SOIL CARBON VARIABILITY AND ASSESSMENT IN A CORN CROPPING SYSTEM IN THE UNITED STATES AND IN ZAMBIA

A Thesis

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by

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ABSTRACT

In eastern Zambia soil carbon (C) and nitrogen (N) in the top 15 cm were higher ($p<0.01$) in conservation agriculture (CA) compared to traditionally managed corn plots, and soils beneath existing *Faidherbia albida* trees (a legume being intercropped on CA farms) had higher C and N in the top 15 cm ($p<0.05$ in trees > 100cm diameter at breast height). Sampling across 10 cropping systems of a 650 ha corn and dairy farm in New York State, bulk density (BD) and organic matter (OM) had a lower coefficient of variation (CV) and smaller sample requirement than soil C concentration. Linear regression models could predict t C ha^{-1} for the 0-60cm soil profile from measurements of C and BD at the 0-20 or 20-40cm depths ($p<0.001$, r^2 = 0.63 and 0.89, respectively). Soil survey estimates of OM at lower depths were improved with regression models based on field data.

BIOGRAPHICAL SKETCH

Samuel Bosco was born July 31, 1986 in Millburn, New Jersey to Ann Shoshkes and Frank Bosco. He has one older sister, Rosina and currently shares his life with his partner Simone Lackey and daughter Aurora in Ithaca, New York. Originally on a path to pursuing a career in music, this all changed after reading the novel *Ishmael*, by Daniel Quinn. It was a life changing experience that inspired him to devote his life to environmental justice.

Following this new path, Samuel began his post-secondary studies in the fall of 2004 at the State University of New York, College of Environmental Science and Forestry (SUNY ESF) in Syracuse, New York. He completed his Bachelors of Science at the University of Maryland, where he discovered a new passion for soil science and sustainable agriculture. He explored various applications of this, including employment at the USDA Environmental Management and Byproducts Utilization Lab working on turning agriculture wastes in biofuels. Samuel enrolled in the department of Horticulture’s graduate program at Cornell University in the spring of 2009. During that time he served as the Treasurer and President of the New World Agriculture and Ecology Group at Cornell.

Samuel deeply enjoys learning to live more sustainably as well as creating a life style that is more in harmony with the natural rhythms of the earth. His life mission is in service to collaborative community-led solutions that transition our culture from oil-dependency to local resilience. He is inspired to develop a localized agriculture that is regenerative to its social and ecological communities.

For the scientists, policy makers, educators, and activists whose work has informed my own and to those whom this will inform,

For those committed to creating positive change, and

For the future of the Earth

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Thank you to all who have come before me, ancestors, elders and otherwise, who remind us to be grateful and for whose accomplishments, insights, and blunders have no doubt impressed upon me my purpose in this world.

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Many thanks to the New World Agriculture and Ecology Group at Cornell for opening me to the world of food justice, offering me a place in leadership, and the inspiration to give back to the community. Thank you to the community leaders for your openness, trust, collaboration, and your dedication to transformative change.

To my friends whom have made me feel at home here, without you I would not have the inspiration to be who I am. To my peers, who too were students, though also my teachers.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Evaluation of Conservation Agriculture Techniques

in Relation to Soil Carbon and Nitrogen in Zambia

ABSTRACT

Community Markets for Conservation (COMACO) is a small land-holder cooperative of 19,000 farmers in eastern Zambia that has sought to reduce poverty and wildlife poaching by improving food security. Farmers are encouraged to adopt conservation agriculture (CA) practices that are designed to build soil fertility and organic matter through reduced tillage, rotation with legumes, and returning crop resides to the soil. A recent COMACO effort is to intercrop the leguminous *Faidherbia albida* (FA) tree on CA farms (100 trees ha^{-1}), as a source of organic matter (OM) and nitrogen (N). We collected replicated composite soil samples at 0-15 and 15-30cm near the end of the dry season and before planting (October, 2009) on a small subset of CA (n=13) and traditional managed (n=16) farm plots across the COMACO region. We measured bulk density (BD), soil carbon (C), nitrogen (N), organic matter (OM), and permanganate oxidizable active C (AC). Soils in CA plots had 65% higher t C ha^{-1} in the top 15 cm compared to traditional plots ($p<0.01$), and also had significantly more C than three of the four relatively undisturbed miombo woodlands sampled at sites near to the farms. Although t N ha^{-1} was also significantly higher at 0-15cm in CA compared to traditional plots, soil N and the C/N ratio values for CA as well as traditional plots indicated the need for N additions for optimum yield. We found higher soil C, OM, and N beneath *F. albida* trees compared to 10 m beyond the canopy, and this was statistically significant at $p<0.05$ at the 0-15 cm depth for large trees (>100 cm dbh). Larger trees also had significantly higher soil C and N beneath the canopy than smaller trees (<100 cm). While our results suggest that CA practices are already having

positive effects on soil C and N, and that the soils in the COMACO region could respond positively to the recent *F. albida* plantings, this is based on a small sample size and our results could be biased by inherent soil fertility and prior land use. Nevertheless, our results expand our knowledge base beyond data from a few controlled experiments to include information from a broader range of soil, environmental, and management conditions.

INTRODUCTION

Conservation agriculture (CA) is an ecologically-based approach to farming that attempts to conserve soil, water, and nutrient resources within the farm while maintaining yields and quality. It is a knowledge-intensive management approach, not one fixed set of practices, but typically it involves minimizing tillage, maintaining vegetation cover year-round, diversifying crop rotations, re-incorporating crop residues, and use of composts, manures or other organic amendments (FAO, 2010; Hobbs, 2007). All of these practices intend to maintain or build organic matter in the soil, which may have beneficial effects on "ecosystem services" attributable to "soil health" such as crop productivity, improved water and nutrient cycling, beneficial soil microbial activity, and improved drainage (Kassam et al., 2009; Gugino et al., 2009).

At a broader landscape scale, CA can encompass good agroforestry practices and the avoidance of slash-and-burn clearing of forests. A comprehensive regional CA approach has the potential to enhance food security and alleviate poverty while minimizing land degradation and meeting other conservation goals at regional scales (Milder et al., 2011). In addition, CA practices can increase resilience to climate change (e.g., better soil water holding capacity, more diverse cropping system) and increase soil and biomass carbon (C) sequestration, thus contributing to climate change mitigation (Milder et al., 2011; Scherr and Sthapit, 2009).

CA has the potential to reduce the need for external inputs, and thus is an attractive strategy for poor small land-holders in developing countries with limited access to capital for inputs such as fertilizers (Derpsch et al., 2010; Kassam et al., 2009). In sub-Saharan Africa, fertilizer use averages 13 kg ha^{-1} compared to a global average of about 100 kg ha^{-1}, and irrigation is used on only 3% of farm land (AGRA, 2010).

Within Africa, Zambia has been at the forefront of recent attempts to expand use of CA practices with small landholder farmers. Primarily through the research and outreach efforts of the Conservation Farming Unit, the number of small farmers adopting CA in Zambia rose from 20,000 in 2001 to 180,000 in 2009 (CFU, 2010). The CFU goal for 2011 is adoption by 250,000 families, about 30% of Zambia's small farmers.

Our project focused on the Luangwa Valley of Zambia, where a non-profit organization, the Community Markets for Conservation (COMACO), has worked since 2003 to improve the food security of small land-holder farmers in the region. The Luangwa Valley is home to several of Zambia's most prominent national parks that are important to the local economy, but wildlife poaching by the local expanding human population has been a problem that is directly linked to chronic poverty and food insecurity. The goal of COMACO has been to reduce poaching by promoting CA practices (most derived from research at CFU) for farmers in the region through extension support and access to high value markets for participants. A recent analysis by Lewis et al. (2011) has shown that the COMACO model is promising. Although still dependent to some extent on support from the Wildlife Conservation Society and other sources, COMACO is moving toward self-reliance and a successful and complex agribusiness that operates across the value chain and supports both conservation and food security goals.

In the past several years COMACO's 60 extension staff have trained about 40,000 farmers, and over 19,000 are registered as being compliant with CA practices (Lewis et al., 2011). Specifically, COMACO's CA practices include: dry-season land preparation using minimal tillage (tillage often confined to small planting basins); no burning of crop residues but rather using them for weed suppression and to mitigate soil erosion; use of composts from livestock and animal dung to recycle nutrients and build soil organic matter; and rotation and/or intercropping with nitrogen (N)-fixing legume crops.

The COMACO system discourages slash-and-burn clearing of forested lands ("chitimene") and the goal is to reduce the need for new land clearing by maintaining or increasing crop yields with CA practices. Recently, COMACO has in addition initiated an ambitious tree planting project- the intercropping of one million leguminous (N-fixing) *Faidherbia albida* trees on COMACO farms, with a planting density of 100 seedlings per hectare (COMACO, 2010).

Barnes and Fagg (2003) reviewed the early literature on *F. albida*, which documents its benefits as a N-fixing intercrop in Africa. It is native to the region, is relatively fast-growing, and provides N-rich organic matter through root turnover and at leaf fall to surrounding plants. It has been estimated that a mature stand of 50 trees ha^{-1} can potentially provide over 400 kg N ha^{-1} and increase total soil C by 60-90% (Barnes and Fagg, 2003, pp. 46, 47). These trees also have a somewhat unusual "reverse phenology", meaning they maintain leaves during the dry season (this is made possible by a deep root system), and they drop leaves at the beginning of the rainy season. This may benefit the farmer because the soil is provided with high-N organic matter just as fields are being prepared for planting, and during the crop growing season the trees are without leaves so have minimal shading effect on crops below.

The leadership at COMACO has recognized for some time that the CA practices they are adopting, including the new *F. albida* agroforestry effort, may open the door to new revenue opportunities through C offset markets (Milder et al., 2010; Scherr and Sthapit, 2009). However, there are many challenges to enter these C markets, in particular the need to document baseline soil C stocks and CA practice effects on soil C (TCG, 2010; Gibbs et al., 2007; Smith et al., 2007).

The objectives of our project were to:

1) provide an initial assessment of the effect of recent adoption of CA practices on soil C and N on farms within the COMACO system; and

2) gather preliminary data on the effect of *F. albida* trees on soil C and N in the region.

METHODS

Site Description

Our field sites for soil sampling were located in the Luangwa Valley region of eastern Zambia (Figure 1.1). This area is classified as Agro-ecological Zone IIa, a plateau with moderate rainfall. In Chipata, a town in the southeast corner of the region, annual mean maximum and minimum temperatures are 32.6C and 12.3C, respectively; annual rainfall is 1000mm (Aregheore, 2011). A geographic information system (GIS) was used to visualize important map layers from which to base soil sampling locations. Map layers used included the Zambian National Soil Map (Zambian Ministry of Agriculture) and European Space Agency GlobCover 300 m resolution map of vegetation cover types. For samples taken on farmer fields, COMACO extension officers helped to locate field plots that had been farmed with CA practices for 2 – 3 years, and for contrast, plots with crops grown with traditional practices (e.g., more tillage,

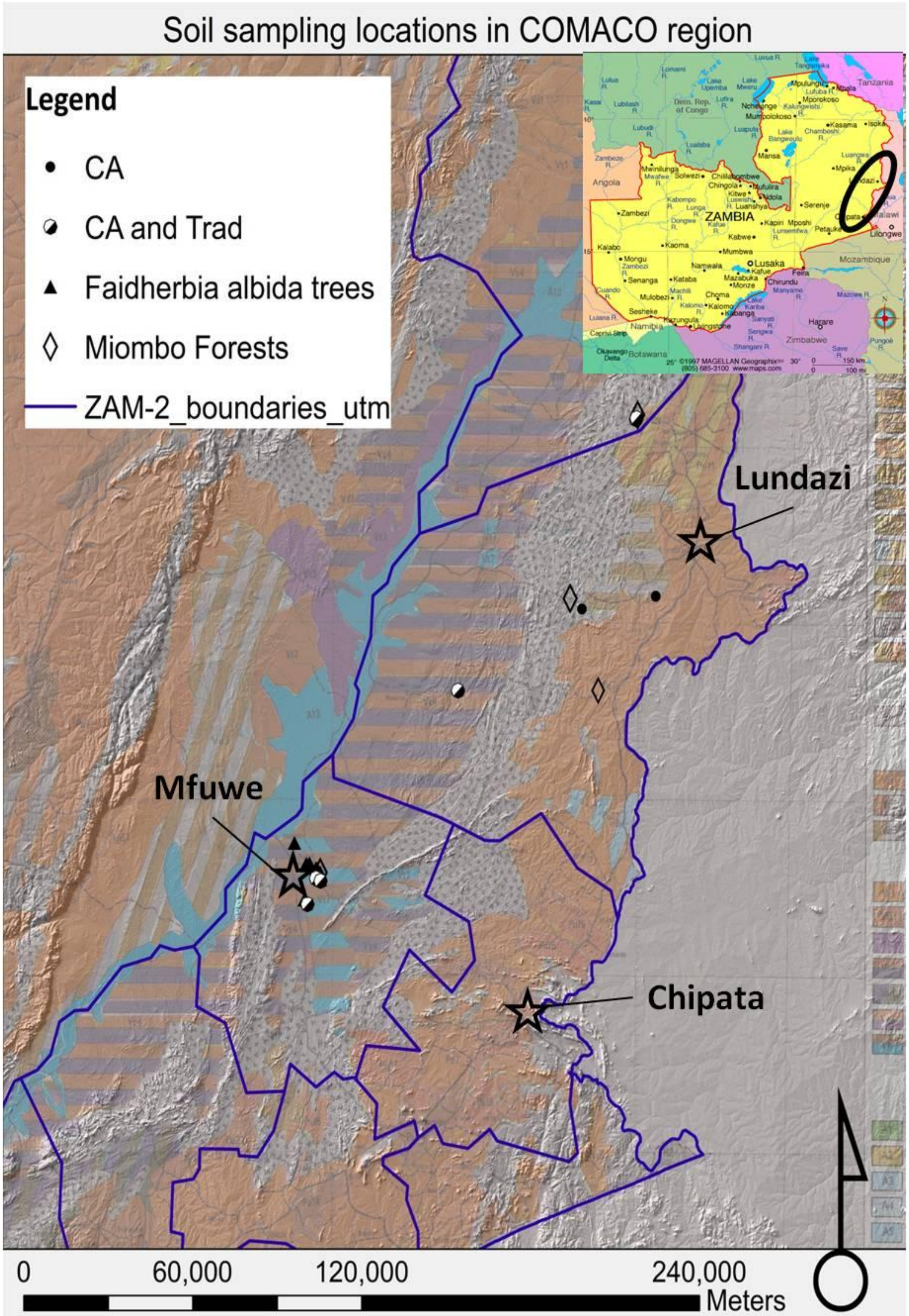


Figure 1.1. Map of soil sampling location in the Luangwa Valley COMACO area. Nearby cities included for reference.

residue burning, less rotation). All plots sampled included maize (*Zea mays* L.), a staple crop of the region, as a dominant crop in their rotation. Farms were selected to capture a range of soil types of the COMACO region, as indicated in Table 1.1. Management history for farm plots beyond the past 2-3 years was not available. We relied on COMACO extension officers to take us to representative farms where CA was being adopted, but the specific practices used on CA-identified plots, and the degree to which farmers adhered to COMACO guidelines could not be otherwise verified and presumably varied from farm to farm.

Four miombo woodland areas near to farm sites (see Figure 1.1) were also selected for soil sampling to represent relatively undisturbed land areas (undisturbed for at least 10 years).

Sampling sites also included the soils beneath nine existing *F. albida* trees, primarily found in the southern part of Luangwa Valley near the town of Mfuwe (Figure 1.1). These trees were in general on or near to farm sites included in our study. They ranged in age from about 15 years to over 70 years (based on information from local residents), and diameter (cm) at breast height (dbh) ranged from 40 to 140 cm.

GPS coordinates of all sampling locations were recorded (Table 1.1).

<u>Soil Sampling Protocol</u>

Soil samples for lab analyses were collected during the first two weeks of October (dry season) in 2009. At each farm plot (selected based on homogeneous cropping system—CA maize rotation or traditional continuous maize for the past 3 years) from 1 to 6 composite soil samples were collected in a randomized fashion to encompass the plot area. Each composite was made up of 3 sub-samples collected within about 1 to 5 m of each other. Planting basins were not visually apparent and thus our sampling did not necessarily exclude or include soil from basin

Table 1.1. List of soil sample locations and types as well as land management and site characteristics. Observed texture is the soil texture category as determined by the "texture by feel" method for each sample location. Classification is the soil type for each sample location according to the Zambian National Soil Map (Ministry of Agriculture, 1991) and Land Cover is the land use type for each sample location extracted from the European Space Agency's Globcov at 300m resolution (Bicheron et al., 2008).

Soil type classification descriptions:
Vt – Landform: Older alluvial plains and higher river terraces in the Rift Valley Trough (slopes 0-3%); **Vt4**: complex of: imperfectly drained, olive brown to brown, firm, sodic, clayey soils, (orthi-Haplic Solonetz) and well drained, very deep, yellowish red to strong brown, friable to slightly firm, friable slightly weathered to moderately leached, clayey soils, having a clear clay increase with depth, in places cracking (chromi haplic Luvisols with eutric Vertisols); **Vt7**: complex of: imperfectly drained, very deep, dark grayish brown to yellowish brown, friable, stratified clayey soils (eutric Fluvisols) and moderately well drained to well drained, yellowish brown to dark yellowish brown, firm, slightly weathered and slightly leached, calcareous clayey soils having a clear clay increase with depth (orthi-calcic Luvisols); **He** – Landform: Hills and faulted scarps of the rift valley (variable slopes) Excessively drained to well drained, shallow to moderately shallow, dark brown to yellowish brown, friable, stony, gravelly, coarse to fine loamy soils (orthi-eutric Leptosols; rudic phase; with lithic Leptosols); **Pd** – Landform: Dissected Plateau (slopes 5-17%); **Pd6:** complex of: excessively drained to well drained, shallow to moderately shallow, yellowish brown, coarse to fine loamy soil (orthi- eutric Leptosols) and well drained, moderately deep to deep, red, friable, fine loamy to clayey soils (chromi- haplic Cambisols);**Pu** – Landform: Plateau, flat to lightly undulating (slopes 0-5%);**Pu7:** well drained, deep to very deep, yellowish red to strong brown, friable, fine loamy to clayey soils, having a clear clay increase with depth; having inclusions (20%) of moderately of moderately drained to imperfectly drained, deep to moderately shallow, gravelly clayey soils (chromi- haplic Acrisols, partly skeletic phase; dystric Leptosols)

Land Cover Codes from 300m GlobCover (European Space Agency, 2009): **60 –** open broadleaved deciduous forest; **100 –** closed to open mixed broadleaved and needleleaved forest; **120 –** Mosiac grassland/Forest-shrubland; **130 –** Closed to open shrubland

Table 1.1. (for description see previous page)

		GPS N	GPS E	n	Soil Type: Observed Texture	Soil Type: Classification	Land Cover
Farms	Traditional	n/a	n/a	6	Sandy	n/a	n/a
	Traditional	435545	8597338	3	Sandy	Vt4	130
	CA	435545	8597338	3	Sandy	Vt4	130
	CA	498764	8682452	1	Sandy Loam	He	130
	Traditional	498764	8682452	1	Sandy Loam	He	130
	CA	499044	8682744	1	Sandy Loam	He	130
	Traditional	499044	8682744	1	Sandy Loam	He	130
	CA	505185	8626888	2	Fine loamy	Pd6	120
	CA	479616	8622902	1	N/A	He	100
	CA	490214	8625978	2	N/A	He	130
	Traditional	385127	8538506	1	Clay loam to sandy loam	Vt7	130
	CA	385127	8538506	1	Clay loam to sandy loam	Vt7	130
	Traditional	386741	8537704	1	Loam	Vt7	130
	CA	386748	8537686	1	Loam	Vt7	130
	Traditional	382106	8530376	3	Loam	Vt7	60
	CA	382106	8530376	3	Loam	Vt7	60
Miombo Forests	Lundazi National Forest	499380	8683792	3	Sandy	He	130
	Zumwanda	475414	8626250	3	Sandy	He	130
	Woodland M1	386632	8540322	3	Sandy Loam	Pu7	60
	Mtandgwu	485350	8597364	3	Sandy	He	130

areas. The *n* number in Table 1.1 represents how many replicates of these composite samples were taken in a given field or site. Because of the small nature of the farms and plots within each farm, a plot area was typically about 0.25 ha or less. For each sub-sample, a 5 cm diameter steel soil probe was pushed or driven by sledgehammer into the soil to a depth of 30 cm. The 0-15 cm and 15-30 cm sections of the soil core were divided and placed into separate plastic buckets. The three sub-samples were well mixed in the buckets and then a sub-sample from this composite was put into a 4 liter plastic bag and placed in a cooler for later lab analysis. At the approximate center of the location of each composite soil sample for lab analyses, 2 undisturbed core samples were collected for bulk density (BD) at the 0-15 cm depth using 7.5 cm inner diameter BD rings with a 247.5 cm^3 volume. The soil from the two sub-samples that precisely filled the BD ring volume was placed into a plastic bag for later drying and BD determination.

