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Soil Organic Carbon Distribution with Depth: Implications for Ecosystem Services

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SOIL ORGANIC CARBON DISTRIBUTION WITH DEPTH: IMPLICATIONS FOR ECOSYSTEM SERVICES

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Master of Science
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by
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ABSTRACT

Most current frameworks of ecosystem services represent soil organic carbon (SOC) as a bulk/composited stock without differentiating SOC ecosystem services in the top and subsoil. This study evaluated SOC, nitrogen (N), and C/N distribution with depth in glaciated soils at the Cornell University Willsboro Research Farm in upstate New York. Soil organic carbon, N, and C/N decreased with depth in all soils sampled. The vertical distribution of SOC was examined quantitatively by soil order, soil depth class (top soil versus subsoil), and other environmentally-relevant soil and landscape variables. Top soils (A horizon) contained more variable SOC concentrations compared with the lower depth horizons (subsoils). Soil depth class was statistically significant in explaining vertical distributions of SOC in all three soil orders present on the farm. Nitrogen concentrations in the soils tracked well with SOC, decreasing sharply with depth from the soil surface to about 40 cm and then declining slowly thereafter to stable low values with additional depth. Despite the soils being highly heterogeneous due to past glaciation, making coarse fraction corrections to the measured SOC concentrations did not result in a statistically significant change in our results. Existing frameworks of ecosystem services for SOC were integrated with an organizational hierarchy of soil systems. Ecosystem services provided by SOC are depth-dependent because of the types of SOC within the soil: top soil having more active or labile SOC and subsoil having less active, more non-labile SOC which is relatively bio-geochemically stable (e.g. humus). Proposed integration of existing ecosystem services framework with organizational hierarchy of

soil systems provides a missing link to scale, time, degree of computation and complexity.

DEDICATION

This thesis is dedicated to my parents Martha and Ed Fitchett for their love, and support throughout my life.

ACKNOWLEDGMENTS

I would like to thank my advisors for their guidance, and support during my graduate studies. Technical Contribution No. 6404 of the Clemson University Experiment Station. This material is based upon work supported by NIFA/USDA, under projects: SC-1700452, and SC-1700462.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

Soil organic carbon (SOC) plays a major role in the global carbon cycle. Soil organic carbon accounts for an estimated 1500 gigatonnes of carbon stores worldwide (Trumbore, 1997). The carbon stocks are supplied by decomposition of organic materials and it is influenced by plants, gas exchanges, agriculture, and fossil fuel consumption (Brady and Weil, 2002). Accurate modelling of soil organic carbon distribution is useful for soil carbon accounting purposes in terms of carbon sequestration because of the large amount of carbon stored within soils.

Soil organic carbon is a portion of soil organic matter (SOM) (Brady and Weil, 2002). Soil organic matter is composed of: <10% fresh organic residue which is mostly leaf litter or mulch in an agricultural setting; <5% living organisms within the soil; 33-50% humus which is plant material that has transformed from one organic compound to another and is considered stabilized organic matter; and 33-50% decomposing organic matter (active fraction of SOM) (Brady and Weil, 2002). The majority of soil organic matter is plant derived. Soil organic carbon is critical for soil function and soil quality and it provides aggregation and stability for better soil structure (Brady and Weil, 2002).

Soil organic carbon may be broken down into three distinct fractions: active, intermediate, or passive (Xu et. al., 2016; Trumbore 1997). The active and intermediate fractions are located in the upper 1 meter of soil and are often grouped together as non-passive or labile SOC (Trumbore, 1997). The SOC found in this fraction is biologically available and more susceptible to changes at the surface (Cheng et al., 2015). The size of the non-passive fraction has been debated (Xu et al., 2016), but Trumbore (1997) considers it as the smallest pool of SOC, containing an estimated 250-350 gigatonnes of soil carbon. This fraction originates from new organic residues and living organisms and turnover generally occurs from less than one year up to a few decades (Trumbore, 1997).

