0.88	$P = 0.61$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Continuous Wheat)	6	15	–2.82	$P = 0.1$	NS
	Indian Head, Sask. Canada	NT vs. CT^2 (Continuous Wheat N + P)	6	15	–0.84	$P = 0.63$	NS
Yang and Kay (2001)	Clinton, Ontario, Canada	NT vs. MP (Fox Loamy Sand)	19	30	70.14	$P < 0.05$	*
	Clinton, Ontario, Canada	NT vs. MP (Brady Sandy Loam)	19	30	14.71	$P > 0.05$	NS
	Clinton, Ontario, Canada	NT vs. MP (Huron Clay Loam)	19	30	4.7	$P > 0.05$	NS

[z]Actual values not listed in paper.
NT, no tillage; MP, moldboard plow; CT^1, harrowed cultivator + disc; CT^2, heavy duty cultivator; CT^3, disc, moldboard, and/or chisel.

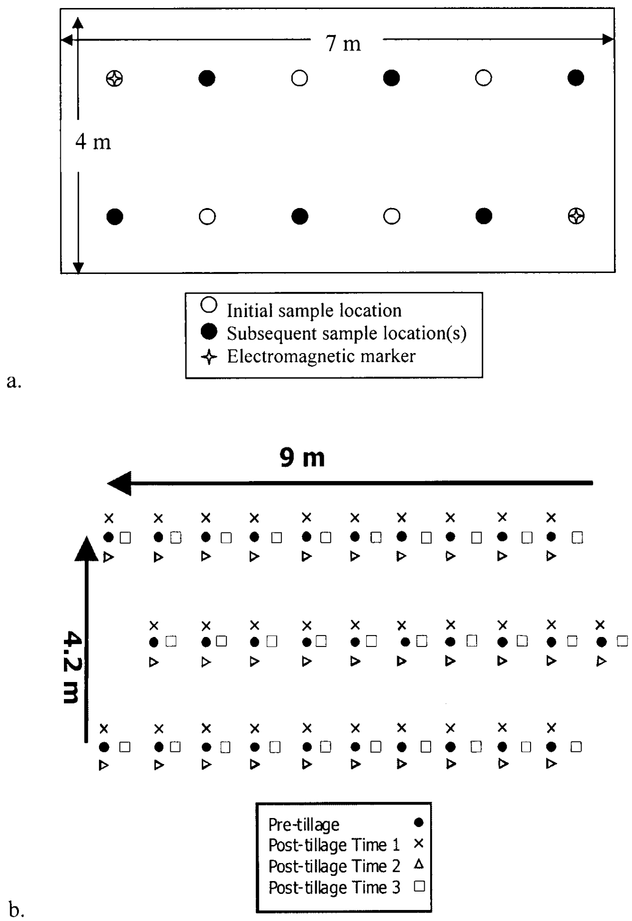

Fig. 4. Plot designs used to detect a small change in SOC stocks for (a) a study in western Canada (modified from Ellert et al. 2002) and (b) a study in eastern Canada (modified from VandenBygaart and Kay 2004).

iment or monitoring program. For example, Yang and Kay (2001) compared long-term (19 yr) NT with conventional moldboard plow tillage in a side-by-side transect design in a farmer's field. In one portion of the field located in a low-lying area they showed an apparent gain of about 70 Mg ha^{-1} under no-tillage (top 30 cm), a difference that was much greater than the net primary productivity of the cropping system. It was later discovered that at this landscape position tile drains were installed 30 yr previously. The no-till treatment prevented some loss of SOC due to mineralization compared with the CT system. In other words the no-till system did not result in a net gain in SOC, but prevented the loss of SOC relative to the CT system. This further emphasizes the caution required in interpretation of results when monitoring changes of SOC over time and the usefulness of comparing these changes to a business-as-usual or reference treatment.

SUMMARY

Countries electing agricultural soil carbon sinks as offsets to GHG emissions must be able to verify any significant increases in SOC in their lands. But there are some issues that need to be resolved when sampling for verifying SOC change. The erroneous interpretation of SOC change when only shallow depths are considered under conservation tillage management can inflate estimates of SOC change. The entire plow layer should be considered because the stratification of SOC can complicate the interpretation of SOC stock data. The lack of consideration for equivalent mass of soil in comparisons could erroneously favor those treatments that show an increase in bulk density by including more soil in the sample (thus more SOC) within the same depth. It is also not clear if what is represented in experiments conducted on small, flat experimental plots could be extrapolated to variable landscapes. In light of the inherently high variability in SOC stocks at the landscape scale, improvement in experimental design is needed to enhance statistical power and improve our ability to detect true differences or changes in SOC stocks over time and reduce the likelihood of type II statistical errors.