For soil samples under *F. albida* trees, one composite sample was taken at three distances relative to the trunk of tree: approximately 1 m from the base of the tree, midway between trunk and edge of canopy (estimated based on tree size), and about 10 m beyond the edge of canopy cover, and on the side of the tree where wind is predominantly incoming (based on discussion with local residents). It was assumed that 10 m beyond the canopy edge would be beyond the tree effect, and could thus serve as a control.

For the woodland samples, 3 separate composite soil samples (replications) were collected in a random, zig-zag pattern from an approximate 0.25 ha section of the forest that seemed representative. Sub-samples were collected between and not directly adjacent to trees.

All soil samples were air-dried, then sealed in plastic bags and shipped to Cornell University for laboratory analyses.

Laboratory Analysis

Bulk Density

BD was measured according to the National Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2004, pp 104-105). Air-dried soils were passed through a 2 mm sieve and dried in a drying oven at 105C for 24 hours. Rock fragment volume was measured by measuring their displacement of water in a 100 ml graduated cylinder. The following formula was used to determine BD:

[1] $$BD = (ODW - RF) / (CV - RV)$$

Where: ODW = oven dried mass (g); RF = rock fragment mass (g); CV = core volume (cm^3); and RV = rock volume (mL)

Total Carbon and Nitrogen

Lab soil samples were sieved to 2 mm and prepared for four soil measurements. Total C and total N were measured using the Dumas method with a LEICO2000 Auto analyzer (Elementar Americas, Inc., Mt. Laurel, NJ, USA). Results are reported as percent of soil mass. Based on soil maps and soil series descriptions, C measurements were assumed to not contain inorganic forms of C and thus C values are attributable to organic C.

Soil Organic Matter

Soil OM was measured following the loss-on-ignition method (Storer, 1984) and performed by the Cornell Nutrient Analysis Laboratory. Results are reported as percent of soil mass.

Permanganate oxidizable "active" carbon

Active carbon (AC) was measured by potassium permanganate ($KMnO_4$) oxidation of 2 mm sieved, 40 C-dried soil with 0.02 *M* $KMnO_4$ as described in Weil et al. (2003). A standard linear calibration curve was developed at each lab run from three concentrations of standard $KMnO_4$ solution, 0.005 M, 0.01 *M*, and 0.02 *M*. Active C (mg kg^{-1}) was then determined by the following equation:

[2] $\text{AC (mg kg}^{-1}\text{)} = [0.02\ mol{\cdot}L^{-1} - (a + b \times absorbance)] \times (9000\ mg\ C{\cdot}mol^{-1}) \times (0.021\ solution{\cdot}0.0025\ kg^{-1}\ soil)$

Where 0.02mol L^{-1} is the initial $KMnO_4$ concentration, *a* is the intercept and *b* is the slope of the standard curve, 9000 is mg C (0.75 mol) oxidized by 1 mol of MnO_4 changing from Mn^{7+} to Mn^{2+}, 0.021 L is the volume of $KMnO_4$ solution reacted, 0.0025 is the kg of soil used (Weil et al., 2003).

<u>Data Analysis</u>

Converting Soil Data to Mass Per Unit Area Basis

BD data was used to convert C, N, OM, and AC data from units of concentration or percent into mass per area as tons per hectare (t ha^{-1}) using the following formulae:

[3] $\text{C, N, or OM (t}{\cdot}\text{ha}^{-1}\text{)} = [C, N, or\ OM\ (g{\cdot}100\ g^{-1}\ soil) \times [1{\times}10^{4}\ (100\ g{\cdot}t^{-1})] \times [BD\ (g{\cdot}cm^{-3}) \times 20\ cm] \times (1{\times}10^{6}\ cm^{2}{\cdot}ha^{-1}) \times (t{\cdot}1{\times}10^{-6}\ g)]$

$AC\ (t{\cdot}ha^{-1}) = [AC\ (mg{\cdot}kg^{-1}) \times (1{\times}10^{4}\ kg{\cdot}t^{-1}) \times [BD\ (g{\cdot}cm^{-3}) \times 20\ cm] \times (1{\times}10^{6}\ cm^{2}{\cdot}ha^{-1}) \times (t{\cdot}1{\times}10^{-6} g)]$

Statistical Analysis

Statistical analysis was performed with JMP 9 (SAS Institute, 2010). For an analysis of variance (ANOVA), soil properties (N, C, OM, AC, in % and t ha^{-1}) were response variables while management (traditional, CA, or miombo woodlands) comprised the "treatment" effect. For determining statistical differences, management effects on soil properties were compared using student's-t test within each depth segment (0-15 cm, 15-30 cm).

RESULTS AND DISCUSSION

<u>CA Effects on Soil C and N</u>

The soil C levels we found in traditional farm plots (Table 1.2) are similar to what Walker and Desanker (2004) found on similar soils (based on their soils description) in maize agricultural systems near Kasungu, Malawai, approximately 90 km from Lundazi in the northeast corner of the COMACO region of Zambia. In our study, pooling data from all farm plots sampled (n=12 for CA and n=16 for traditional) we found that C, OM, and N were consistently higher in CA compared to traditional plots, and these differences were statistically significant in some instances. For example, C% and t N ha^{-1} were significantly higher ($p< 0.05$) in CA compared to traditional plots at the 0-15 cm depth. When we conducted an analysis confined only to those sites with paired CA and traditional plots on the same farmer field and soil type (n=6) we again found a statistically significant ($p<0.05$) higher C% at the 0-15 cm depth (as reported in Lewis et al. (2011, Figure S10).

Table 1.2. Soil property means and t-test p-values comparing conservation agriculture (CA) and traditional management techniques at 0-15cm and 15-30cm. Bulk density (BD) was not measured at 15-30cm and therefore soil property mass per unit area not available (na) at that depth

Depth (cm)	Treatment	BD ($g\ cm^{-3}$)	C (%)	N (%)	OM (%)	AC ($mg\ kg^{-1}$)	C ($t\ ha^{-1}$)	N ($t\ ha^{-1}$)	OM ($t\ ha^{-1}$)	AC ($t\ ha^{-1}$)	C/N	C/OM	AC/C
0-15	CA (n=13)	1.36	1.46	0.07	4.38	358.41	28.54	1.35	85.90	0.67	24.67	0.36	0.03
	Traditional (n=16)	1.38	0.89	0.05	3.20	272.41	19.09	0.85	63.76	0.54	26.39	0.31	0.03
	p	0.450	0.007	0.191	0.144	0.143	0.075	0.016	0.131	0.160	0.841	0.138	0.182
15-30	CA (n=12)	na	1.13	0.05	4.00	278.01	na	na	na	na	26.22	0.29	0.03
	Trad (n=16)	na	0.75	0.03	2.91	193.04	na	na	na	na	59.44	0.24	0.03
	p	na	0.126	0.087	0.154	0.122	na	na	na	na	0.117	0.098	0.198

The farm plots we sampled and report on in Table 1.2 were not part of a designed and controlled experiment and no baseline data were gathered, so we cannot rule out the possibility that CA plots tended to have higher initial soil C and N due to prior land use, thus biasing our results. However, empirical evidence from controlled experiments support an interpretation that CA practices promoted by COMACO, such as residue retention, rotation with legumes, and reduced tillage, played a role in increasing soil organic C and N. Boddey et al. (2010), in a long-term experiment on Brazilian subtropical Oxisols, documented that soil organic C sequestration rates in zero tillage plots exceeded those in conventional plots, and this beneficial effect of reduced tillage was enhanced in plots where legume cover- or inter-crops were used. Dalal et al. (2011) looked at 40 years of tillage, crop residue management, and N fertilizer on a Vertisol in a subtropical semi-arid region of Queensland, Australia. They found that residue retention resulted in larger increases in soil organic C in the top 20cm than zero-tillage when both were compared to conventional practices. They also reported that N additions increased soil organic C only when in combination with crop residues returned to the soil. In a 16-year study with various maize and wheat rotations in sub-tropical semi-arid highlands of Central Mexico, Fuentes et al. (2010) found that crop residue retention had more effect on reducing soil organic C losses at the 0-20cm depth compared to rotation or tillage treatment.

Although we found higher N levels in CA compared to traditional plots (Table 1.2), the levels for both management systems were well below an optimum for crop production (Seiter and Horwath, 2004). This is also reflected in the relatively high C:N ratios, ranging from 24.7 to 59.4. For comparison, Magdoff and van Es (2009) report ratios of 10 to 12 being typical of OM in “healthy” loam soils. Thus, despite the addition of legumes in rotation in CA plots, these soils are N-limited. The high C/N ratios will tend to slow microbial activity and decomposition, constrain the amount of N released by N mineralization, and ultimately constrain crop growth and yield (Seiter and Horwath, 2004).

Active C was included in our measurements as an indicator of labile C and as an early indicator of longer term changes in OM% in response to management (Weil et al., 2003, Mirsky et al., 2008, and Culman et al., In press). We saw a 31.6% increase in AC with CA (Table 1.2), though this was not statistically significant (p=0.143). Several factors may explain why we did not document a clear CA effect on AC even though we saw significant effects on C. One is that we sampled in October, which is at the end of the hot dry season (August - November), where mean maximum temperatures range from 30-44 C. High temperatures will tend to accelerate C mineralization (Weil and Magdoff, 2004). Low soil organic C concentrations have generally been found where the ratio of mean annual temperature (in C) to annual precipitation (in mm) × 0.01 approaches and exceeds 3.0 (Weil and Magdoff, 2004). Using the climate data for Chipata in the COMACO region, the soils have a ratio of 2.6, indicating that this agro-ecological zone would be prone to rapid C mineralization, leading to low labile C accumulation. Another possible explanation for no statistically significant CA effect on AC was high variability of the AC data, perhaps due to experimental error in the laboratory protocol. Finally, it is possible that variability in black C among the plots of our study area affected AC results. The permanganate oxidation method for determining AC has been shown to incidentally measure labile fractions of pyrogenic C (Skjemstead et al., 2006), which would be present in these soils due to natural fire occurences in this area, in addition to the long-standing land clearing practice of chitmene. However, the actual size of this labile fraction of black C is likely to be quite small in comparison to the total C pool (J. Lehmann, personal communication)

Soil C and N in Miombo Woodlands

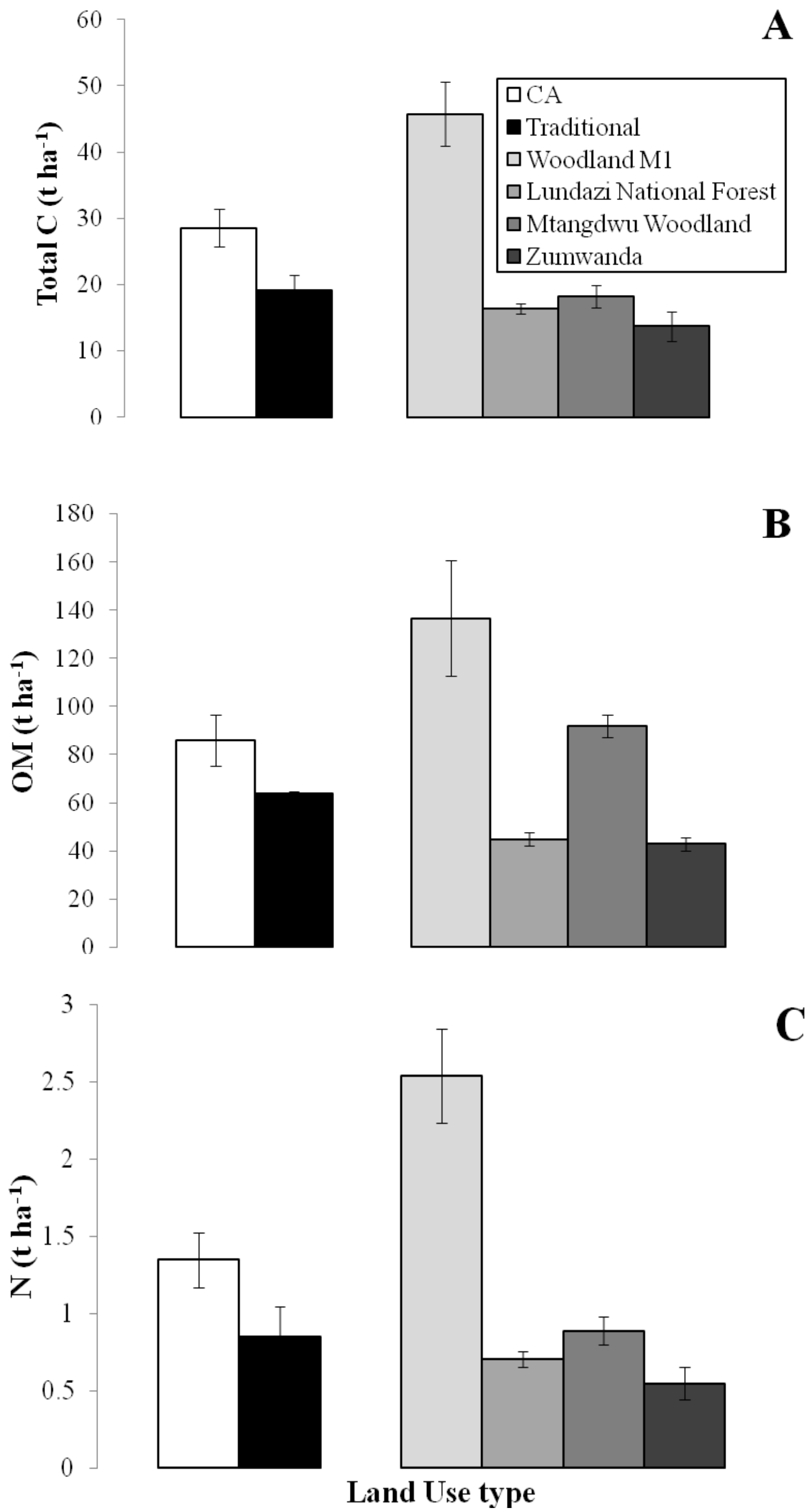
Soils at the M1 miombo woodland site, situated near Mfuwe in the southern part of the COMACO region, were unique from the other three woodlands, with higher C, OM and N (Table 1.3). Individual paired t-test comparisons indicated this difference was significant ($p<0.05$) for C, OM, and N on both a percent and mass per unit area basis. The Zambian Soil Map (Ministry of Agriculture Zambia, 1991) indicates that the M1 woodland is on a fine loamy to clayey soil, while the other three were on shallow, gravelly sandy soils (Table 1.1). Walker and Denanker (2004) found a positive correlation between soil clay percentage and soil C stocks in Malawian miombo woodlands, and this correlation is corroborated by others (Hassink, 1997; Six et al., 2002; Blanco-canqui and Lal, 2008).

Figure 1.2 contrasts soils (0-15 cm) from CA and traditional farms with the four miombo woodlands. The highest levels of C, OM and N were found at the M1 woodland, which not only exceeded other woodland sites, but also was significantly higher than both CA and traditional farm soils sampled ($p<0.05$ by paired t-test comparisons). However, the average across all CA soils was higher in total C and N than the other three miombo woodlands (Mtangdwu, and Lundazi and Zumwanda National Forest). As already indicated, these three woodlands were on sandy soils with inherently low soil C sequestration potential, while the data for farm plots is the average across several soil types and regions (Table 1.1). Also, the woodlands are subject to frequent fire (Boaler, 1966) that would reduce OM and C retention. It is also possible that the residue retention and compost additions in CA plots exceeded litter fall contributions to OM and C in the three miombo woodlands with low values.

Table 1.3. Means and standard deviations for soil parameters at four miombo woodland sites sampled. Bulk density (BD) was not measured at 15-30 cm and therefore soil property mass per unit area is not available (na) for that depth.

Depth (cm)	Site name		BD	C (%)	N (%)	OM (%)	AC (mg kg^{-1})	C (t ha^{-1})	N (t ha^{-1})	OM (t ha^{-1})	AC (t ha^{-1})	C/N	C/OM	AC/C
0 -15	Woodland M1	Mean	1.41	2.16	0.12	6.42	437.93	45.75	2.54	136.68	0.93	18.01	0.35	0.02
		Std Dev	0.05	0.33	0.02	1.77	68.79	8.48	0.53	41.67	0.17	1.06	0.05	0.00
	Lundazi National Forest	Mean	1.34	0.81	0.04	2.23	230.80	16.33	0.71	44.89	0.47	22.19	0.36	0.03
		Std Dev	0.04	0.07	0.01	0.23	12.24	1.29	0.09	5.04	0.01	1.86	0.01	0.00
	Mtangdwu	Mean	1.32	0.92	0.05	4.65	278.81	18.20	0.89	91.87	0.55	19.63	0.20	0.03
		Std Dev	0.06	0.12	0.01	0.23	40.82	3.01	0.16	7.94	0.07	0.32	0.02	0.01
	Zumwanda	Mean	1.40	0.65	0.03	2.04	177.97	13.69	0.55	42.86	0.37	24.33	0.32	0.03
		Std Dev	0.07	0.18	0.01	0.16	21.23	3.86	0.18	4.86	0.05	2.31	0.07	0.01
	Forest Average	Mean	1.37	1.13	0.06	3.83	281.38	23.49	1.17	79.07	0.58	21.04	0.31	0.03
		Std Dev	0.06	0.17	0.01	0.60	35.77	4.16	0.24	14.88	0.07	1.39	0.04	0.00
15 - 30	Woodland M1	Mean	na	1.53	0.07	5.05	357.82	na	na	na	na	20.90	0.32	0.02
		Std Dev	na	0.07	0.01	1.75	29.88	na	na	na	na	0.93	0.08	0.00
	Lundazi National Forest	Mean	na	0.48	0.02	1.63	110.04	na	na	na	na	31.50	0.30	0.02
		Std Dev	na	0.05	0.01	0.22	8.15	na	na	na	na	10.90	0.03	0.00
	Mtangdwu	Mean	na	1.08	0.05	3.99	200.76	na	na	na	na	21.59	0.27	0.02
		Std Dev	na	0.24	0.01	0.15	13.42	na	na	na	na	1.05	0.05	0.00
	Zumwanda	Mean	na	0.51	0.02	1.65	101.17	na	na	na	na	28.33	0.31	0.02
		Std Dev	na	0.12	0.01	0.18	19.49	na	na	na	na	8.50	0.05	0.00
	Forest Average	Mean	na	0.90	0.04	3.08	192.45	na	na	na	na	25.58	0.30	0.02
		Std Dev	na	0.12	0.01	0.57	17.74	na	na	na	na	5.35	0.05	0.00

Figure 1.2. Comparing soil C (A), soil OM (B), and soil N (C) at the two farming sites (CA, n=12; Trad, n=16) and the mean of each Miombo woodland site (n=3, per site).Vertical bars represent standard error of the mean.


A
Total C (t ha-1)
60
50
40
30
20
10
0
CA
Traditional
Woodland M1
Lundazi National Forest
Mtangdwu Woodland
Zumwanda
B
OM (t ha-1)
180
160
140
120
100
80
60
40
20
0
C
N (t ha-1)
3
2.5
2
1.5
1
0.5
0
Land Use type

Soil C and N Beneath *F. albida* Trees

Tree size of the nine *F. albida* trees we selected for soil sampling ranged from 40 to 140 cm dbh, with a mean of 94 cm. For purposes of our analysis, we divided these into two size categories, < 100 cm dbh (n= 5) and > 100 cm dbh (n=4). Average annual tree growth rates reported in the literature vary between 5.2 cm diameter per year (Barnes and Fagg, 2003) to 2 cm diameter per year (Poschen, 1986). Based on this we would estimate that the trees in our study were approximately between 8 and 50 years old, though information from local residents estimated that trees were 15 – 70 years old.