The passive fraction of SOC is often found below 1 meter and it is considered chemically stable humus that is very resistant to decomposition from microorganisms (Trumbore, 1997). According to Rumpel and Kogel-Knabner (2011), a high radiocarbon age of SOC found in subsoils contributes to the stability and longevity of deep SOC. It can take anywhere from 100 years to more than 2500 years for turnover to occur (Trumbore, 1997; Xu et. al., 2016). The subsoil contains the largest pool of SOC and is the least likely to be influenced by changes in management practice and often may be subjected to different environmental conditions than top soil (Rumpel and Kogel-Knabner, 2011).

Carbon-to-nitrogen (C/N) ratio is often used as a determinant for the health of a soil (Xu et. al., 2016). Soil microorganisms (fungi, bacteria, protozoa, nematodes, etc.) are directly affected by C/N ratio. Nitrogen is essential for microbial growth, therefore a higher C/N ratio results in lower decomposition activities by soil microorganisms (Brady and Weil, 2002; Xu et. al., 2016). Soil microorganisms require a constant supply of fresh SOM and many will enter a starvation mode, a dormant state, in soils that do not provide adequate food and fuel (Alexander, 1991). This is particularly true with soil depth as subsoils do not have active supplies of SOM and shallow roots systems often fail to penetrate into the subsoil (Brady and Weil, 2002). In addition, the bulk of soil fungi and bacteria are found to be concentrated in the upper 10 cm of soil as there is a high availability of SOM and oxygen (Brady and Weil, 2002).

The concept of ecosystem services groups together the positive effects gained by humans and human well-being either directly or indirectly from the natural world (García-Nieto et al., 2013; Schägner et al., 2013). Most often this concept is used as a tool to put monetary value to natural capital (Baveye et al., 2016), and plays an increasingly major role in decision making and forming policy by government agencies (Schägner et al., 2013). Even though research on the characteristics and functions of soil has been conducted for decades, only recently has soil been linked to ecosystem services (Adhikari and Hartemink, 2016). Considering ecosystem services provided by soils began in the mid-1990's, with the concept gaining momentum in literature after 2005 (Baveye et al., 2016). The use of ecosystem services in publications and proposals is increasingly important as the concept allows for a link to real-world relevance for ecological concerns (Baveye et al., 2016).

A study completed by Paudyal et al. (2015) sought to distinguish which methods may be used to identify ecosystem services of a forest in a rural region of Nepal. They identified methods such as expert opinion or professional judgment, biophysical and environmental models, user perception, social and community value, visual knowledge/repeat photography, participatory approaches, and use of GIS and remote sensing. Paudyal et al. (2015) determined that interviews with local communities may be the best tool for determining and prioritizing the ecosystem services of that particular region. In a separate study seeking to map ecosystem services, García-Nieto et al. (2013) used a combination of interviews with local stakeholders and existing GIS databases and tools to identify and map ecosystem services in south-east Spain. Crespin and Simonetti (2016) used a broader approach to identify ecosystem services in Ecuador. Using a spatially explicit value transfer framework proposed by Troy and Wilson (2006), they identified ecosystem services digitally and used GIS tools to track changes in land use to estimate losses of natural capital.

Soil properties, including SOC, are a key part in many ecosystems and therefore provide their own inherent ecosystem services. Though there is current global debate and are several different interpretations of ecosystem services categorization exist, it may be generally viewed that ecosystem services can be broadly classified by four categories; regulating, cultural, provisional, or supporting services (Adhikari and Hartemink, 2016; Baveye et al., 2016).

Provisional services are defined by the products gained from an ecosystem which may include fuel, food, fresh water, wood, or fiber (Adhikari and Hartemink, 2016; Baveye et al., 2016). In linking soil properties, all soil properties contribute to providing food, fuel and fiber. Many provide fresh water or water retention, and few soil properties are responsible for providing raw materials or genetic diversity (Adhikari and Hartemink, 2016). When only considering SOC, Adhikari and Hartemink (2016) listed food, fuel and fiber, raw materials, and fresh water or water retention as provisioning services provided by SOC.