ACKNOWLEDGMENTS

We would like to thank Ed Gregorich, Martin Bolinder and Craig Drury for commenting on an earlier version of the manuscript. Three anonymous reviewers provided useful suggestions that improved the manuscript.

Balesdent, J., Mariotti, A. and Boisgontier, D. 1990. Effect of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. **41**: 587–596.

Campbell, C. A., Zentner, R. P., Liang, B. C., Roloff, G., Gregorich, E. C. and Blomert, B. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan – Effect of crop rotations and fertilizers. Can. J. Soil Sci. **80**: 179–182.

Cambell, C. A., Selles, F., Lafond, G. P., McConkey, B. G. and Hahn, D. 1998. Effect of crop management on C and N in long-term crop rotations after adopting no-tillage management: Comparison of soil sampling strategies. Can. J. Soil. Sci. **78**: 155–162.

Campbell, C. A., Janzen, H. H., Paustian, K., Gregorich, E. G., Sherrod, L., Liang, B. C. and Zentner, R. P. 2005. Carbon storage in soils of the North American Great Plains: Effect of cropping frequency. Agron. J. **97**: 349–363.

Deen, W. and Kataki, P. K. 2003. Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Till. Res. **74**: 143–150.

Ellert, B. H. and Bettany, J. R. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. **75**: 529–538.

Ellert, B. H., Janzen, H. H. and McConkey, B. G. 2001. Measuring and comparing soil carbon storage. Pages 131–146 *in* R. Lal, J. M., Kimble, R. F. Follett, and B. A. Stewart, eds. Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Ellert, B. H., Janzen, H. H. and Entz, T. 2002. Assessment of a method to measure temporal changes in soil carbon storage. Soil Sci. Soc. Am. J. **66**: 1687–1695.

Falloon, P. and Smith, P. 2003. Accounting for changes in soil carbon under the Kyoto Protocol: the need for improved long-term data sets to reduce uncertainty in model projections. Soil Use Manage. **19**: 265–269

Intergovernmental Panel on Climate Change. 2004. Good Practice Guidance For Land Use, Land-Use Change and Forestry

(GPG LULUCF). IPCC National Greenhouse Gas Inventories Programme. [Online] Available: http://www.ipcc-nggip.iges.or.jp/lulucf/gpglulucf_unedit.html [2004 Jul. 01].

Kay, B. D. and VandenBygaart, A. J. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. **66**: 107–118.

McConkey, B. G., Liang, B. C., Campbell, C. A., Curtin, D., Moulin, A., Brandt, S. A. and Lafond, G. P. 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil Tillage Res. **74**: 81–90.

Needelman, B. A., Wander, M. M., Bollero, G. A., Boast, C. W., Sims, G. K. and Bullock, D. G. 1999. Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois. Soil Sci. Soc. Am. J. **63**: 1326–1334.

Post, W. M., Izaurralde, R. C., Mann, L. K. and Bliss, N. 2001. Monitoring and verifying changes of organic carbon in soil. Climate Change **51**: 73–99.

Royal Society 2001. The role of land carbon sinks in mitigating global climate change. Royal Society, London UK.

Sherrod, L. A., Peterson, G. A., Westfall, D. G. and Ahuja, L. R. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agro ecosystem. Soil Sci. Soc. Am. J. **67**: 1533–1543.

Six, J., Feller, C., Denef, K., Ogle, S. M,. de Moraes Sa, J. C. and Albrecht, A. 2002. Soil organic matter, biota, and aggregation in temperate and tropical soils – Effects of no tillage. Agronomie **22**: 755–775.

United States Department of Agriculture. 1997. Soil Survey Staff 2005 National Soil Survey Characterization Data, Soil Survey Laboratory, National Soil Survey Center, USDA-NRCS, Lincoln, NE.

VandenBygaart, A. J., Yang, X. M., Kay, B. D. and Aspinall, D. 2002. Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. Soil Tillage Res. **65**: 231–241.

VandenBygaart, A. J., Gregorich, E. G. and Angers, D. A. 2003. Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Can. J. Soil Sci. **83**: 363–380.

VandenBygaart, A. J. and Kay, B. D. 2004. Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. Soil Sci. Soc. Am. J. **68**: 1394–1402.

VandenBygaart, A. J. 2006. Monitoring soil organic carbon stock changes in agricultural landscapes: Issues and a proposed approach. Can. J. Soil Sci. **86**: 451–463.

Wander, M. M., Bidart Bouzat, G. and Aref, S. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Soc. Am. J. **62**: 1704–1711.

West, T. O. and Post, W. M. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. **66**: 1930–1946.

Yang, X. M. and Kay, B. D. 2001. Impacts of tillage practices on total, loose- and occluded-particulate, and humified organic carbon fractions in soils within a field in southern Ontario. Can. J. Soil Sci. **81**: 149–156.

Yang, X. M. and Wander, M. M. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Tillage Res. **52**: 1–9.