We found that C, OM, and N were consistently higher in soils beneath the canopy (midcanopy) of *F. albida* trees in both size categories compared to beyond the canopy (Table 1.4). The mid- to beyond-canopy difference was statistically significant at $p<0.05$ for C%, N%, as well as t N ha^{-1} at 0-15 cm for the older (>100 cm dbh) trees. The higher C% at 0-15 cm was significant at $p<0.10$ for the younger trees. In general, the C, OM, and N, on both a percent and mass per unit area basis, was two-fold higher at midcanopy beneath larger compared to smaller trees, and this was significant for the 0-15 cm depth at $p<0.05$. Okorio (1992) examined *F. albida* trees in Tanzania and also found significant increases in soil C and N sampling to a 60 cm depth with 6 year old trees and compared this to a study in Kenya with 4 year old trees showing no significant effect. Poschen (1986) estimated that 20 years of tree growth is needed to ensure soil fertility enhancement that can significantly improve crop yields based on experiments in Ethiopia. In Burkina Faso, Depommier et al. (1992) documented a 45% increase in OM and an 85% increase in C beneath *F. albida* trees. Additionally, they compared yields of sorghum grown under the canopy versus away from the canopy and found significantly higher sorghum stalk and grain yield beneath the trees.

Table 1.4. Percent increase or decrease in measured soil properties relative to sampling location under canopy (mid-canopy vs 10m beyond canopy) and relative to tree size (< or > 100 cm dbh). Bulk density (BD) was not measured at 15-30 and thus soil property mass per unit area is not available (na) at that depth. * indicates statistical significance according to a t-test contrast: * ($p<0.1$); ** ($p<0.05$); *** ($p<0.01$)

[a] Diameter at breast height, refers to the diameter of a tree trunk in cm being measured at the center-chest height (approx. 4ft) of the person making the measurement

[b] Mid-canopy refers to the area of soil sampled which is under the midway point between the trunk and the edge of the canopy; Beyond-canopy refers to the area of soil sampled which is not under any canopy effect of the tree and is used as a control effect.

Table 1.4. (see previous page for description)

Tree dbh [a]	Depth (cm)	C (%)	*p*	N (%)	*p*	OM (%)	*p*	AC (mg kg^{-1})	*p*	C (t ha^{-1})	*p*	N (t ha^{-1})	*p*	OM (t ha^{-1})	*p*	AC (t ha^{-1})	*p*
		% Change between canopy positions (mid-canopy relative to beyond-canopy)															
< 100	0-15	45.7		63.8	*	32.5		3.3		44.5		61.6		22.9		-16.0	
	15-30	33.4		48.3		20.0		67.6		na	na	na	na	na	na	na	na
> 100	0-15	36.2	**	60.5	***	17.0		9.6		28.3	*	50.6	***	9.9		3.1	
	15-30	46.9		71.4	*	21.9		29.7		na	na	na	na	na	na	na	na
Canopy Position [b]		**% Change between tree sizes (>100cm DBH relative to <100cm DBH)**															
Mid	0-15	142.9	***	207.8	***	106.7	***	94.9	***	110.7	***	173.2	***	183.5	**	153.9	**
	15-30	120.6	**	171.3	**	83.7	*	58.5		na	na	na	na	na	na	na	na
Beyond	0-15	159.9	***	214.3	**	134.0	***	83.8	**	137.3	***	193.2	***	217.0	**	106.7	**
	15-30	100.2		134.7		80.9		104.8		na	na	na	na	na	na	na	na

Table 1.4 (continued)

	Depth (cm)	C/N	*p*	C/OM	*p*	AC/C	*p*
Tree dbh [a]	**% Change between canopy positions (mid-canopy relative to beyond-canopy)**						
< 100	0-15	198.3		-85.5		-27.7	
	15-30	-6.2		-3.9		52.2	
> 100	0-15	-14.6		15.5		-20.0	
	15-30	-15.7		20.5	*	-14.2	
Canopy Position [b]	**% Change between tree sizes (>100cm DBH relative to <100cm DBH)**						
Mid	0-15	-76.2		-85.4		-28.8	***
	15-30	-19.9		47.1		-28.1	
Beyond	0-15	-16.9		-98.2		-35.6	*
	15-30	-10.7		17.3		27.5	

While our results suggest that the presence of *F. albida* trees increased soil C and N, especially with larger trees, we do not have base line data to confirm whether this was an "effect" of the trees, or whether larger trees became established on inherently more fertile sites. The fact that soil C and N were significantly higher at sampling locations 10 m beyond the edge of the canopies of larger trees (presumably beyond tree effects) compared to 10 m beyond the canopies of smaller trees, suggests that the apparent tree effect was at least in part due to inherent differences in soil fertility. However, it also possible that large tree effects extended further out from the canopy than 10 m, so that our assumption that 10 m beyond the canopy could serve as a control was not adequate.

CONCLUSIONS AND SUGGESTED FUTURE RESEARCH

Despite the relatively recent adoption of CA practices (past 2 to 3 years) on farms we evaluated, our measurements from a small subset of COMACO farms found significant increases in soil C in CA plots compared to traditionally farmed plots in the upper soil profile (0-15cm). Additionally, we found consistently higher soil C, OM, and N beneath *F. albida* trees compared to beyond the canopy, and this was statistically significant at $p<0.05$ at the 0-15 cm depth for large trees (>100 cm dbh). Larger trees also had significantly higher soil C and N beneath the canopy than smaller trees (<100 cm).

While these results suggest that CA practices are already having positive effects on soil C and N, and that the soils in the COMACO region could respond positively to the recent *F. albida* plantings (100 trees per ha), this was not a replicated, controlled experiment on a single homogenous soil and a particular microclimate, so we cannot reach this conclusion from the data presented here. Our results could be biased by inherent soil fertility and prior land use. It is possible, for example, that farmers tended to establish CA plots on more fertile parts of their fields, and that *F. albida* trees tended to establish on "fertile islands" across the landscape. This is a common challenge in observational and systems-based studies of this type where reliable baseline data are not available. Nevertheless, this study expands our knowledge base beyond experimental farms to include a broader sweep of soil, environmental, and management conditions. The trends we observed are supported on both theoretical grounds and by empirical data from more controlled experiments.

Areas of further study that could expand upon what was found here include: replicated experiments on farms in the COMACO region to investigate specific CA techniques in singularity and in concert on contributions to soil C accumulations; soil C fractionation and mean residence time analysis to estimate the longevity of C additions and real contribution to climate change mitigation; nutrient analysis of *F. albida* litter fall and root biomass; deeper soil sampling under trees and further beyond the tree canopy; and field trials investigating yield response of crops grown under *F. albida* trees of known and varying ages.

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Approaches to Soil Carbon Assessment

as Affected by Manure, Crop Rotation and Soil Type

ABSTRACT

Soil variability presents a challenge in developing soil carbon (C) assessments that are reliable and cost efficient. We evaluated soil spatial variability in C and related soil properties across a 650 ha dairy farm in southern New York with corn and alfalfa rotations as well as pasture, in relation to optimizing soil sampling strategy. We evaluated correlations between measured soil properties and explored options for predicting soil C through proxy measures such as OM, or by using OM values from the USDA National Resource Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) database. We collected 118 soil cores to 60cm in 20 cm intervals across 10 combinations of crop rotation, manure, and soil type, and measured bulk density (BD), soil C, nitrogen (N), organic matter (OM), permanganate oxidizable active C (AC) and texture. Total soil C in the top 60 cm ranged from 111.8 to 205.2 t C ha^{-1} across the 10 cropping system combinations, with manured, continuous alfalfa on Howard (Hd) soil having the highest value, 68% more t C ha^{-1} compared to non-manured alfalfa on the same soil type ($p<0.001$). The coefficient of variation (CV) for most soil properties more than doubled at 40-60 cm compared to 0-20 cm (significantly different at $p<0.001$), except for BD, which had a similar CV at all depths. Bulk density and OM had the lowest CV compared to other soil properties at all depths, which reduced calculated minimum sample requirements for any desired level of confidence or magnitude of detectable difference between treatment means. We developed significant ($p<0.01$) linear prediction models of C from OM at all depths, and also found that C stocks for the entire 0-60cm soil profile could be predicted from measurements at just the 0-20,

20-40, or 40-60cm depths ($p<0.001$, $r^2 = 0.63$, 0.89, and 0.73, respectively). We found that SSURGO consistently underestimated OM at depths below 20cm, but field data were used to develop a linear regression model that improved SSURGO estimates for lower depths. This project identified several approaches to reduce sampling requirements especially at deeper soil depths. This can help to better inform strategic sampling and reduce costs for future soil C assessments.

INTRODUCTION

The world's soils represent the largest terrestrial stock of carbon (C) containing roughly 1500 Pg C (Pg = 1×10^{15} g), which is nearly twice as much C as in the earth's vegetation and atmosphere combined (Moreira et al., 2009; Bartholomeus et al., 2008; Stevens et al., 2006). As a result, small changes in C flux to or from the soil via biological processes such as photosynthesis and decomposition can have large effects on atmospheric concentrations of the key greenhouse gas (GHG), carbon dioxide (CO_2). Optimizing land-based practices to reduce atmospheric CO_2 and sequester C in soils and biomass is one strategy for reducing atmospheric GHG concentrations and mitigating climate change (Paustian et al., 2009).

Historically, soil organic C (SOC) stocks decline up to 50% when native or perennial ecosystems, such as forests and grasslands, are converted to agriculture (Lal, 2005). The stored soil C is released as CO_2 into the atmosphere, and the decline in SOC reduces soil productivity over time. Farm management approaches to slow or reverse SOC decline include reducing tillage, modifying crop rotations, using winter cover crops, improving nitrogen (N) management, and using composts, biochar or other high-C organic matter amendments (Smith et al., 2007a ; Niggli et al., 2009). These approaches often have the co-benefit of improving soil health and crop productivity, in addition to the environmental benefit of contributing to climate change mitigation.

While farmers have productivity incentives to increase SOC, the additional incentive of entering C markets and receiving "offset payments" for sequestering C in soils has been discussed for many years. However, the inclusion of the agriculture sector in C markets has been severely hampered by the challenges of monitoring, recordkeeping and verification (MRV) of SOC changes (Smith et al., 2007b). The main difficulty is not with measuring SOC concentration *per se*, as standard and analytically precise methods are well established (review: Chatterjee et al., 2009). The problem is designing an efficient, low-cost, and reliable SOC stock estimation system given the large sampling requirements to accurately capture high inherent soil variability, the associated costs for field labor and laboratory analysis, and the time required (often, years) to document SOC response to management (Grinand et al., 2008; Don et al., 2007; Frogbrook et al., 2009).

Soil C stock determination on an area basis (t C ha^{-1}) as required for C markets is a function of soil C concentration and bulk density (BD), so both must be measured or estimated. Variability of C calculated on a t C ha^{-1} basis thus involves variability associated with both BD and C concentration measurements. Bulk density requires that undisturbed soil cores be collected, which is labor intensive and difficult to do accurately, particularly at depths beyond the plow layer (i.e., below 20-30 cm). Recent research has suggested that accurate assessment of tillage effects on SOC, particularly effects of full-inversion tillage (moldboard plowing), will require sampling to depths of 50 cm or more (Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2007; Baker et al., 2007).

Both bulk density and C concentration measurements are prone to changes over time but are affected by different processes. C concentration is closely linked to biotic processes like biomass production and decomposition. Bulk density is largely a function of parent material and physical processes associated with soil genesis, but is also affected directly by tillage and indirectly by biotic processes influencing aggregation (Don et al., 2007).

One simple and inexpensive approach to circumvent the problems with field measurements of SOC change has been to use practice-based estimates of SOC change in response to management derived from a synthesis of previously published work (e.g., Ogle et al., 2005). Then the challenge is primarily to monitor land use and management patterns, or determine these from land use data bases such as the Conservation Technology Information Center (CTIC, 1998). This has proven unsatisfactory for C market schemes, however, because of obvious inaccuracies of extrapolating from a few detailed and geographically limited research studies, and the need therefore to substantially discount permitted SOC offset payments (Conant et al., 2011). Another approach is to use existing soil databases, such as the USDA National Resource Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) data, to determine percent organic matter (OM) for specific sites, and from this estimate baseline SOC stocks. However, survey data do not account for recent farm management effects on C concentration, and assumptions must be made regarding BD and the soil C concentration of OM to calculate SOC on an area basis as required for C markets. Only a few studies have investigated the use of SSURGO for SOC inventory analysis (Gelder et al., 2011; Zhong and Xu, 2011; Causarano et al., 2008; Rasmussen, 2006; and Davidson and Lefebvre, 1993). Only two of those compared SSURGO estimates with field measurements (Gelder et al., 2011 and Zhong and Xu, 2011), however in both of those studies the lab analyses were conducted at least 10 years prior to the published research. Conant and Paustian (2002) investigated data from the original USDA/NRCS pedon database, though only compared these data to soil samples from the top 20cm. The shortcomings of these previous studies identify a gap in the exploration of using SSURGO to augment or assist soil C inventory analysis.

Because of the poor reliability of alternatives as discussed above, direct field measurements appear to be essential at the present time for MRV of SOC stocks and stock changes over time. We therefore need to develop sampling schemes that minimize the number of samples required for a given level of confidence. Intensive grid sampling will be cost-prohibitive in most cases, so soil survey and other geospatial data bases and knowledge of cropping systems can be used to strategically select sampling locations to stratify across landscapes by dominant soil types, land use, and management. Proxies for direct soil C concentration measurement (e.g., per cent OM derived from soil survey databases or measured) can be evaluated for their correlation with and use as predictors of actual soil C concentration. Simple linear regression or more sophisticated geospatial statistical procedures and models can be used to predict soil C in locations and depths not directly measured (e.g., Bilgili et al., 2010; Don et al., 2007). Sample number can be optimized for a desired confidence level in relation to geospatial soil variability. Conant et al. (2011) suggest a multi-pronged approach to determination of SOC stocks from existing soil databases, strategic soil measurements, and use of biogeochemical models (e.g., DayCent, Parton et al., 2001) to estimate SOC change.

In the present study we evaluate the variability in SOC concentration and bulk density across the landscape and with depth (to 60 cm) for a 650 ha research dairy farm in New York State. We use a sampling scheme that stratifies across three soil types, pasture and various corn-

alfalfa cropping systems, and use of manure on some fields. In addition to SOC concentration and BD, all samples were also measured for soil texture, OM percent, and the labile or active C fraction of OM (permanganate oxidation method, Weil et al., 2003). Spatial variability of each factor measured (horizontally and with depth) was evaluated in relation to optimizing sample number for selected confidence levels and desired magnitude of difference to detect.
Specifically, our objectives were to:

1. Evaluate cropping system and soil type effects on total soil C and related soil attributes down to a 60 cm depth in 20-cm increments

2. Compare different measures of SOC, and measures of other soil properties including BD and texture, for their variability across a farm and with depth in relation to optimum sample number requirements

3. Develop and evaluate simple regression models for predicting SOC from other proxy soil measurements, and the potential for predicting total soil C for an entire 0-60cm profile from measurements at upper regions of the soil profile.

4. Evaluate the reliability of SSURGO data to estimate SOC, and the opportunities to calibrate SSURGO estimates of SOC with linear regression models derived from strategic soil sampling.

MATERIALS & METHODS

Site Description

Soil samples for this study were collected during the summer of 2010 at the Cornell University Teaching and Research Center (T&R Center), located in Harford, NY (42.427° N, 76.228° W, elevation of 362 m), in Cortland County. The majority of this approximate 650 ha working dairy farm lies in the Susquehanna River basin, draining to the Chesapeake Bay (the remaining portion is in the St. Lawrence River basin, draining north to Lake Ontario). Mean annual precipitation is 956 mm and the native vegetation is mixed temperate deciduous and coniferous forest. Cropping systems range from permanent pasture to maize silage production in rotation with alfalfa (with and without manure application). The farm is situated on a glacial till landscape. The dominant soil type on the farm is Howard silt loam (Hd, loamy-skeletal, mixed, active, mesic Glossic Hapludalfs). Other major soils include Langford (La, Fine-loamy, mixed, active, mesic Typic Fragiudepts), and Valois (Va, Coarse-loamy, mixed, superactive, mesic Typic Dystrudepts).

Field Selection Across Soil Types and Cropping System

Twenty-three fields (19 cropped and 4 pastures) amounting to 164.6 ha, were selected for soil sampling among a total of 121 fields (649.2 total ha) that are cropped or pastured at the T&R Center. Our field selection represented 25.4% of the cropped and pastured land area at the farm. Our selected sampling sites represent a broad diversity of the dominant biophysical and management combinations on the farm and stratified based on soil type, manure application, and crop rotation of the past four years (continuous corn, continuous alfalfa, corn-alfalfa rotation, and pasture (Table 2.1). The corn-alfalfa rotations were an aggregation of rotations ranging from 2

Table 2.1. List of field management variables that were sampled, including crop rotation, manure addition, major soil type, number of fields, hectares and sample number in each cropping system

Crop System	4 year rotation (2006-2009)[a]	Soil Type[b]	Manure[c]	Fields	Combined hectares[d]	Sample n[e]
1	C-C	Hd	Y	14, 15,18	13.33	15
2	C-C	Hd	N	13, 49	2.1	8
3	A-A	Hd	Y	3	13.49	5
4	A-A	Hd	N	10A, 10B, 10C	32.88	28
5	A-A	La	N	53	6.24	5
6	A-A	Va	N	48	4.22	5
7	C-A	Hd	N	16	21.91	6
8	C-A	La	N	31, 32	20.10	10
9	C-A	Va	N	34, 38, 4, 45, 47	34.55	24
10	P	Va	N	SHI, SHJ, SHP1, SHP8	16.16	12

[a] Crop rotation in the 4 years proceeding soil sampling for this study: continuous corn (C-C), continuous alfalfa (A-A), corn-alfalfa (C-A), and pasture (P)

[b] Soil types listed represent the major soil types found on the corresponding fields and are aggregations of slope phases within a single soil map unit and of minor soil types

[c] Manure additions are coded Y (yes) or N (no) corresponding to whether or not manure was spread directly on fields. Does not include Pastured fields

[d] The sum of the hectares of the fields corresponding to each Crop System

[e] The sum of the samples taken from each field in the correspoding Crop System

years corn-2 years alfalfa, 1 year corn-3 years alfalfa, and 3 years corn-1 year alfalfa. Soil types were: Howard (Hd), Langford (La), and Valois (Va).

Map Layer Data Sources

Soil type and other soil attributes were gathered from the USDA/NRCS SSURGO database (1:24,000 scale). These spatial and tabular data are available from NRCS Soil Data Data Mart (Soil Survey Staff, 2010; http://soildatamart.nrcs.usda.gov). The Cortland County soil survey was conducted from 2005 – 2010, while the Tompkins County soil survey soil survey was conducted from 2006 – 2010. Both surveys were published in 2010.

. Elevation data were obtained from the US Geological Survey (USGS), EROS Center's National Elevation Data (NED) 7.5 minute tiles at 1/3 arc-second resolution (10m) (http://datagateway.nrcs.usda.gov/GDGOrder.aspx)

ArcGIS 9.2 software was used to incorporate landscape topography and other features and create maps and map layers (Figure 2.1).