Baveye et al. (2016) defines regulating services as the benefits that are gained from just the regulation of ecological processes. In more specific terms, soil properties may be involved with water and gas regulation (atmospheric CO_2), carbon sequestration, water purification, climate regulation, flood controls, erosion, and biological processes (pollination, disease) (Adhikari and Hartemink, 2016). Soil organic carbon plays a particular role in most of the regulating services according to the framework provided by Adhikari and Hartemink (2016).

Supporting services provide a foundation for all other ecosystem services, and as Baveye et al. (2016) states, are necessary for the production of the other ecosystem services. The soil properties identified by Adhikari and Hartemink (2016) related to supporting services include the formation of soil including the weathering of parent material, nutrient cycling, and provisioning of habitat.

Finally, the cultural benefits provided by ecosystem services are non-tangibles benefitting human well-being either esthetically, spiritually, educationally, or recreationally (Baveye et al., 2016). More specifically, cultural services can benefit ecotourism and recreation, inspiration and education, creating a "sense of place", or providing a place for cultural heritage (Adhikari and Hartemink, 2016). Crespin and Simonetti (2016) suggested that only with the valuation of ecosystem services do policy-makers begin to take natural capital of ecosystem services into consideration.

CHAPTER TWO

SOIL ORGANIC CARBON DISTRIBUTION WITH DEPTH: IMPLICATIONS FOR ECOSYSTEM SERVICES

INTRODUCTION

As the largest terrestrial organic carbon pool and the third largest carbon (C) reservoir worldwide, soil organic carbon (SOC) has an important role in the global C cycle (Gray et al., 2015; Song et al., 2016; Stockmann et al., 2013; Weissert et al., 2016). Soil organic carbon stock estimates are important for C sequestration and global change predictions (Wiesmeier et al., 2012; Jandl et al., 2014; Li et al., 2013). The SOC in soil promotes soil health, plant growth, and production (Li et al., 2013; Liu et al., 2015). Therefore, SOC is fundamental to ecosystem services and plays an important part in provisional services (e.g. food, fuel, fiber), regulating services (e.g. climate and greenhouse regulation), cultural services (e.g. recreation, ecotourism), and supporting services (e.g. weathering, soil formation, nutrient cycling) (Stockmann et al., 2013; Gray et al., 2015; Adhikari and Hartemink, 2016).

Variability of SOC within a landscape complicates making estimates of its contributions to ecosystem services (Stockman et al., 2013). Quantifying SOC variability creates challenges for methodologies of soil monitoring, and often requires more extensive soil sampling to accurately estimate SOC stocks (Jandl et al., 2014; Kumar et al., 2013; Roudier et al., 2015; Song et al., 2016). Estimates of SOC concentrations can be enhanced by modelling (Gray et al., 2015; Kumar et al., 2013; Wiesmeier et al., 2012) to account for the variation that exists in soil properties across landscapes and within soil profiles (Orton et al., 2016). Spatial variability of SOC within the landscape is well documented, although standardization is needed for calculating SOC concentrations and SOC variability within a given area (Roudier et al., 2015). Environmental variables such as elevation, slope and topography can play major roles in the content and spatial variability of soil properties, including SOC (Kumar et al., 2013; Liu et al., 2013; Obi et al., 2014). These interrelated variables often complicate attempts to understand and quantify the distribution of SOC (Wells et al., 2012).

Vertical variability of SOC in relation to ecosystem services is somewhat overlooked because many studies do not account for different soil horizons or composite soil horizons together to derive bulk values (Mikhailova et al., 2016). The correlation of physical properties of soil to SOC with depth is an area of particular interest (Wells et al., 2012). However, Wiesmeier et al. (2012) stated that the use of estimates rather than measured data of soil factors such as SOC content, bulk density, and stone content causes a lack of accuracy of SOC inventories. Some research has concluded that investigating SOC by soil horizons rather than fixed depth intervals may provide better accuracy as soil horizons vary in depth across any given location and are subject to different pedogenic processes (Wiesmeier et al., 2012; Orton et al., 2015). Kempen et al. (2011) used three-dimensional mapping of soil matter content using soil type-specific depth functions: constant or exponentially decreasing over depth.

The total depth in which soil properties, including SOC, are measured is largely debated (Olson and Al-Kaisi, 2014; Wells et al., 2011). A review by Stockmann et al. (2013) stated that most soil carbon models do not account for factors that would affect SOC content vertically, and that subsoil (>30 cm) SOC stocks are often not considered in soil carbon estimates. While there is much published research recommending sampling for SOC within 0-30 cm depth, some have questioned how universally suitable that recommendation may be (Wells et al., 2011; Wiesmeier et al., 2012). Many studies state that the majority of SOC is found primarily between 0 to 30 cm because it is the most biologically active (Wells et al., 2011); however, according to Wiesmeier et al. (2012), SOC content is greater than 50% in the subsoils of most ecosystems. Trumbore (1997) stated that of the 1500 gigatonnes of SOC stored in soils, only 250-350 gigatonnes are found in the active carbon pool, within the top 1 m of soil. This indicates that passive SOC found in subsoils make up a large portion of the carbon cycle and may play an important ecological role.

Soils are an important part of many ecosystems, so understanding their role within the concept of ecosystem services may be beneficial. The framework for ecosystem services is becoming increasingly important and thus being adopted by many international and governmental agencies in order to track conservation and sustainable use of soils (Baveye et al., 2016). Few studies have linked ecosystem services to soil properties (Adhikari and Hartemink et al., 2016), but no studies have examined SOC vertical distribution at different scales in relation to ecosystem services. The inherent differences in active and passive fractions of SOC indicate that soil organic carbon at different depths will have different functions in terms of ecosystem services. Baveye et al. (2016) discussed the importance of looking beyond the plow layer (0.25-0.3 m) in order to determine carbon stocks, and stated that deeper soil horizons are responsible for a sizable amount of carbon storage. Furthermore, it has been shown through radiocarbon dating that stability of SOC through time is different in top soils versus subsoils (Rumpel and Kogel-Knabner, 2011).

The aim of this study was to assess the vertical distribution of SOC within the context of ecosystem services. The specific objectives were to: 1) determine SOC distribution with depth in the glaciated soils present at the Cornell University Willsboro Research Farm, NY; 2) evaluate the need for coarse fraction corrections for SOC concentrations in the glaciated soils; 3) compare SOC concentrations in top soil (A horizon) versus subsoil (below A horizon), and 4) determine which soil and landscape parameters statistically explain/predict SOC concentrations with depth.

2. Materials and methods

2.1. Study area

This study was conducted in an area underlain by a lacustrine plain in New York State, USA. Samples used for the study were collected in Upstate New York, specifically at the Cornell University Willsboro research farm located in Willsboro, NY (44° 22' N, 73° 26' W) (Fig. 1). Upstate New York features a humid continental climate with an average annual high temperature is 12.9º C, average annual low temperature of 2.5º C, and an average annual rainfall of 78.7 cm with summer months seeing more average rainfall than winter months. The study area was utilized primarily for agriculture with crop and land cover varying across the farm. The growing season for the region is about 150 days (Mikhailova et al., 1996). Located along Lake Champlain, the property totals 142 hectares in area (Mikhailova et al., 1996). Soil found in the study area (Table 2, Table 3) developed with glacial deposits and are therefore highly variable. The soils included at this site are from three distinct soil orders: Entisols, Inceptisols, and Alfisols.

2.2. Sampling

Fifty-four deep soil cores were sampled on a square grid (Fig. 1), with each cell being 137.16 meters by 137.16 meters in the summer of 1995. Coordinates (NAD27 State Plane Coordinate System's New York East Zone, using Station ESSEX2 and Poke-A-Moonshine L.O.T. and Bench Mark H 395) and elevation values for the 78 grid locations were obtained from a professional land survey team that used an Intelligent Total Station, Set 2C SOKKISHA (Standard deviation: + 3 mm + 2 ppmD) (Mikhailova et al., 1996). Undisturbed soil cores of variable depth were extracted using a Giddings hydraulic sampler (Model – GSR-T-S) and plastic tubes with the average diameter of 4.5 cm (Mikhailova et al., 1996).