Soil Sampling

General protocol

On fields where the soils were relatively free of obstructing coarse fragments, 0 – 60 cm intact soil cores were extracted using the slide-hammer driven JMC Environmentalist Sub Soil Probe Plus (Clements, Inc., Newtown, IA) with a 3.048 cm inner diameter cutting tip and soil tube. The soil core was collected into an internal plastic sleeve, which was removed and capped on both ends after sampling, and kept cool until returning to the lab where they were stored in a cooler at 2 C until sieving and analyses (generally within a few days). The length of the extracted cores

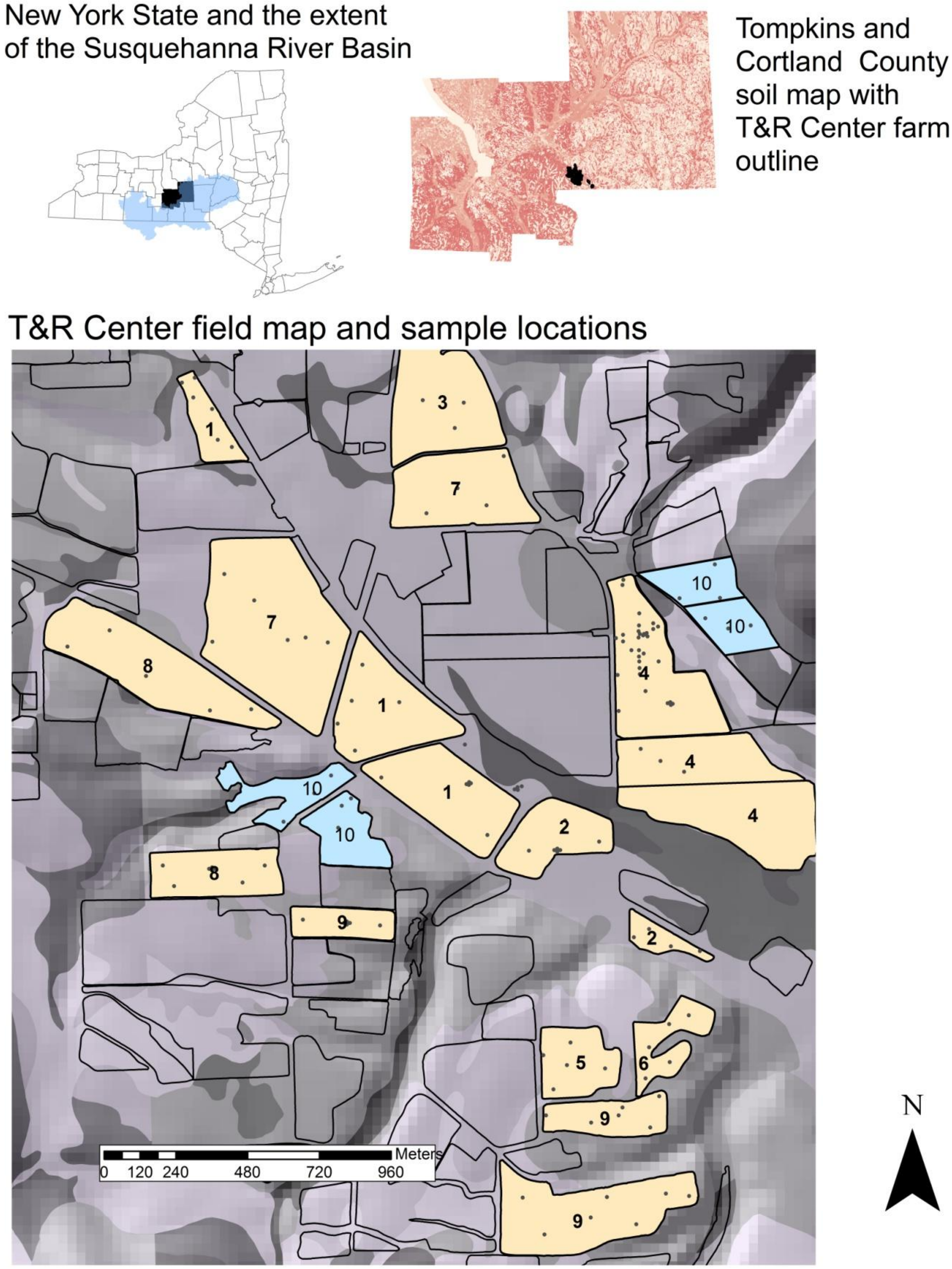


Figure 2.1. Plot map of the Harford T&R Center overlaid on the soil map. Sample locations are displayed and fields are labeled according to the cropping system classification. For a description of the cropping systems, refer to Table 1.1.

and the length of the burrow created during sampling were recorded, and the ratio of extracted core length:burrow depth was used as a compaction correction factor. When later dividing the core into the three depth segments in the lab, the calculated coefficient of compaction was multiplied to each segment. We did this under the assumption that compaction affected all three segments equally.

On fields where the JMC soil probe could be used, one randomly selected soil sample location was chosen to be the center of a small spatial-scale cluster of soil samples. Four samples were collected at 5m to the north and south and at 10m to the east and west surrounding that central sample location. The satellite samples were individually analyzed and their values were averaged as a composite for the central location.

When soil sampling was found to create substantial core compaction or sampling was made too difficult due to a large proportion of rock fragments, sampling was accomplished by digging soil pits to a depth of 70 – 100 cm (with $1.5m^2$ footprint). The 20, 40, and 60 cm depths were marked and soil samples for lab analyses were collected from the side wall of the pit using a trowel. Samples for BD determination were obtained by tapping 7.5 cm diameter BD rings (247.5 cm^3) horizontally into the pit walls.

In general, a minimum of 3 – 5 sample cores were collected in a zig-zag pattern from fields listed in Table 1, similar to the protocol for obtaining soil samples for the Cornell Soil Health Test (Gugino et al., 2009, pp 18, 19). The number of samples was determined based on a visual assessment of the variability in topography and other features. Small, atypical areas of the field, such as low-lying areas with poor drainage, were avoided. Over the 164.6 ha occupied by the 23 fields sampled, we collected 118 cores, which averaged to 5.13 cores per field, or 0.72 cores per hectare.

At each sample location within a field, soil samples for BD determination, chemical analyses, and texture were obtained from the depth intervals of 0 – 20 cm, 20 – 40 cm, and 40 – 60 cm. The geographic coordinates of each sample location were recorded into a global position system (GPS) device in the Universal Transverse Mercator projection using the North American Datum of 1983 (UTM NAD83).

Laboratory Analysis

Field moist soil was brought back to the lab, passed through a 2 mm sieve and dried in a drying oven at 105 C for bulk density measurements, or air-dried to constant dry weight for other analyses.

Bulk density (BD)

BD was measured according to the National Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2010). The stones were dried at 105 C overnight, weighed, and their volume was estimated by measuring their displacement of water in a 100 ml graduated cylinder. The following formula was used to determine BD:

[1] $$BD = (ODW – RF) / (CV – RV)$$

Where: ODW = sample oven dried mass (g); RF = rock fragment dry mass (g); CV = core volume (cm^{-3}); and RV = rock volume (mL)

Total carbon and nitrogen

Air-dried, sieved soils were subsampled for percent total C and percent total N determination using the Dumas combustion method with a LEICO2000 Auto infra-red gas analyzer (Elementar Americas, Inc., Mt. Laurel, NJ, USA) (results are reported as percent of soil mass). Based on soil maps, soil series descriptions, and exploration of soil inorganic C occurrence using Soil Data Viewer (see below for Soil Data Viewer description) from SSURGO data, C % measurements were assumed to not contain inorganic forms of C and thus soil C values reflect total SOC.

Soil organic matter

Soil OM was determined by weighing air-dried, sieved soil samples before and after combustion at 500 C ("loss-on-ignition" (LOI) method, Storer, 1984) performed by the Cornell Nutrient Analysis Laboratory. (Results are reported as percent of soil mass).

Permanganate oxidizable "active" carbon

Active carbon (AC) was measured by potassium permanganate ($KMnO_4$) oxidation of 2 mm sieved, 40 C-dried soil with 0.02 *M* $KMnO_4$ as described in Weil et al. (2003). A standard linear calibration curve was developed at each lab run from three concentrations of standard $KMnO_4$ solution, 0.005 M, 0.01 *M*, and 0.02 *M*. Active C (mg kg^{-1}) was then determined by the following equation:

[2] $AC\ (\mathrm{mg\ kg^{-1}}) = [\mathit{0.02\ mol{\cdot}L^{-1}} - (a + b * \mathit{absorbance})] \times (\mathit{9000mg\ C{\cdot}mol^{-1}}) \times (\mathit{0.021\ solution{\cdot}0.0025\ kg^{-1}\ soil})$

Where 0.02mol L^{-1} is the initial $KMnO_4$ concentration, *a* is the intercept and *b* is the slope of the standard curve, 9000 is mg C (0.75 mol) oxidized by 1 mol of MnO_4 changing from Mn^{7+} to Mn^{2+}, 0.021 L is the volume of $KMnO_4$ solution reacted, 0.0025 is the kg of soil used (Weil et al., 2003).

Texture analysis

Texture determination followed the Rapid Soil Particle Determination method described by Kettler et al. (2001). 14g of air-dried soil, sieved soil was dispersed in 42 mL of soap solution followed by 2 hours of shaking at 120 rpm. Samples were then washed through a 0.53 mm sieve to separate the sand fraction, which was collected into metal cans, oven dried (105 C), and weighed. The remaining silt and clay suspension was allowed to settle for 6 hours. At 6 hours, the supernatant (clay fraction) is discarded and the silt fraction is washed into metal cans, oven dried (105 C) and weighed. The weight proportions of sand and silt are calculated by

[3] *Sand% = (oven dried sand mass / original sample mass) ×100*

Silt% = (oven dried silt mass / original sample mass) ×100

The clay percent is calculated by difference.

[4] *Clay% = 100% - (Sand% + Silt%)*

Data Analysis

Conversion to units of mass/area

BD data was used to convert C, N, OM, and AC data from units of concentration or percent into mass per area as tons per hectare ($t\ ha^{-1}$) using the following formulae:

[5] TC, TN, or OM ($t \cdot ha^{-1}$) = [$TC, TN, or\ OM\ (g \cdot 100\ g^{-1}\ soil) \times 1x10^{4}\ (10\ 0g \cdot t^{-1}) \times (BD\ (g \cdot cm^{-3}) \times 20\ cm) \times (1\times10^{6}\ cm^{2} \cdot ha^{-1}) \times (t \cdot 1\times10^{-6} g)$]

AC ($t \cdot ha^{-1}$) = [$AC\ (mg \cdot kg^{-1}) \times (1\times10^{4}\ kg \cdot t^{-1}) \times (BD\ (g \cdot cm^{-3}) \times 20\ cm) \times (1\times10^{6}\ cm^{2} \cdot ha^{-1}) \times (t \cdot 1\times10^{-6} g)$]

Preparing SSURGO data for contrast with field measurements

One of our research questions was to compare SSURGO tabulated soil property data to field measurements and lab-determined values. This study is especially interested in C, however SSURGO only provides OM % data for each soil map unit (SMU). Using the Soil Data Viewer application for ArcMap, we were able to geospatially view the tabulated data contained in the soil survey. For each of sample locations at each sample depth we compared

1) SSURGO OM % to OM % measured from our field samples
2) Corrected SSURGO OM % to C % using the standard conversion factor of 0.58 (Pulske et. al., 2011) and compared with C % values from field samples

This was done in ArcMap by

1) Entering sample location GPS coordinates (waypoints) as a point data layer

2) Using Soil Data Viewer view the OM % property for all SMUs

   a. In the Soil Data View dialogue box, the weighted average preference was chosen to represent the OM % values for each SMU. The weighted average computes the average OM % values weighted by the % area that each component of the SMU occupies.

   b. The procedure was repeated three times, one for each 20 cm depth interval.

3) Extracting OM % values by the sample waypoints for each depth interval

4) Exporting the resulting three data tables to Excel

5) Multiplying SSURGO values by 0.58 to obtain SSURGO C %

6) Multiply SSURGO C % by stock conversion procedure using lab determined BD values

Statistical analyses

Statistical analyses were performed with JMP 9 (SAS Institute, Cary, NC, 2010). Our sampling sites were selected to represent dominant biophysical and management variables on the farm but this was not designed as a factorial experiment with equal replication. Means, standard deviation, standard error, coefficient of variation (CV) were calculated for measured variables, and ANOVA for means separation using student's t-test for two sample means comparison and Tukey's HSD for comparing multiple means was used. Scatter plot, correlation, and simple linear regression procedures were used for evaluating predictive models of soil C.

Optimal sample size determination

The minimum sample number (n) was estimated for soil properties using: the sample variance (s^2), sample mean (μ_x), t-test probability values (t_α) at any level of confidence (α) for infinite degrees of freedom, and at user specified level of precision (±d%, detectable percent difference between means) in the following expression from Wilson et al. (2010) and McKenzie et al. (2002, p 66):

[6] $n = (t_\alpha^2 \times s^2) / (\mu_x \times d)^2$

In our study we examined n across three levels of α (0.1, 0.05, and 0.01) and two levels of ±d (5% and 10%).

RESULTS

Croping System and Soil Type Effects

Soil texture

The three major soil series within the study were similar in that all were silt-loams, with 58% or more silt and 69% or more silt+clay at all depths down to 60 cm (Table 2.2). The Hd soil had the lowest clay content (from 10.5% to 12% across all depths), La had the highest clay increase with depth, 40% from 0-60 cm, and Va had the most at the surface layer, 17.6%. The percent clay increased at lower depths for all soil types while percent silt declined by an average of 5% to 60 cm.

Soil OM and C

Averaging across all 10 cropping system/soil type treatments, the OM % in the upper (0-20 cm) profile ranged from 4.3% to 6.0%, and this declined to 1.6% to 2.9% OM at the lowest depth (40-60 cm; Table 2.3). Total C and AC also declined by 50% or more with depth for all 10

Table 2.2 Texture characterization of major soil types sampled by depth

Depth (cm)	Soil Type[a]	n[b]		Sand (%)	Silt (%)	Clay (%)	Silt + Clay (%)
0-20	Hd	66	Mean	26.1	62.9	10.9	73.8
			Std Err	1.4	1.3	0.7	1.4
			CV	44.4	17.1	55.5	15.8
	La	15	Mean	20.3	65.8	13.8	79.6
			Std Err	2.1	1.5	1.1	2.1
			CV	40.0	9.0	30.4	10.3
	Va	25	Mean	18.0	64.4	17.6	82.0
			Std Err	1.5	1.1	1.2	1.5
			CV	49.1	10.4	41.6	11.0
20-40	Hd	66	Mean	30.6	58.8	10.5	69.4
			Std Err	2.2	1.8	0.6	2.2
			CV	56.9	25.2	43.6	25.1
	La	15	Mean	19.0	63.3	17.7	81.0
			Std Err	2.1	2.0	1.9	2.0
			CV	42.1	12.2	40.9	9.8
	Va	25	Mean	20.7	62.3	17.0	79.3
			Std Err	1.9	1.2	1.6	1.9
			CV	57.2	11.8	57.9	14.9
40-60	Hd	66	Mean	30.0	58.1	11.9	70.0
			Std Err	2.1	1.7	0.7	2.1
			CV	54.3	23.3	46.6	23.4
	La	15	Mean	17.4	63.4	19.3	82.7
			Std Err	2.6	2.1	2.5	2.6
			CV	57.4	13.0	50.4	12.2
	Va	25	Mean	18.8	62.1	19.3	81.4
			Std Err	1.5	2.0	1.8	1.5
			CV	47.8	20.0	56.0	10.9

[a] Major soil types sampled: Howard (Hd), Langford (La), and Valois (Va) slope phases are aggregated

[b] summed number of sample locations within each soil type

Table 2.3. Means and variability of soil bulk density (BD), carbon (C), nitrogen (N), organic matter (OM) and Active C (AC), as well as C/N, C/OM, and AC/C by each crop system by depth. For a description of the cropping systems, refer to Table 2.1.

[a] Cropping system refers to the crop rotation, soil type, and manure addition combinations described in Table 2.1.

[b] The sum of the samples taken from each field in the corresponding Crop System

Table 2.3. (for description see previous page)

Depth (cm)	Cropping System [a]	n [b]		C (t ha^{-1})	N (t ha^{-1})	OM (t ha^{-1})	AC (t ha^{-1})
0 - 20	1	16	Mean	77.45	6.14	111.76	1.49
			Std Err	9.08	0.68	13.91	0.16
			CV	46.90	44.29	49.77	43.33
	2	8	Mean	77.34	6.60	119.26	1.67
			Std Err	4.18	0.42	6.21	0.12
			CV	15.28	17.87	14.74	21.06
	3	5	Mean	88.14	7.37	124.04	1.77
			Std Err	14.18	1.12	21.57	0.30
			CV	35.97	33.96	38.89	37.96
	4	27	Mean	61.64	5.23	94.47	1.38
			Std Err	3.17	0.29	5.51	0.08
			CV	26.26	27.82	30.29	27.66
	5	5	Mean	65.61	4.82	106.40	1.14
			Std Err	7.08	0.41	8.62	0.06
			CV	24.11	19.12	18.12	10.84
	6	5	Mean	60.58	4.50	91.52	1.33
			Std Err	1.93	0.29	7.61	0.12
			CV	7.13	14.43	18.58	20.81
	7	10	Mean	66.57	5.42	103.75	1.63
			Std Err	5.20	0.53	6.83	0.07
			CV	19.12	23.76	16.13	10.38
	8	10	Mean	72.19	5.74	107.55	1.20
			Std Err	6.30	0.62	11.08	0.07
			CV	27.62	34.03	30.91	17.13
	9	19	Mean	71.49	4.93	107.83	1.45
			Std Err	4.87	0.52	6.42	0.11
			CV	32.69	49.13	28.56	38.05
	10	12	Mean	77.95	5.80	107.82	1.20
			Std Err	7.17	0.99	7.32	0.13
			CV	30.53	56.29	23.52	38.54

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		BD ($g\ cm^{-3}$)	C (%)	N (%)	OM (%)	AC ($mg\ kg^{-1}$)
0 - 20	1	16	Mean	0.99	3.86	0.30	5.74	745.41
			Std Err	0.08	0.26	0.02	0.26	64.96
			CV	34.28	26.50	30.97	18.24	34.86
	2	8	Mean	1.18	3.33	0.29	5.07	700.38
			Std Err	0.06	0.23	0.02	0.18	26.12
			CV	14.47	19.27	23.12	9.82	10.55
	3	5	Mean	1.03	4.30	0.36	6.00	861.29
			Std Err	0.16	0.21	0.02	0.31	34.52
			CV	35.86	10.69	13.18	11.49	8.96
	4	27	Mean	1.12	2.72	0.23	4.21	613.87
			Std Err	0.03	0.10	0.01	0.16	25.88
			CV	15.77	19.68	21.67	20.31	21.08
	5	5	Mean	1.19	2.76	0.20	4.46	484.28
			Std Err	0.05	0.28	0.02	0.22	33.93
			CV	8.73	22.49	17.88	10.82	15.67
	6	5	Mean	1.06	2.86	0.21	4.30	623.90
			Std Err	0.05	0.10	0.01	0.29	51.85
			CV	11.54	7.56	12.66	15.07	18.58
	7	10	Mean	1.13	2.92	0.24	4.55	720.60
			Std Err	0.04	0.14	0.02	0.18	27.07
			CV	8.12	12.13	18.64	9.90	9.20
	8	10	Mean	1.09	3.38	0.27	4.96	607.95
			Std Err	0.10	0.23	0.03	0.34	46.14
			CV	28.37	21.22	32.45	20.53	22.77
	9	19	Mean	1.16	3.04	0.21	4.64	616.80
			Std Err	0.06	0.18	0.02	0.18	24.92
			CV	25.60	29.59	38.08	19.51	19.79
	10	12	Mean	0.98	3.94	0.28	5.53	623.43
			Std Err	0.04	0.32	0.04	0.36	68.81
			CV	14.15	26.90	45.96	22.50	38.24

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		C/N	C/OM	AC/C
0 - 20	1	16	Mean	16.18	0.67	0.02
			Std Err	4.12	0.02	0.00
			CV	101.75	12.41	38.43
	2	8	Mean	11.78	0.65	0.02
			Std Err	0.27	0.03	0.00
			CV	6.56	13.64	22.68
	3	5	Mean	11.97	0.72	0.02
			Std Err	0.16	0.02	0.00
			CV	3.04	6.24	16.68
	4	27	Mean	12.53	0.66	0.02
			Std Err	1.11	0.02	0.00
			CV	45.96	17.49	24.91
	5	5	Mean	13.46	0.62	0.02
			Std Err	0.41	0.05	0.00
			CV	6.75	17.98	34.11
	6	5	Mean	13.60	0.67	0.02
			Std Err	0.51	0.04	0.00
			CV	8.38	12.86	22.49
	7	10	Mean	12.49	0.64	0.03
			Std Err	0.50	0.02	0.00
			CV	9.76	7.92	20.29
	8	10	Mean	12.91	0.68	0.02
			Std Err	0.71	0.03	0.00
			CV	17.41	11.48	30.93
	9	19	Mean	17.31	0.65	0.02
			Std Err	2.42	0.03	0.00
			CV	67.06	21.33	33.72
	10	12	Mean	17.17	0.72	0.02
			Std Err	2.92	0.02	0.00
			CV	56.33	7.91	52.20