2.3. Laboratory analysis

Plastic tubes with soil samples closed with plastic caps were stored vertically in the refrigerator (at approximately 1°C) until processing and analysis (Mikhailova et al., 1996). For each of the soil cores the following information was recorded: upper and lower boundary of soil horizon, moist and dry soil color (Munsell Color Chart), pH, reaction to weak HCl ("0" = no reaction, "1" = presence of effervescence), and coarse fraction (percent of soil sample that was greater than 2 mm fraction. Soil samples were air-dried, manually ground and passed through a 2-mm-mesh sieve. Particle-size distribution of the less than 2-mm fraction was determined by the pipette method after pre-treating for carbonates and soluble salts with 1M NaOAc (adjusted to pH 5), and organic matter was removed with 30% H2O2 (Gee and Bauder, 1986). Soil pH was measured in 1:1 soil/water suspension (Mc Lean, 1982). Organic carbon (C) was determined by dry-combustion spectrometry using a Robo-prep-Tracemass system, Europa Scientific (Cheshire, U.K.). Carbonates were removed from samples that reacted to weak HCl prior to the analysis.

2.4. Statistical analysis

The amount of SOC reported in each sample was corrected for coarse fraction (CF) material using the following equation:

$$SOC, \%\ (CF\ corrected) = SOC, \%\ *\ ((100 - CF, \%)\ /\ 100) \qquad (1)$$

where SOC, % is the laboratory measured percent organic carbon of a given sample, and CF, % is the percent of coarse fracture reported in laboratory analysis of each sample.

The relationship between SOC and SOC corrected for coarse fracture (CF) were evaluated by using Pearson's correlations (p=0.95).

In order to compare top soil and subsoil depth classes, the SOC, % measurements for samples within the subsoil depth class were composited using weighted averaging with the following equation:

$$SOC, \%\ (composited) = \frac{\Sigma(SOC_i, \%)(Depth_i, cm)}{Total\ subsoil\ depth, cm} \qquad (2)$$

where SOC, % is the laboratory measured percent organic carbon of a given sample within the subsoil, depth is the lower boundary for each soil horizon, and total subsoil depth is the sum of the depths of the horizons below A horizon. These calculations were completed using the assumption that bulk density of soils did not vary within the study site and would not affect the results.

Carbon-to-nitrogen (C/N) ratios were completed using the mass ratio as opposed to the atomic ratio. A mixed linear nested model was created using JMP® Software, version 12 (SAS Institute Inc., 2016) to test the significance of soil parameters (depth, pH, land use) against SOC, % as a dependent variable.

3. Results and discussion

3.1. Integration of framework for ecosystem services with organizational hierarchy of soil systems

This study proposed to integrate framework for ecosystem services with organizational hierarchy of soil systems (Table 1) since soil properties have different ecosystem services depending on scale hierarchy (e.g. pedon, polypedon etc.), time (e.g. age of the soil etc.), degree of computation (qualitative or quantitative), and degree of complexity (mechanistic or empirical). In case of study at Willsboro farm, SOC was investigated at soil horizon (i-1), pedon (i), and polypedon (i+1) levels with variable time (e.g. soil orders: Entisols, Inceptisols, and Alfisols; variations in SOC pools with depth) by quantitative methods using both empirical (e.g. distribution of SOC with depth) and mechanistic (e.g. prediction of SOC based on soil depth class, pH, and land use) degrees of complexity.

Ecosystem services provided by SOC are depth-dependent because of the types of SOC within the soil: top soil having more active or labile SOC which experiences higher turnover and subsoil having more slow or passive SOC which is chemically stable (e.g. humus). Top soil SOC plays an important role in provisional (e.g. food, feed, fiber etc.), regulatory (e.g. atmospheric CO2 exchange), and supporting (e.g. soil structure, nutrient retention) services. Meanwhile, subsoil SOC plays a more dominant role in regulatory (e.g. carbon sequestration) services, and somewhat less important in provisional and supporting services. Lawrence et al. (2015) proposed a conceptual framework for depth and time dependent evolution of SOC, where formation, transport and transformation of secondary weathering products were intertwined with SOC cycling, but not with ecosystem services. Tiessen et al. (1994) examined the role of soil organic matter in sustaining soil fertility by comparing agricultural life-spans of soils. They found that agriculture was economically productive for 65 years in temperate prairie ecosystems and for 3 years in tropical rainforest ecosystems, suggesting that managing SOC inputs to the top soil is necessary for prolonging the fertility of a given soil. Understanding the role of SOC to agricultural output is significant in determining the provisional ecosystem services that may be provided by soil (Tiessen et al., 1994).