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		BD ($g\ cm^{-3}$)	C (%)	N (%)	OM (%)	AC ($mg\ kg^{-1}$)
20 - 40	1	16	Mean	1.10	2.49	0.22	4.30	639.70
			Std Err	0.03	0.24	0.02	0.36	73.41
			CV	11.74	38.79	41.25	33.80	42.94
	2	8	Mean	1.13	2.40	0.19	3.79	433.90
			Std Err	0.08	0.42	0.03	0.38	66.21
			CV	21.19	45.98	49.20	28.62	43.16
	3	5	Mean	0.99	4.28	0.36	6.16	861.43
			Std Err	0.04	0.30	0.03	0.47	52.63
			CV	9.74	15.50	17.49	16.89	13.66
	4	27	Mean	1.17	2.11	0.19	3.71	453.72
			Std Err	0.03	0.15	0.01	0.17	32.27
			CV	12.42	36.50	32.44	24.59	37.63
	5	5	Mean	1.39	1.30	0.10	2.70	257.46
			Std Err	0.17	0.47	0.03	0.45	109.24
			CV	27.72	80.60	66.94	36.94	94.87
	6	5	Mean	1.11	1.52	0.11	2.94	303.13
			Std Err	0.05	0.31	0.02	0.15	52.09
			CV	9.08	45.00	34.81	11.68	38.42
	7	10	Mean	1.29	2.73	0.22	4.15	585.87
			Std Err	0.05	0.33	0.03	0.53	70.71
			CV	8.67	30.02	36.70	31.19	29.56
	8	10	Mean	1.23	1.65	0.12	3.09	384.89
			Std Err	0.04	0.20	0.01	0.26	49.70
			CV	10.70	38.48	36.57	26.75	40.83
	9	19	Mean	1.25	2.01	0.16	3.30	448.31
			Std Err	0.06	0.21	0.02	0.27	44.85
			CV	22.34	51.89	70.28	39.71	49.01
	10	12	Mean	1.27	1.67	0.14	2.73	268.16
			Std Err	0.06	0.23	0.02	0.26	43.37
			CV	17.43	45.32	44.88	32.64	53.64

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		C (t ha^{-1})	N (t ha^{-1})	OM (t ha^{-1})	AC (t ha^{-1})
20 - 40	1	16	Mean	54.02	4.85	93.23	1.38
			Std Err	5.25	0.54	8.16	0.16
			CV	38.87	44.35	35.02	42.62
	2	8	Mean	46.30	4.11	84.60	0.91
			Std Err	10.80	0.73	9.49	0.08
			CV	65.96	50.45	31.72	26.21
	3	5	Mean	84.55	7.08	120.68	1.69
			Std Err	7.17	0.67	8.67	0.07
			CV	18.95	21.19	16.07	9.93
	4	27	Mean	48.56	4.58	86.19	1.06
			Std Err	3.14	0.29	3.90	0.08
			CV	34.21	32.63	23.97	39.04
	5	5	Mean	39.07	2.92	78.90	0.57
			Std Err	16.36	1.07	19.44	0.19
			CV	93.61	81.62	55.09	72.76
	6	5	Mean	33.72	2.53	64.87	0.66
			Std Err	6.72	0.40	2.53	0.11
			CV	44.59	35.22	8.72	35.70
	7	10	Mean	71.45	5.86	109.14	1.49
			Std Err	10.13	1.01	16.73	0.15
			CV	34.72	42.05	37.55	25.09
	8	10	Mean	40.72	2.95	74.93	0.95
			Std Err	5.16	0.35	5.74	0.13
			CV	40.05	37.62	24.21	43.25
	9	19	Mean	48.47	3.89	80.66	1.06
			Std Err	5.01	0.54	6.49	0.10
			CV	50.61	68.47	39.39	46.58
	10	12	Mean	42.31	3.56	69.01	0.63
			Std Err	5.73	0.53	6.98	0.09
			CV	44.95	49.75	35.02	46.45

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		C/N	C/OM	AC/C
20 - 40	1	16	Mean	12.03	0.58	0.02
			Std Err	0.97	0.03	0.00
			CV	32.25	21.70	35.48
	2	8	Mean	13.74	0.61	0.02
			Std Err	1.78	0.05	0.00
			CV	34.23	21.51	56.29
	3	5	Mean	11.99	0.70	0.02
			Std Err	0.10	0.04	0.00
			CV	1.90	13.49	22.73
	4	27	Mean	11.20	0.56	0.02
			Std Err	0.43	0.02	0.00
			CV	20.14	22.09	39.77
	5	5	Mean	12.65	0.43	0.04
			Std Err	1.72	0.10	0.02
			CV	30.34	52.41	99.06
	6	5	Mean	13.20	0.51	0.03
			Std Err	0.94	0.09	0.01
			CV	15.97	40.19	67.37
	7	10	Mean	12.73	0.66	0.03
			Std Err	0.61	0.03	0.01
			CV	11.72	9.56	76.11
	8	10	Mean	14.35	0.53	0.03
			Std Err	1.98	0.06	0.01
			CV	43.65	33.70	99.55
	9	19	Mean	16.85	0.59	0.03
			Std Err	2.28	0.03	0.00
			CV	66.26	21.46	66.78
	10	12	Mean	18.42	0.57	0.02
			Std Err	6.29	0.04	0.00
			CV	113.27	22.20	63.19

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		BD (g cm^{-3})	C (%)	N (%)	OM (%)	AC (mg kg^{-1})
40 - 60	1	16	Mean	1.17	1.43	0.13	2.94	361.90
			Std Err	0.11	0.21	0.02	0.27	88.47
			CV	34.07	53.00	55.03	33.48	81.08
	2	8	Mean	1.26	1.26	0.09	2.43	178.11
			Std Err	0.08	0.17	0.02	0.18	22.45
			CV	17.41	36.18	47.34	20.59	35.65
	3	5	Mean	1.19	1.33	0.11	2.28	328.63
			Std Err	0.04	0.22	0.02	0.23	97.23
			CV	7.51	37.55	36.49	22.45	66.15
	4	27	Mean	1.25	0.99	0.11	2.43	187.56
			Std Err	0.04	0.09	0.01	0.17	24.03
			CV	16.03	47.21	53.68	35.53	66.57
	5	5	Mean	1.47	0.45	0.04	1.62	146.21
			Std Err	0.19	0.11	0.01	0.10	64.45
			CV	28.20	55.52	37.27	13.38	98.57
	6	5	Mean	1.42	0.63	0.05	1.74	104.65
			Std Err	0.10	0.11	0.00	0.17	27.98
			CV	15.78	37.80	20.00	22.48	59.78
	7	10	Mean	1.31	0.94	0.07	2.07	176.79
			Std Err	0.22	0.18	0.02	0.27	54.27
			CV	40.95	47.98	54.96	32.48	75.20
	8	10	Mean	1.53	0.61	0.10	1.53	148.41
			Std Err	0.07	0.14	0.03	0.15	69.90
			CV	13.80	73.03	80.81	31.11	148.94
	9	19	Mean	1.35	1.04	0.12	1.95	226.79
			Std Err	0.07	0.20	0.02	0.27	39.49
			CV	23.52	92.34	73.90	66.97	81.67
	10	12	Mean	1.32	0.85	0.14	1.94	198.49
			Std Err	0.09	0.16	0.03	0.25	57.47
			CV	23.20	59.26	69.46	44.11	96.03

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		C ($t\ ha^{-1}$)	N ($t\ ha^{-1}$)	OM ($t\ ha^{-1}$)	AC ($t\ ha^{-1}$)
40 - 60	1	16	Mean	32.75	3.25	71.89	0.77
			Std Err	6.21	0.57	9.80	0.09
			CV	70.95	63.79	49.18	39.86
	2	8	Mean	27.03	2.20	60.27	0.44
			Std Err	4.71	0.32	4.06	0.04
			CV	49.27	41.02	19.07	27.70
	3	5	Mean	32.48	2.75	55.00	0.78
			Std Err	6.68	0.55	7.51	0.22
			CV	46.00	44.85	30.51	63.90
	4	27	Mean	23.68	2.72	60.29	0.46
			Std Err	2.03	0.32	4.61	0.06
			CV	43.72	58.55	39.77	65.64
	5	5	Mean	14.03	1.08	47.20	0.34
			Std Err	4.55	0.26	5.98	0.10
			CV	72.47	54.02	28.33	64.19
	6	5	Mean	17.59	1.43	50.28	0.28
			Std Err	2.69	0.15	7.69	0.07
			CV	34.23	22.92	34.21	52.26
	7	10	Mean	26.97	2.08	59.44	0.35
			Std Err	7.69	0.63	15.96	0.09
			CV	69.83	73.86	65.78	65.69
	8	10	Mean	18.55	2.64	46.96	0.40
			Std Err	4.22	0.73	4.84	0.16
			CV	71.97	87.73	32.59	126.09
	9	19	Mean	29.56	3.29	55.05	0.65
			Std Err	6.01	0.55	8.71	0.16
			CV	97.57	80.32	75.87	116.20
	10	12	Mean	19.98	3.58	51.12	0.46
			Std Err	4.40	0.79	6.52	0.12
			CV	73.13	70.00	44.19	88.65

Table 2.3. (continued)

Depth (cm)	Cropping System [a]	n [b]		C/N	C/OM	AC/C
40 - 60	1	16	Mean	12.56	0.50	0.04
			Std Err	2.01	0.05	0.02
			CV	55.54	34.46	175.94
	2	8	Mean	14.69	0.50	0.01
			Std Err	2.14	0.05	0.00
			CV	38.54	26.28	23.78
	3	5	Mean	11.89	0.57	0.03
			Std Err	0.79	0.04	0.01
			CV	14.76	14.15	66.88
	4	27	Mean	10.00	0.42	0.02
			Std Err	0.84	0.03	0.01
			CV	42.75	30.67	123.57
	5	5	Mean	11.95	0.28	0.04
			Std Err	1.14	0.07	0.02
			CV	21.26	52.61	99.81
	6	5	Mean	13.24	0.38	0.02
			Std Err	2.54	0.07	0.00
			CV	42.87	43.38	60.42
	7	10	Mean	13.95	0.44	0.03
			Std Err	1.12	0.05	0.02
			CV	19.63	30.24	137.34
	8	10	Mean	7.35	0.36	0.05
			Std Err	1.52	0.06	0.03
			CV	62.10	54.38	215.41
	9	19	Mean	11.21	0.49	0.05
			Std Err	1.26	0.05	0.02
			CV	55.28	50.25	159.61
	10	12	Mean	7.56	0.39	0.04
			Std Err	1.97	0.04	0.02
			CV	82.36	28.62	142.40

crop systems/soil type combinations, as would be expected because of less crop residue and root biomass reaching lower depths. There was no clear evidence, however, that cropping systems that included the relatively deep-rooted alfalfa in rotation (3-9) had less C decline with depth, or more C at depth, compared to continuous corn (cropping systems 1-2). However, fields with alfalfa during the past four years did have 24% and 18.5%, more C (t ha-1) at 20-40 cm and 40-60 cm, respectively than pasture (10). Bulk density showed a trend opposite to OM, C, and AC, with a slight increase (19.5% on average) with depth, presumably associated with lower BD in the upper profile due to tillage and higher C stocks.

The top-ranked three systems for C% and OM % in the 0-20 cm depth were 1, 3, and 10, for C (t ha^{-1}) they were 3, 7 and 10, and for AC (t ha^{-1}) they were 2, 3, and 7 (Table 2.3). In general, this relative ranking of cropping system effects was also observed at the 20-40 cm depth, except for the pasture (10), which fell in ranking. At the deepest zone measured, 40-60 cm, cropping systems 1, 3, and 7 continued to rank high, but differences between cropping systems were in general diminished at the lower depths.

Manure additions reduced C/N by nearly 200% and increased AC/C by almost 400% in C-C rotations compared to non-manured C-C fields, though having more marginal effects on A-A rotations. Pasture showed a 56% decrease in C/N and a 144.6% increase in AC/C to 60 cm.

Total soil C stock in the entire 0-60 cm profile for the 10 cropping systems ranged from 111.9 to 205.2 t C ha^{-1}(Figure 2.2a). The ranking among treatments were somewhat similar to what was seen for the top 20 cm in Table 2.3, with cropping systems 1,3, and 7

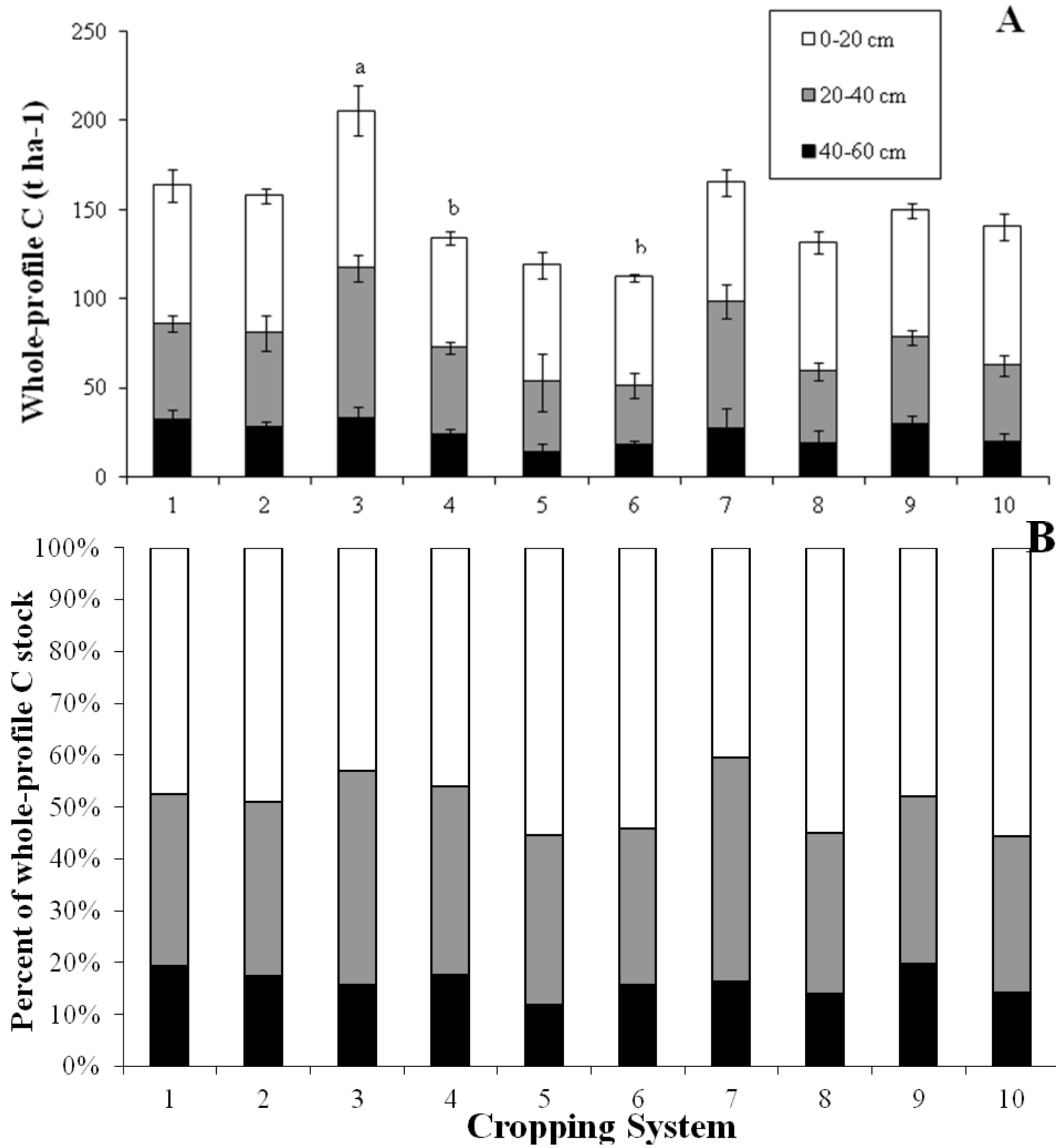


Figure 2.2. A) Whole-profile C stocks for each cropping system (refer to Table 2.1 for descriptions of each cropping system), displaying t C ha^{-1} in each 20 cm sample depth for the entire 60 cm sampling depth. Vertical bars represent standard error of the mean. Letters of separation indicate significantly ($p<0.05$) differences between the 0-60 cm C stocks of the cropping systems, as determined by a Tukey's HSD. **B)** Total C stocks at each 20 cm sampling depth as a proportion of the 60 cm total sampling depth.

having the highest values of 163.2, 205.2, and 164.9 t C ha^{-1}, respectively. We observed a general trend that cropping systems on Hd soils (1, 3 and 7) had the most soil C from 0-60 cm (Figure 2.2a).

While manure significantly increased soil C at 0-60 cm in continuous alfalfa (comparison between cropping systems 3 and 4 significant at $p<0.01$), the manure effect was not significant in continuous corn (cropping systems 1 and 2). In general, continuous alfalfa and continuous corn when compared across the same soil type and manure treatment were not significantly different (e.g., system 1 vs. 3 and 2 vs. 5, Figure 2.2a). The corn-alfalfa rotation system had 25 % more total soil profile C to continuous corn (not manured) and 41% more than continuous alfalfa (not manured) when compared across the same soil type (e.g., system 7 vs. 2 or 4 on Hd soil and 9 vs 6 on Va soil).

In general, less than 20% of C in the entire 0-60 cm soil profile was found in the 40-60 cm zone (Figure 2.2b). Averaged across the 10 cropping systems, 48.8, 33.9, and 17.3% of the total profile C was in the 0-20, 20-40, and 40-60 cm depths, respectively. This distribution of C as a proportion among the three depth zones had 81.2 % less variance than the variance observed for absolute C values (t ha^{-1}) in each depth increment.

<u>Variability Analysis</u>

Bulk density had lower CV than any soil chemical property measured (Figure 2.3). Of the soil C properties of interest, OM as both concentration (%) and mass per unit area (t ha^{-1}) basis had the lowest CVs at the three depth increments. The CV for C and AC were in some cases two or three-fold higher than OM at the lower depths.

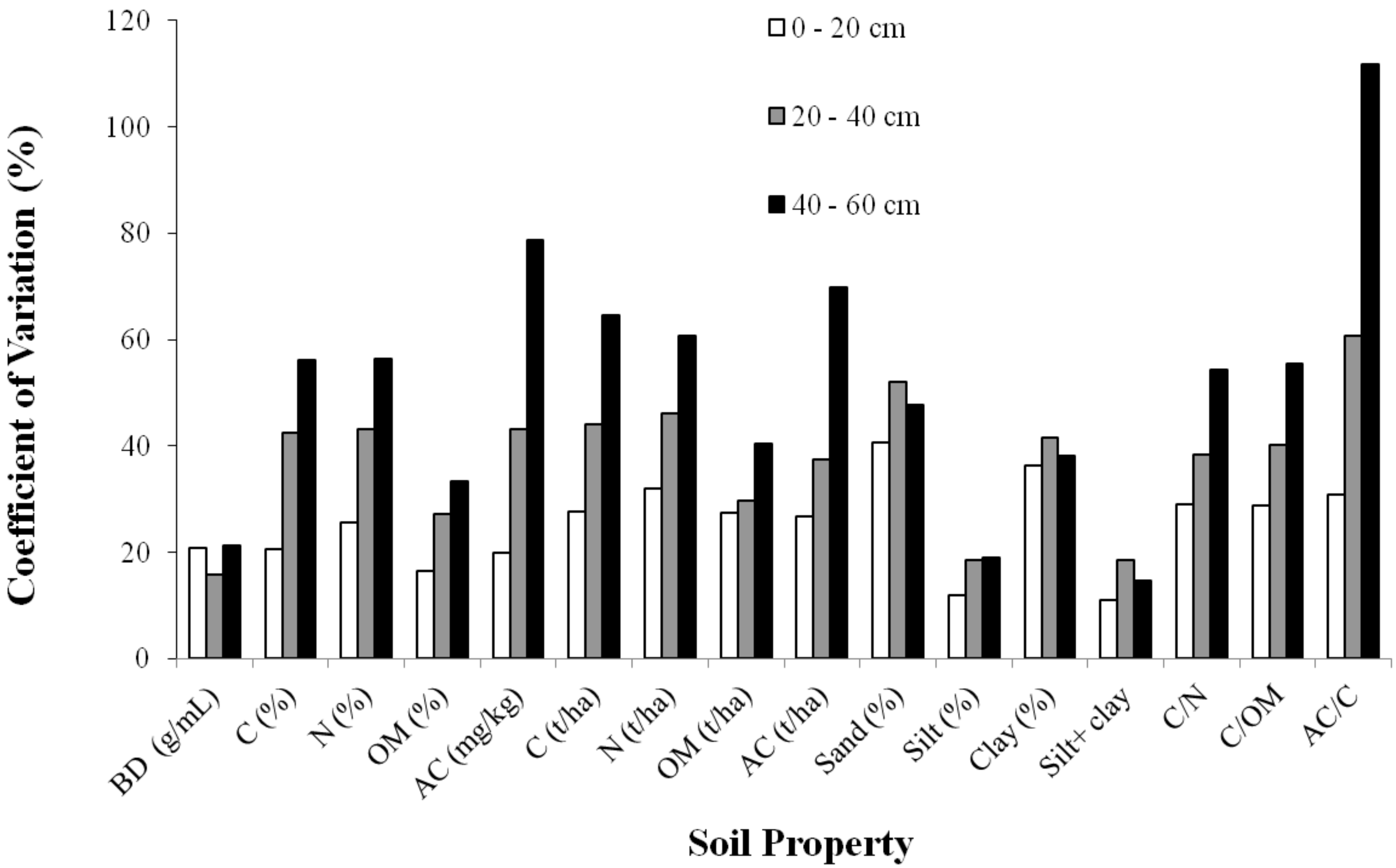


Figure 2.3. Coefficient of variation (CV) for soil properties at each sampling depth, averaged across the 10 cropping systems

Averaged across the 10 cropping systems, the CV of soil C and OM properties increased with depth (Figure 2.3), while the CV of BD was relatively similar at upper and lower depths. For concentrations of OM, C, and AC, the CV at 0-20 cm compared to 40-60 cm increased by 103.2, 173.6, and 293.4%, respectively. The CV of the ratio of AC/C was extremely high—highest of any soil property. This is probably because the means of this ratio were very close to zero (mean was 0.03 at 0-20 cm and 40-60 cm), which may reduce the reliability of the CV statistic.

Correlation Analyses

In our study we were interested to see which of the measured soil properties were highly correlated with C with the goal of identifying soil properties that could be measured as a proxy for soil C. Table 4 shows the correlation matrix at each 20 cm sampling interval.

Not surprisingly, OM consistently showed the strongest correlations with C at any depth, with like units (%-to-%; t ha^{-1}-to-t ha^{-1}) having stronger correlations than cross units (%-to-t ha^{-1}). The correlations at 0-20 cm, 20-40 cm and 40-60 cm were all very similar, 0.86, 0.89, 0.88, respectively for OM-to-C (%) and 0.87, 0.83, and 0.82, respectively for OM (t ha^{-1}). Nitrogen had the second best correlations with C, and followed a similar pattern (Table 2.4).

The negative correlations between C (on both concentration (%) and mass per unit area basis) with % clay (Table 2.4) were surprising given an expected positive correlation (Hassink, 1997). This may be due to a confounding effect of manured plots increasing C on Hd soils (in cropping systems 1 and 3), which have inherently lower clay % (Table

Table 2.4. Correlation matrix of all soil properties. Degree of correlation and level of statistical significance reported. Levels of significance determined from a Tukey's HSD test: *** ($p<0.01$); ** ($p<0.05$); * ($p<0.10$); n.s. denotes no statistical significance

Depth (cm)	Soil Property		**BD** g cm^{-3}	*p*	**C** %	*p*	**N** %	*p*	**OM** %	*p*	**AC** mg kg^{-1}	*p*	**C** t ha^{-1}	*p*	**N** t ha^{-1}	*p*
0-20	**C**	**%**	-0.17	n.s.												
	N	**%**	-0.04	n.s.	0.63	***										
	OM	**%**	-0.12	n.s.	0.86	***	0.47	***								
	AC	**mg kg^{-1}**	-0.06	n.s.	0.08	n.s.	0.14	n.s.	0.10	n.s.						
	C	**t ha^{-1}**	0.54	***	0.70	***	0.48	***	0.63	***	0.02	n.s.				
	N	**t ha^{-1}**	0.54	***	0.43	***	0.79	***	0.35	***	0.05	n.s.	0.75	***		
	OM	**t ha^{-1}**	0.70	***	0.45	***	0.33	***	0.59	***	0.07	n.s.	0.87	***	0.70	***
	AC	**t ha^{-1}**	0.65	***	-0.06	n.s.	0.05	n.s.	0.02	n.s.	0.70	***	0.39	***	0.41	***
	Sand	**%**	0.02	n.s.	0.37	***	0.26	**	0.40	**	0.28	**	0.34	***	0.24	**
	Silt	**%**	-0.05	n.s.	-0.29	n.s.	-0.16	n.s.	-0.34	n.s.	-0.23	*	-0.29	n.s.	-0.19	*
	Clay	**%**	0.03	n.s.	-0.21	***	-0.19	**	-0.18	*	-0.14	*	-0.15	***	-0.14	n.s.
	Silt+ clay	**%**	-0.02	n.s.	-0.37	***	-0.26	**	-0.40	**	-0.28	**	-0.33	***	-0.24	**

Table 2.4. (continued)

Depth (cm)	Soil Property		OM $t\ ha^{-1}$	*p*	AC $t\ ha^{-1}$	*p*	Sand %	*p*	Silt %	*p*	Clay %	*p*
0-20	**Sand**	**%**	0.30	**	0.25	**						
	Silt	**%**	-0.30	*	-0.23	**	-0.78	***				
	Clay	**%**	-0.08	n.s.	-0.09	n.s.	-0.57	***	-0.06	n.s.		
	Silt+clay	**%**	-0.30	**	-0.25	**	-1.00	***	0.78	***	0.57	***

Table 2.4. (continued)

Depth (cm)	Soil Property		BD g cm^{-3}	*p*	C %	*p*	N %	*p*	OM %	*p*	AC mg kg^{-1}	*p*	C t ha^{-1}	*p*	N t ha^{-1}	*p*
20-40	**C**	**%**	-0.27	**												
	N	**%**	-0.25	**	0.81	***										
	OM	**%**	-0.28	***	0.89	***	0.77	***								
	AC	**mg kg^{-1}**	-0.46	***	0.51	***	0.48	***	0.53	***						
	C	**t ha^{-1}**	0.09	n.s.	0.89	***	0.69	***	0.74	***	0.32	***				
	N	**t ha^{-1}**	0.08	n.s.	0.72	***	0.92	***	0.66	***	0.32	***	0.73	***		
	OM	**t ha^{-1}**	0.21	*	0.77	***	0.65	***	0.86	***	0.30	***	0.83	***	0.73	***
	AC	**t ha^{-1}**	-0.21	**	0.45	***	0.43	***	0.47	***	0.94	***	0.37	***	0.38	***
	Sand	**%**	-0.22	***	0.19	**	0.20	**	0.18	*	0.40	***	0.18	n.s.	0.08	n.s.
	Silt	**%**	0.17	*	-0.11	n.s.	-0.11	n.s.	-0.06	n.s.	-0.28	***	-0.12	n.s.	-0.01	n.s.
	Clay	**%**	0.19	**	-0.22	***	-0.24	**	-0.27	**	-0.34	***	-0.17	**	-0.15	n.s.
	Silt+ clay	**%**	0.22	**	-0.19	**	-0.21	**	-0.18	*	-0.39	***	-0.18	n.s.	-0.08	n.s.

Table 2.4. (continued)

Depth (cm)	Soil Property		OM t ha^{-1}	*p*	AC t ha^{-1}	*p*	Sand %	*p*	Silt %	*p*	Clay %	*p*
20-40	**Sand**	**%**	0.03	n.s.	0.32	***						
	Silt	**%**	0.06	n.s.	-0.20	**	-0.88	***				
	Clay	**%**	-0.16	n.s.	-0.31	***	-0.65	***	0.20	**		
	Silt+clay	**%**	-0.03	n.s.	-0.32	***	-1.00	***	0.88	***	0.65	***

Table 2.4. (continued)

Depth (cm)	Soil Property		BD g cm^{-3}	p	C %	p	N %	p	OM %	p	AC mg kg^{-1}	p	C t ha^{-1}	p	N t ha^{-1}	p
40-60	**C**	**%**	-0.05	n.s.												
	N	**%**	-0.05	n.s.	0.52	***										
	OM	**%**	-0.02	n.s.	0.88	***	0.49	***								
	AC	**mg kg^{-1}**	-0.38	***	0.19	n.s.	0.04	n.s.	0.21	**						
	C	**t ha^{-1}**	0.32	**	0.84	***	0.52	***	0.74	***	0.13	n.s.				
	N	**t ha^{-1}**	0.24	**	0.52	***	0.94	***	0.49	***	0.00	n.s.	0.65	***		
	OM	**t ha^{-1}**	0.46	***	0.72	***	0.41	***	0.86	***	0.06	n.s.	0.82	***	0.56	***
	AC	**t ha^{-1}**	0.02	n.s.	0.27	*	0.10	n.s.	0.27	**	0.84	***	0.35	**	0.19	**
	Sand	**%**	-0.24	**	0.19	n.s.	0.05	n.s.	0.16	**	0.28	***	0.13	n.s.	0.02	n.s.
	Silt	**%**	0.16	n.s.	-0.03	n.s.	0.09	n.s.	-0.02	n.s.	-0.10	n.s.	0.01	n.s.	0.11	n.s.
	Clay	**%**	0.18	*	-0.27	**	-0.22	**	-0.24	**	-0.32	***	-0.23	**	-0.20	*
	Silt+ clay	**%**	0.24	**	-0.19	n.s.	-0.05	n.s.	-0.16	**	-0.28	***	-0.13	n.s.	-0.03	n.s.

Table 2.4. (continued)

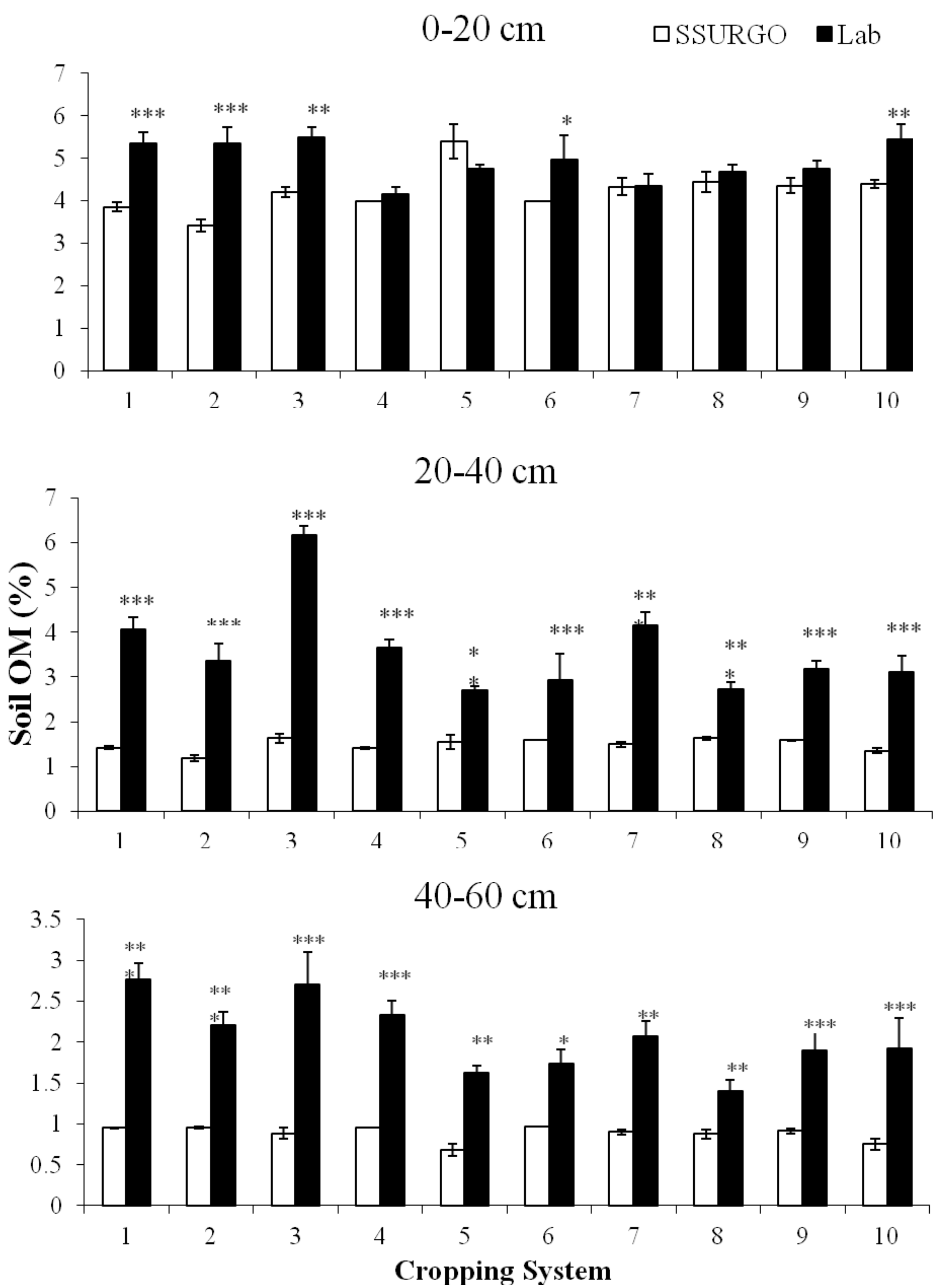
Depth (cm)	Soil Property		OM t ha^{-1}	*p*	AC t ha^{-1}	*p*	Sand %	*p*	Silt %	*p*	Clay %	*p*
40-60	**Sand**	**%**	0.04	n.s.	0.18	*						
	Silt	**%**	0.06	n.s.	0.00	n.s.	-0.80	***				
	Clay	**%**	-0.15	*	-0.29	***	-0.52	***	-0.10	n.s.		
	Silt+clay	**%**	-0.04	n.s.	-0.18	*	-1.00	***	0.80	***	0.52	***

2.2). The manured continuous alfalfa plots on Hd soil in particular had high SOC (Table 2.3, Figure 2.2a). Reanalyzing the correlation without these particular treatments (cropping systems 1 and 3), did not result in a positive correlation, however. This may be due to other land management preceding the 4-year rotations and manure additions we investigated was extremely high—highest of any soil property. This is probably because the means of this ratio were very close to zero (mean was 0.03 at 0-20 cm and 40-60 cm), which may reduce the reliability of the CV statistic.

SSURGO Evaluation

In most cases at 0-20 cm and in all cases from 20-60cm, OM % estimated for specific field sites based on SSURGO data were lower than OM % determined from direct field sampling and lab measurements in this study (Figure 2.4). This discrepancy was most pronounced below 20 cm, where differences were statistically significant ($p<0.05$) in most cases. At 0-20 cm, the differences were statistically significant in the continuous corn and manure-amended cropping systems (1-3) and the pasture fields (10), while the systems involving alfalfa, other than the case where manure was added, were not statistically significant. From 0-20 to 20-40cm SSURGO estimates of OM declined on average by about 65%, while lab data showed a reduction of only 24% averaging across all cropping systems Between 20-40 and 40-60 cm however, SSURGO's estimates showed an OM decline that was slightly less (38%) than that determined from actual field measurements (44%).

Figure 2.4. OM % from SSURGO reports compared to field samples across the 10 crop systems at each sampling depth, for a description of the cropping systems, refer to Table 2.1. Vertical bars represent stand error of the mean for each crop system. Significant differences were determined with a paired t-test: ***($p<0.01$); ** ($p<0.05$); * ($p<0.10$)


0-20 cm
SSURGO
Lab
20-40 cm
40-60 cm
Soil OM (%)
Cropping System

DISCUSSION

<u>Cropping System and Soil Type Effects on Soil C</u>

Our sampling scheme for soil C and related soil properties encompassed approximately 25% of the 649 ha of the Harford research dairy farm (Table 2.1). Across the 10 cropping systems measured, total soil C in the 0-60 cm profile ranged from 111.8 to 205.2 t C ha^{-1}. While we collected replicated samples within all of the dominant cropping systems and soil types of the farm, this was not a complete factorial design experiment with controlled treatments, so a comprehensive statistical analysis of effects of soil type, crop rotation, manure management, and their interactions on soil C are not possible. Nevertheless, specific t-test paired comparisons between cropping systems on the same soil type and between soil types with similar cropping system were possible.

For example, we documented that total soil C in the 0-60 cm profile in manured continuous alfalfa on Hd soil (cropping system 3) vs. non-manured continuous alfalfa on Hd soil was 68% higher (Fig. 2.2a), and this was statistically significant at $p<0.01$. This manure effect was not attributable exclusively to OM and C increases in the upper profile, but also reflected higher OM and C at the lowest depth (Table 2.3). Sommerfeldt et al., (1988) also reported a manure effect below 30 cm. They investigated the effects of long term manure additions in Alberta, Canada on soil OM, N and C/N and found that the accumulation of OM and N below 30cm was affected by the manure amount applied as well as frequency of application.

The La and Va soils had a higher proportion of clay than Hd soils, and yet the Hd soils, even those not amended with manure, tended to have higher C (Table 2.3). This result, along with a lack of a positive correlation between clay % and C (Table 2.4), was contrary to the expectation of chemical interaction of clay particles with C to enhance C sequestration in high clay soils (Six et al., 2002; Hassink, 1997; Blanco-Canqui and Lal, 2008). We did not have access to long-term land management history, and it is possible that the Hd soils sampled in our study have historically had more manure or crop residue additions than either La or Va soils sampled. It is also possible that the variation in clay % between these soils was not enough to adequately evaluate the clay-C correlation, or that our sample size was inadequate.

In general, the distinctions in total soil C between non-manured fields of continuous corn, continuous alfalfa, and pasture were not substantial (i.e., excluding cropping systems 1 and 3 from the evaluation, Figure 2.2a). While alfalfa biomass production and subsequent crop residue contribution to soil C presumably benefited from inherent N-fixing capacity, the non-manured corn plots did receive some synthetic N fertilizer, which may have compensated to some extent, or they may have received manure prior to the records we had available going back four years. Biomass and annual crop residue incorporation was not directly measured in our study. Within one season, corn and alfalfa roots can be expected to similarly reach 1.5 – 1.8 m in soil depth, but in continuous multi-year growth of alfalfa a root length of 3 – 6 m is not unusual (Weaver, 1926). We did find some indication that a corn-alfalfa rotation (in the past 4 years) led to more soil C than the continuous systems.

Our experimental design was not set-up with controlled and imposed treatments, nor did we have access to long-term detailed land use histories for each field that we sampled from. Thus the results of this current study represent differences that our sampling design was able to reveal, though we cannot rule out the possibility that our data is biased by unknown factors. This is because land management (e.g. crop rotation, manure application) prior to the 4 years we accounted for, detailed manure application rates and amounts, and yield and biomass sampling were not known. Given that, the trends observed in our study must rely on results from replicated controlled experiments for support. Prior meta-analyses and long-term controlled experiments (Ludwig et al. 2011; Liu et al., 2006; Chianese et al., 2006; Sommerfeldt et al., 1988) have established, for example, that manure additions play an important role in increasing soil C stocks, as we also found for at least the continuous alfalfa fields. Use of manure along crop rotations and reduced tillage, are well-recognized strategies for increasing soil C sequestration (Lal et al., 2011; Delgado et al., 2011; Min et al., 2003; Reeves, 1997; Christensen and Johnston, 1997).

Spatial Variability and Optimum Sample Number

The spatial variability data of Table 2.4 can be used to estimate an optimum sample number for a given confidence level (α) and level of precision or percent difference (d%) you want to be able to detect (Wilson et al., 2010; McKenzie et al., 2002) as described in Methods. In Table 2.5 the optimum sample requirements for BD, OM, C, and AC were calculated at three levels of confidence ($\alpha = 0.1$, 0.05, and 0.01) and two levels of precision ($\pm d\% = 5$ and 10). This was done to explore options for reducing sample number requirements while still addressing MRV requirements for reliable estimates of soil C stocks.

In general, across soil depths, BD had the lowest sample size requirement (Table 2.5) for any given α and d%, reflecting the fact that it had lower variability than measures

Table 2.5. Soil property sample size requirements at each 20 cm sampling interval; and computed at three different confidence interval: α=0.1; α=0.05; α=0.01 and two levels of precision (percent difference from the mean): ±d (%) = 10; ±d (%) = 5

		BD (g cm^{-3})			C (%)			OM (%)			AC (mg kg^{-1})		
		0-20	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**
α = 0.10	**Crop Rotation**	13	8	15	18	59	110	11	31	51	22	65	209
	Soil Type	12	9	12	20	57	126	12	25	42	17	62	270
±d (%) = 10	**Manure**	21	6	18	17	52	97	9	29	43	19	49	171
	Crop Systems	14	8	15	13	55	94	8	22	36	13	61	190
α = 0.10	**Crop Rotation**	52	31	61	71	235	442	43	124	203	89	260	838
	Soil Type	50	35	49	79	229	504	47	98	167	66	247	1080
±d (%) = 5	**Manure**	82	25	72	67	208	390	38	116	170	77	197	685
	Crop Systems	57	31	59	51	222	375	31	87	143	53	244	762
α = 0.05	**Crop Rotation**	18	11	22	25	83	157	15	44	72	31	92	297
	Soil Type	18	12	17	28	81	179	17	35	59	23	88	383
±d (%) = 10	**Manure**	29	9	25	24	74	138	13	41	60	27	70	243
	Crop Systems	20	11	21	18	79	133	11	31	51	19	87	270
α = 0.05	**Crop Rotation**	74	45	87	101	333	627	62	176	288	126	369	1190
±d (%) = 5	**Manure**	117	36	102	94	295	553	53	165	242	110	280	973
	Crop Systems	80	44	84	72	315	532	44	123	203	75	347	1081
α = 0.01	**Crop Rotation**	32	19	38	43	144	271	27	76	124	54	160	514
	Soil Type	31	21	30	48	140	309	29	60	102	41	151	662
±d (%) = 10	**Manure**	51	15	44	41	127	239	23	71	104	47	121	420
	Crop Systems	35	19	36	31	136	230	19	53	88	32	150	467
α = 0.01	**Crop Rotation**	128	77	151	174	575	1084	106	304	497	218	638	2055
	Soil Type	123	86	119	193	561	1235	116	241	410	162	605	2648
±d (%) = 5	**Manure**	202	62	175	163	509	956	92	284	417	189	484	1681
	Crop Systems	139	76	144	124	544	919	77	212	351	129	599	1868

Table 2.5 (continued)

		C (t ha^{-1})			OM (t ha^{-1})			AC (t ha^{-1})		
		0-20	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**	**0-20**	**20-40**	**40-60**
α = 0.10	**Crop Rotation**	29	56	131	26	32	65	32	55	198
	Soil Type	26	63	194	22	30	51	19	54	224
±d (%) = 10	**Manure**	37	45	130	38	29	65	36	46	158
	Crop Systems	24	61	127	23	28	50	22	45	155
α = 0.10	**Crop Rotation**	116	223	525	104	128	262	129	221	792
	Soil Type	103	251	777	89	119	205	74	215	898
±d (%) = 5	**Manure**	147	180	521	153	118	259	144	185	632
	Crop Systems	94	244	509	93	111	199	89	178	619
α = 0.05	**Crop Rotation**	41	79	186	37	46	93	46	78	281
	Soil Type	37	89	276	32	42	73	26	76	319
±d (%) = 10	**Manure**	52	64	185	54	42	92	51	66	224
	Crop Systems	33	87	181	33	39	70	32	63	220
α = 0.05	**Crop Rotation**	165	317	745	148	182	371	183	314	1124
	Soil Type	147	356	1103	126	168	292	106	306	1275
±d (%) = 5	**Manure**	209	255	740	218	167	367	204	263	898
	Crop Systems	134	346	722	133	157	282	127	253	879
α = 0.01	**Crop Rotation**	71	137	322	64	79	160	79	136	485
	Soil Type	63	154	476	55	73	126	46	132	550
±d (%) = 10	**Manure**	90	110	320	94	72	159	88	114	388
	Crop Systems	58	150	312	57	68	122	55	109	380
α = 0.01	**Crop Rotation**	285	547	1286	255	314	642	316	542	1941
	Soil Type	254	615	1905	218	291	504	182	528	2202
±d (%) = 5	**Manure**	360	440	1278	376	289	635	353	454	1551
	Crop Systems	231	598	1248	229	272	487	219	438	1519

of OM, C, and AC (Figure 2.3). Don et al. (2007), reported similar results—a smaller sample requirement for BD than for SOC concentration because of smaller BD variability. The agreement between these studies is encouraging. If corroborated more broadly by other studies in the future this would suggest sampling schemes with fewer BD than C concentration samples required, which could reduce costs for MRV for C markets substantially.

For all soil properties except BD, there was a similar trend towards increasing variability with depth, which sometimes approached a 300% increase in soil property CV at 40-60 cm compared with 0-20 (Figure 2.3). The variability in BD remained relatively low and stable with depth, which was also corroborated by Don et al. (2007). According to our analysis, C % required 10% more samples than BD at 0-20 cm, which then increases to 600% more for 20-40 and 40-60 cm. Information such as this will be helpful in designing future soil sampling efforts.

BD exhibited near equal CVs at 0-20 and 40-60 cm, while 20-40 cm exhibited the least variability. We feel that this can be explained by the interaction of managerial induced variability and inherent differences in soil properties that change with depth. From 0-20 cm, variability in BD can be attributed to influences from tillage, wheel traffic, difference in plant growth, manure spreading, and measurement errors due to uneven and cloddy soil surface. This variability was equal to the variability found from 40-60 cm, which had its own possible sources of variability, such as compaction, difficulty in assessing if the soil in the sampling tube reflected all of the soil collected to that depth, or if some soil had fallen out while the core was extracted. Variability from 20-40 cm was lowest perhaps because of not being as subject to as many sources of variation as the depth zones above and below.

Regression Analyses for Predicting Soil C

Averaged across all α, d%, and depth combinations, OM had lower variability and thus smaller sample requirements than measuring soil C concentration (less than half in some cases, Table 2.5). Although direct measure of soil C would be preferred, given budgetary constraints and the need to reduce sampling requirements, these results suggest that OM % by LOI might be substituted for soil C concentration, assuming a reliable predictive model for C concentration from OM data can be established. A conversion factor of 0.58 is commonly used (Gelder et al., 2011; Zhong and Xu, 2011; Pulske et al., 2011; Soil Survey Division Staff 1993), but below we developed simple linear regression models based on our data.

The regression analyses below indicate that for our data set, variability in OM could account for a large fraction of variability in C (based on r^2 for simple linear regression models) and therefore could be a useful predictor of C at all depths.

- 0-20cm (n=116)

  TC (%) = -0.329 + [0.735 * OM (%)]; r^2 = 0.734; RSME = 0.463

  TC (t·ha^{-1}) = 6.29 + [0.608 * OM (t·ha^{-1})]; r^2 = 0.76; RSME = 11.59

- 20-40cm (n=117)

  TC (%) = -0.447 + [0.715 * OM (%)]; r^2 = 0.787; RSME = 0.48

  TC (t·ha^{-1}) = -6.49 + [0.676 * OM (t·ha^{-1})]; r^2 = 0.685; RSME = 13.39

- 40-60cm (n=110)

  TC (%) = -0.372 + [0.638 * OM (%)]; r^2 = 0.769; RSME = 0.323

  TC (t·ha^{-1}) = -6.85 + [0.604 * OM (t·ha^{-1})]; r^2 = 0.677; RSME = 11.64

We also evaluated the potential for predicting whole profile C stocks using the C mass per unit area data at each soil sampling layer (Figure 2.5). Using the cropping system averages as opposed to using individual data points reduced model variability (higher r^2), we found that using C (t ha^{-1}) from the 0-20, 20-40, and 40-60 cm depths, respectively, to predict the whole-profile (0-60 cm) C stocks resulted in r^2= 0.63, 0.89, 0.74 (n=10). This indicates that a majority of the whole-profile variability can be adequately explained by upper soil depth measurements. Since BD was used to convert values from concentration to mass per unit area in the regression analyses of Fig. 2.5, differences in r^2 at each depth may be partially explained by the fact that BD had lowest CV at the middle (20-40 cm) depth, for reasons associated with tillage at the upper depth and sampling difficulty and compaction at the lowest depth, as discussed previously. The implications of this are that samples taken at just 20-40 cm could be used to predict soil C stocks of the entire 0-60 cm profile and account for 90% of the variability (based on r^2 values in Fig. 2.5). This would reduce the need to obtain soil samples from the 40-60 cm depth, which take more time to obtain with high confidence, and add to total soil sampling and analysis costs.

We also looked at predicting soil property values at the lowest depth (40-60 cm) from measurements at the 0-20 cm and 20-40 cm for BD and C %. The linear relationship was modest and on average the r^2 was better when using 20-40 cm compared to 0-20 cm, for example the best r^2 we obtained, 0.60, was using 20-40 cm C % to predict 40-60 cm C %. Improvements in this kind of approach could be helpful in reducing the sampling needs at lower depths, which are more challenging to obtain and subject to experimental error.

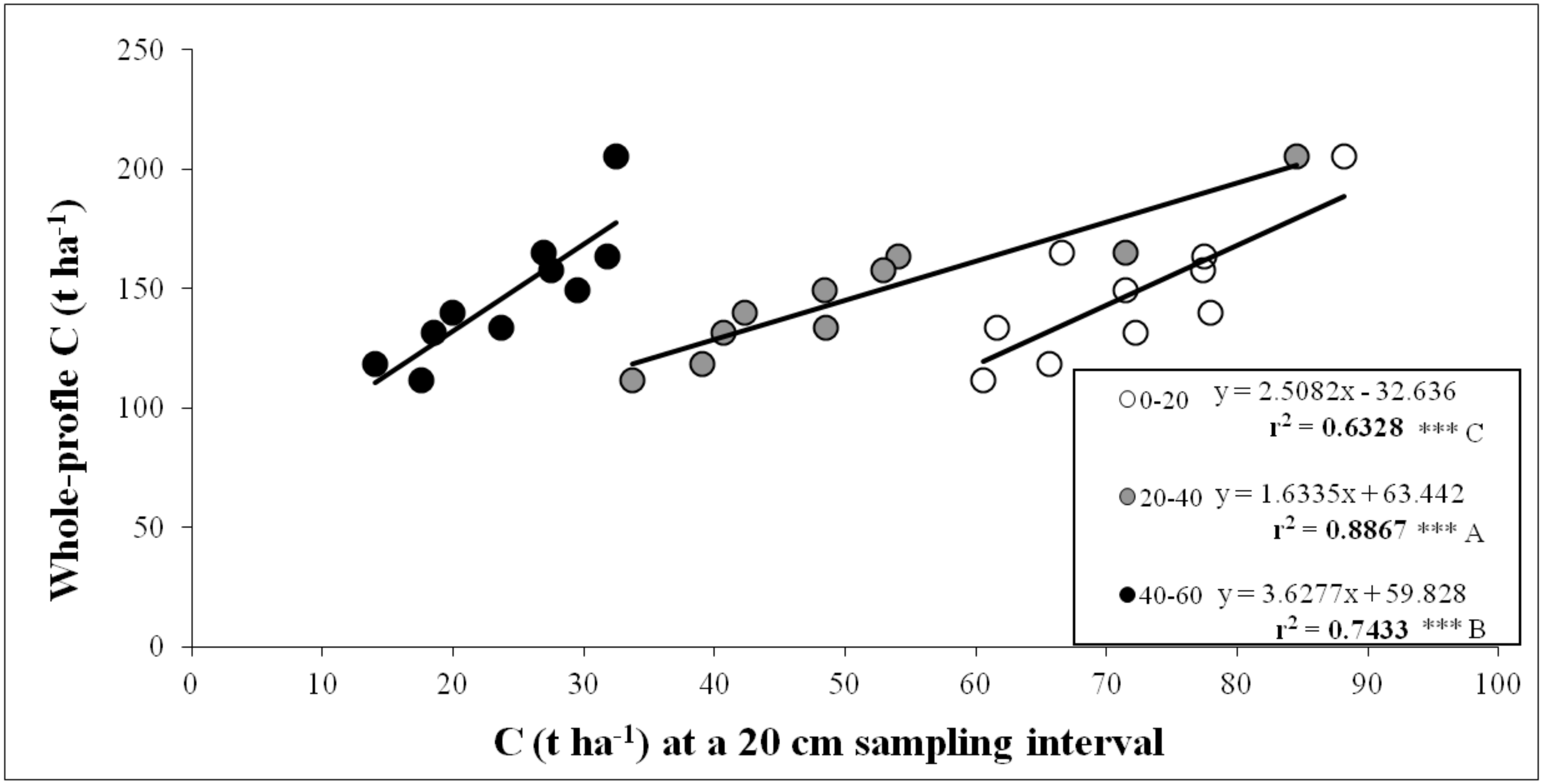


Figure 2.5. Simple linear regressions to predict 0-60 cm whole-profile soil C stocks from soil C stocks within each 20 cm sampling interval. Data points are averages of each of the 10 cropping systems and linear combination equations were derived from the 10 cropping systems averages pooled together within each sampling depth (open circles refer to 0-20 cm, shaded circles refer to 20-40 cm, and black circles refer to 40-60 cm). Statistical significance of regression is indicated by *** ($p<0.01$) and letters of separation indicate that each regression is statistically different from the others, as determined by a Tukey's HSD

Other approaches have been evaluated to reduce sample requirements for soil C assessment. Mooney et al. (2007) presented a spatial autocorrelation approach to improve the confidence interval around the mean of soil C estimates. Huang et al. (2007) used principal component regression to predict and map total soil C in glacial till soils with on-the-go field measurements of visible and near infrared (VNIR) reflectance as an ancillary variable, and obtained regression coefficients between measured and predicted C values of 0.70. The regression coefficients improved to 0.81 when secondary attributes such as elevation and terrain curvature were included in the model. Bilgili et al. (2010) found that co- and regression kriging using high-density VNIR measurements could significantly enhance sampling efficiencies and reduce requirements for more costly measures.

Using SSURGO Data to Estimate SOC

SSURGO data consistently underestimated field-measured OM and C in our study (Figure 2.4), typically by more than 50% at depths > 20 cm. This may be due to land management effects (e.g. manure) having impacts on SOC down to the 60 cm depth, which would not necessarily be captured by the USDA/NRCS soil survey in the study region. Sommerfeldt et al. (1988), Matlou and Haynes (2006), Don et al. (2007) and Kindler et al. (2011) have discussed the importance of OM vertical transport as a significant pathway for terrestrial C storage through gravitational water movement, bioturbation, and nutrient cycling. It may be possible to improve the reliability of SSURGO for soil OM and C estimates by calibrating SSURGO data for particular fields from a small number of samples. In Figure 2.6

Figure 2.6. Linear correlations of cropping system means of SSURGO reported OM % predicting OM % from field samples at 0-20 cm (**A)**, 20-40 cm (**B**), and 40-60 cm (**C**). Each symbol represents the cropping system indicated. For descriptions of each cropping system, refer to Table 2.1. **D)** Shows linear regression equations of the 10 cropping systems pooled together at each 20 cm sampling interval; they are not statistically significant ($p<0.05$)

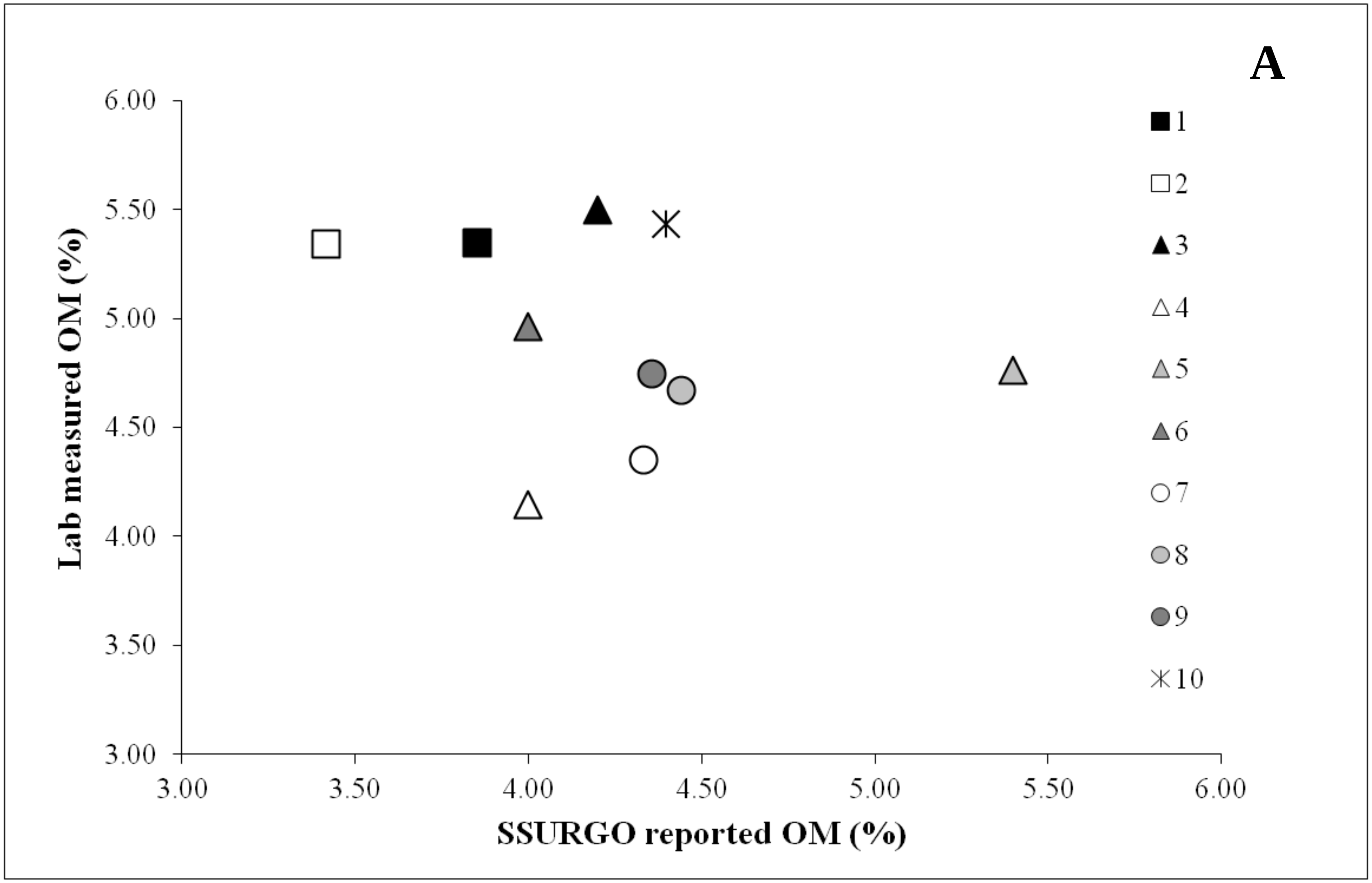

A
6.00
5.50
5.00
4.50
4.00
3.50
3.00
Lab measured OM (%)
3.00
3.50
4.00
4.50
5.00
5.50
6.00
SSURGO reported OM (%)
1
2
3
4
5
6
7
8
9
10

Figure 2.6. (continued)

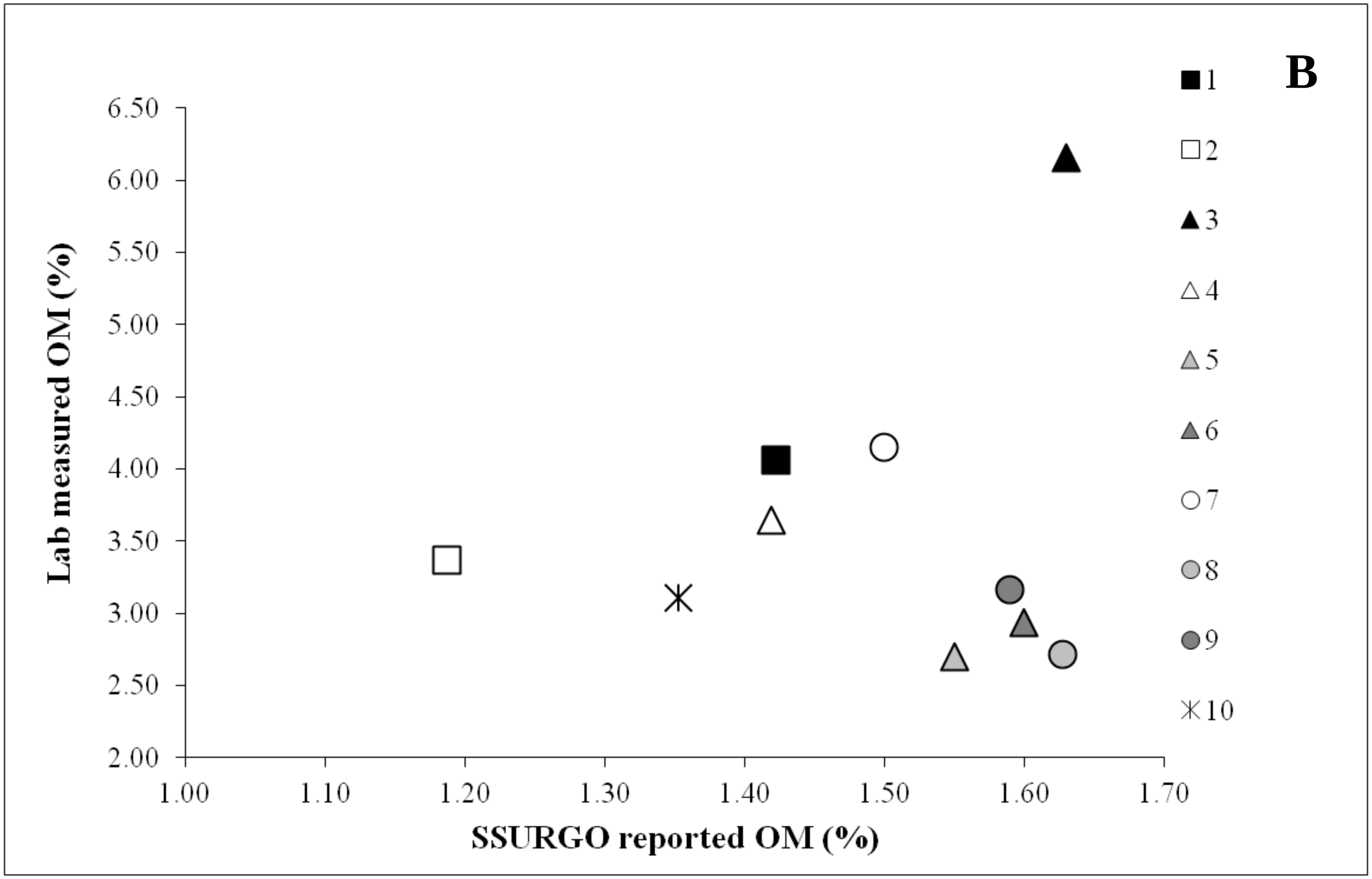


Figure 2.6. (continued)

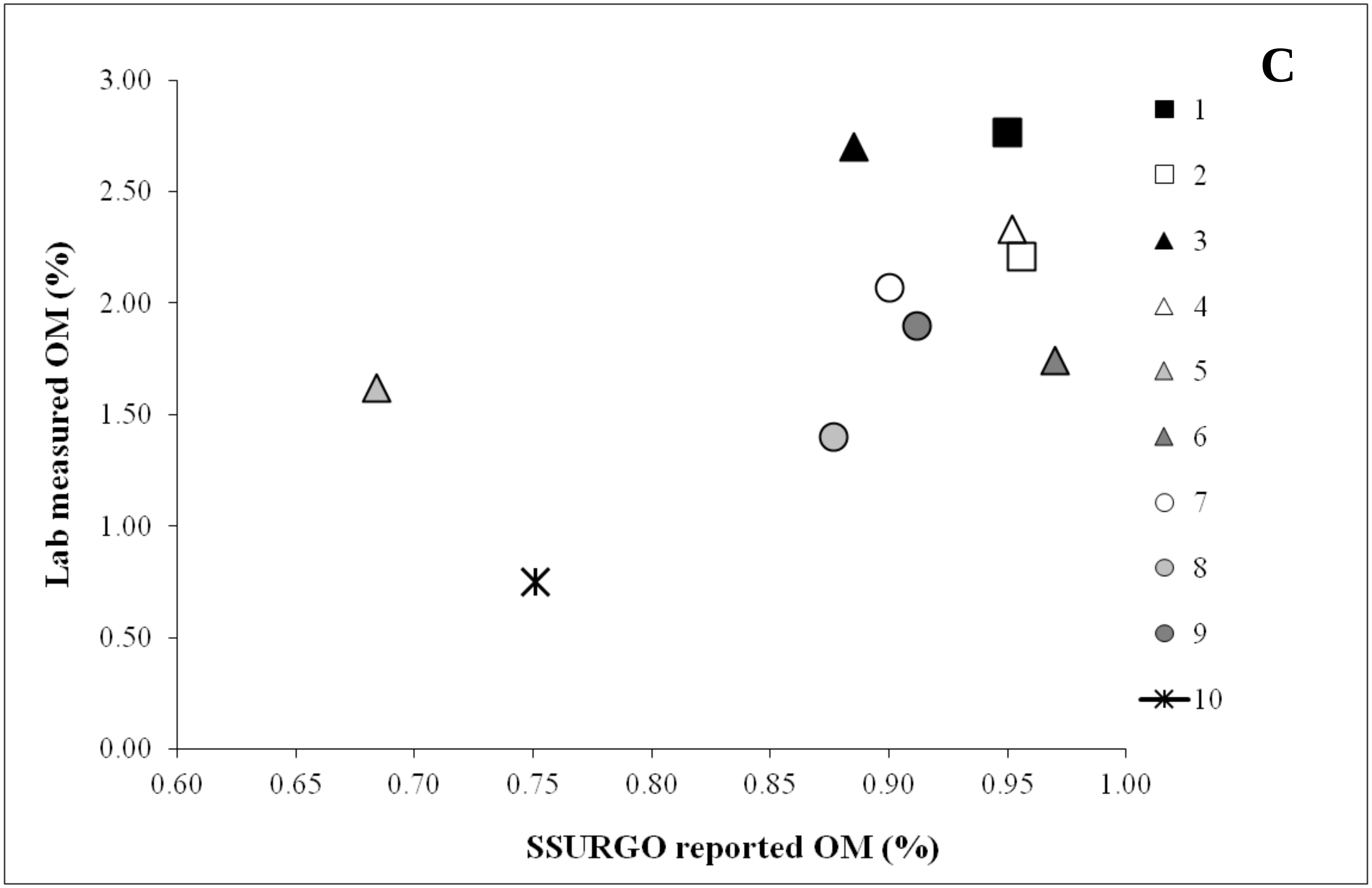
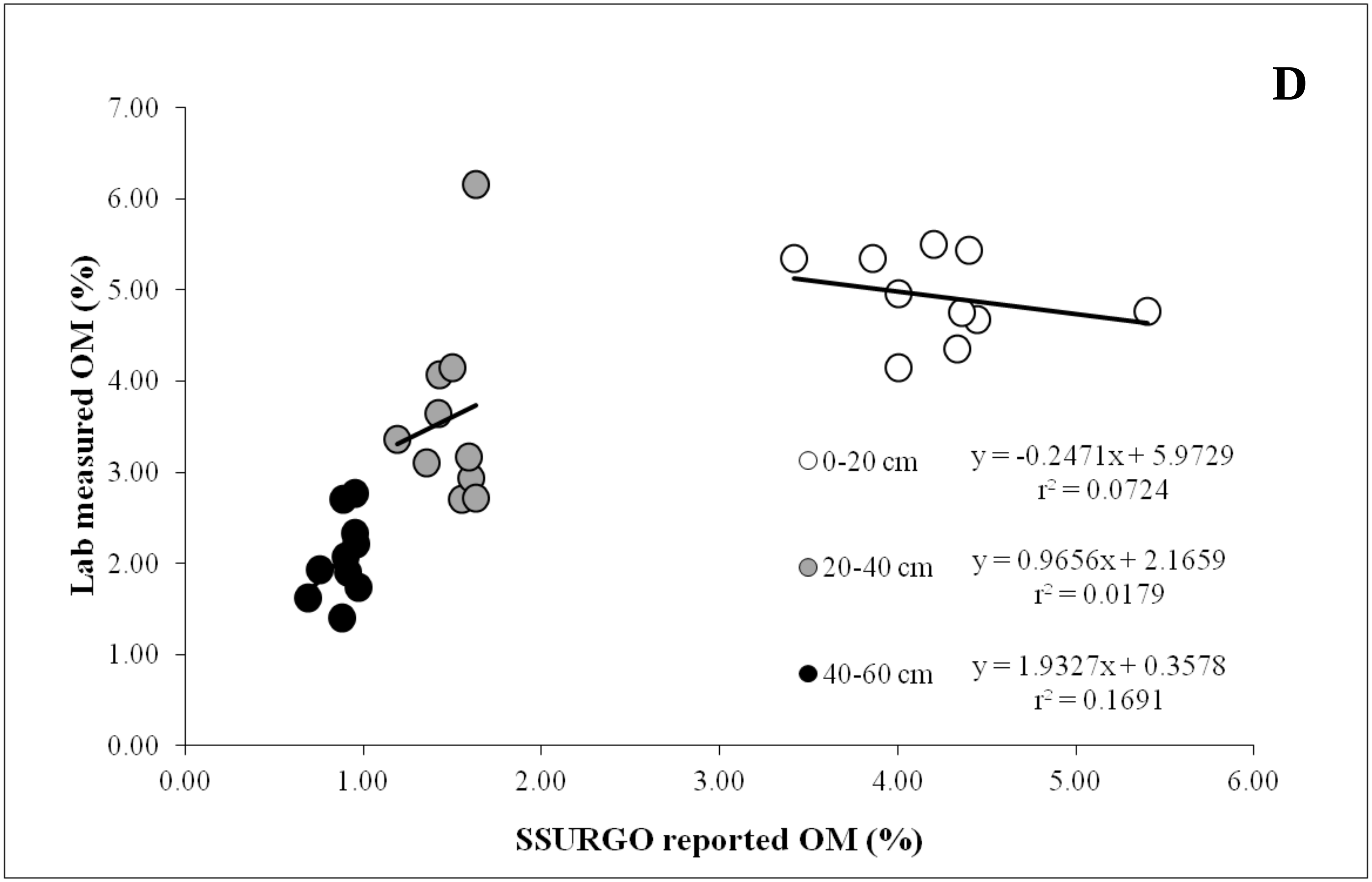


Table 2.6. (continued)



the relationship between SSURGO OM % and actual measured OM % for each of the three depth increments and each cropping system/soil type is illustrated, and predictive regression models are shown.

Attempts to establish a linear correlation for specific depth zones using SSURGO reported OM % to predict lab measured OM % where generally unsuccessful. The r^2 was 0.07, 0.02, and 0.17 for 0-20, 20-40, and 40-60cm respectively. However, excluding the data from the 0-20 cm depth, and pooling the 20-40 and 40-60 cm data together, we found that OM % for 20-40cm and 40-60cm could be predicted from the same linear regression model: OM% = 0.01+ 2.38(OM% from SSURGO); r^2 = 0.51

When the simple correction factor of 2.38 was applied to SSURGO OM values at 20-40 and 40-60 the occurrence of significant differences ($p<0.05$) between SSURGO values and actual field-measured OM% was reduced by 50% and 90% for 20-40 cm and 40-60cm, respectively (Figure 2.7).

Using a combination of the above strategies offers several options for a lower cost approach to assessing soil C stocks at the farm-scale. Stratifying soil samples based on management and soil type combinations helped to reduce the variability of soil properties over broader stratification methods. Zhang et al. (20110 and Wang et al. (2010) also found that the CV of SOC increased with larger sampling areas and suggested that more specific sample stratification could reduce SOC CVs. Informed soil sampling requirements based on soil property variability and stratified by depth and management-soil type combinations can ensure that sampling efforts are labor and cost efficient, while still adequately capturing inherent variability (Table 2.5). To further increase sampling efficiency, predictive relationships between

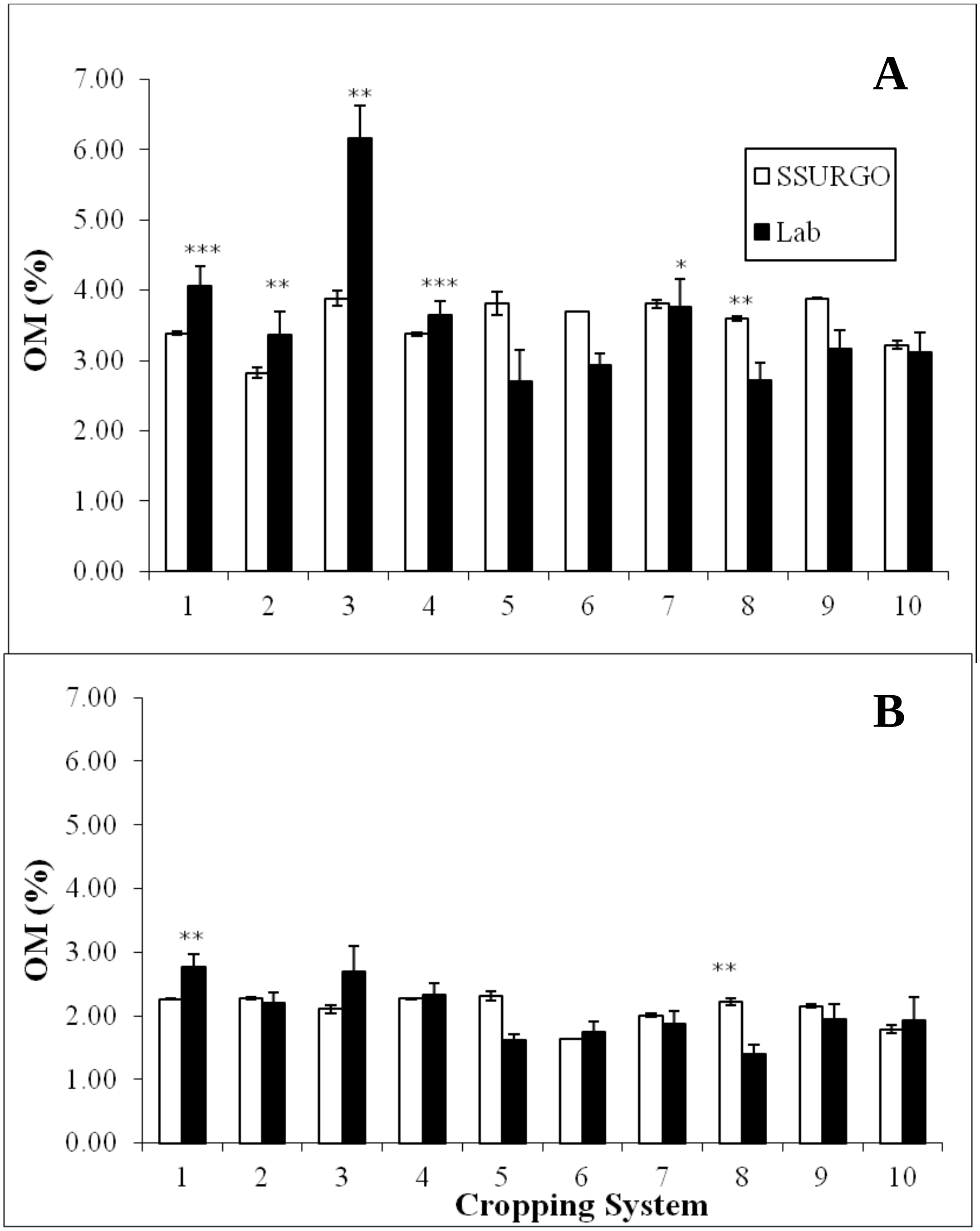


Figure 2.7. SSURGO reported OM % with correction factor of 2.38 compared to OM % from field collected soils by cropping system at 20-40cm (**A**) and at 40-60 cm (**B**). For a description of the cropping systems, refer to Table 2.1. Vertical bars represent standard error of the mean. Statistically significant differences by paired t-test between SSURGO and Lab at each cropping system are notated: *** (p<0.01); ** (p<0.05); * (p<0.1)

C stocks within a sampling depth and the whole profile can be developed to reduce deep sampling and to focus sampling efforts in the top 40 cm, where soil samples are more easily obtained and sampling errors are reduced. This does require selective deep sampling within each cropping system combination to calibrate those predictive relationships. Further, large databases, such as SSURGO, that contain geographical and tabulated data on soil properties related to C (e.g. OM%) are available and have the potential to aid soil C assessments. We found that SSURGO estimates of OM% at the 20-60cm depth could be substantially improved by a simple calibration based on a linear regression model developed from a small number of actual field measurements.

While OM determined by LOI is not the most accurate estimation of SOC due to incidental measurement of soil inorganic C as well as mineralogical water (Salehi et al., 2011), it is a relatively rapid and inexpensive method that has been shown to correlate well with other methods of SOC determinations, provided site-specific calibrations (e.g. Walkley-Black wet oxidation, dry combustion analysis; Konen et al., 2002; Shulte et al., 1991; Howard and Howard, 1990). Our results suggest OM as measured by LOI can be useful in correcting SSURGO OM reports. Additionally, we found a strong correlation of OM to C at each depth indicating that if other preferable methods of measure were not available or out of budget, that OM LOI could be a substitute for direct measurement of SOC.

SUMMARY

Our initial farm-scale assessment across 10 cropping systems and 164.6 ha we found a ranger of soil C stocks in the top 60 cm from 111.8 to 205.2 t C ha^{-1}. We found that land management, especially manure additions, tended to impact soil C concentrations and stocks more than soil type alone. We observed a trend that manure additions on fields that were cultivated with alfalfa in the last four years had the greatest soil C stocks to 60 cm, and that this was reflected by elevated soil C in lower soil depths. Sample stratification using a combination of land management (e.g. crop rotation, manure additions) and biophysical (e.g. soil type) variables better accounted for soil property variability across the farm compared to these variables alone. Though our conclusions are constrained by limited knowledge of the long-term land use histories, the tendencies of our results are corroborated by other replicated controlled research experiments. We presented an approach to assessing soil C on a model dairy farm for the Central New York region characterized by diverse land use practices on several intersecting soil types.

On these soils we found less than 20% of soil C within the 0-60 cm soil profile was found in the deepest, 40-60 cm increment, but manure effects were still observed at this depth.

Variability was lowest for BD and OM % compared to measurements of total C and AC. This indicates that sample number can be reduced for BD and OM % for any given desired α and d%. A possible strategy of reducing soil sampling costs for MRV could be approached by collecting fewer samples for BD and using OM % as a proxy for C %. Linear regression predictive models for estimating C % from OM % were developed. We were able to successfully predict whole profile (0-60 cm) C stocks using mass per unit area values from each 20 cm sampling depth, which can be used to reduce the number of samples taken to the full 60 cm depth.

SSURGO data consistently underestimated OM %, by half or more in most cases at depths below 20 cm. Strategic field measurements could potentially be used to calibrate SSURGO estimates of OM % and improve reliability, but we observed considerable variability in the conversion factor among cropping systems and soil types at the upper 0-20 cm. Using a linear correlation between SSURGO and lab measured OM % from 20-40 and 40-60 cm pooled together, we were able to develop a correction factor that improved the SSURGO reported OM % at those depth**s.**

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