3.2. Soil organic carbon, nitrogen, and C/N distribution with depth in Entisols, Inceptisols, and Alfisols

Soil organic carbon, N, and C/N decreased sharply with depth from the soil surface to about 40 cm and declined to stable values below that depth in all soil orders (Fig. 2, 3, 5). The decreasing relationship SOC, N, C/N and depth has been documented in previous studies (Wells et al., 2012; Li et al., 2013; Sinoga et al., 2012; Lawrence et al., 2015). According to the United States Department of Agriculture (2011) C/N ratio of around 24 is considered optimal for microbial activity. Fig. 5 indicates that C/N ratios are below 24 in both top and subsoils, increasing the rate of decomposition activities by microorganisms. Fontaine et al. (2007) reported that organic carbon in deep soils remains stable because of a lack of fresh carbon supply, an essential source of energy for soil microbes, thus soil at the surface is relatively unstable. Xu et al. (2016) stated that there is a direct impact of C/N ratios to decomposing microorganisms. Rumpel and Kogel-Knabner (2011) discussed that the radiocarbon age of SOC increases with depth, while SOC and C/N ratios decrease with depth.

3.3. Comparison of bulk and coarse fraction corrected SOC concentrations with depth

Coarse fraction can be important in SOC estimates especially if present in large quantities. Soil organic carbon concentrations were corrected for coarse fraction (CF) and compared against samples not corrected for CF (Fig. 2). Table 2 and Table 3 showed that the highest average CF was found in Inceptisols. This was also evident by comparing graphs of bulk and CF corrected SOC concentrations (Fig. 2a, Fig. 2b). The most noticeable change was observed in Inceptisols, while very little change was seen in Alfisols and Entisols. The five highest individual concentrations (>48%) of CF in cores were found in Alfisols, however low corresponding SOC concentration made the affects CF correction insignificant.

Correlations between SOC and SOC corrected for CF were analyzed by soil order (Table 4). The results showed the strongest correlations in Alfisols and Entisols with r^2=0.99 for both. While Inceptisols correlation was still strong, it's worth noting it was less than that of Alfisols and Entisols with r^2=0.93. Though this data reveals CF may not be a significant influence on SOC concentrations in soils at this site, Wiesmeier et al. (2012) determined CF material in different soil types resulted in overestimation of up to 18% in SOC stock calculations.

3.4. Comparison of SOC distribution in top soil and subsoil

Soil samples were separated into top (A horizon) and subsoil depth classes. The top soil depth class represents the A horizon with an average depth of 23 (±6) cm in Alfisols, 24 (±7) in Entisols, and 27 (±8) in Inceptisols. The thickness of the subsoil depth class by soil order is an average 65 (±26) cm in Alfisols, 65 (±20) cm in Entisols, and 55 (±35) cm in Inceptisols. The SOC % found in the A horizon was active SOC. The lower depth class represents all samples within a core collectively that are below the A horizon and considered passive SOC. In order to make comparisons, the SOC concentrations in the lower depth class were composited by weighing them against the depth of each sample within a core. Top soil (A horizon) contained more SOC (2.2 ± 1.0%) and was highly variable compared to the subsoil (below A horizon), which contained less of SOC (0.4 ± 0.3%) (Fig. 4). The importance of scale, time, and uncertainty in estimating SOC in relation to ecosystem services was discussed by Baveye et al. (2016). The importance of subsoil was highlighted by Weismeier et al. (2012) by stating that subsoil SOC stocks make up almost all of the passive SOC pool. Fontaine et al. (2007) carbon-dated SOC with depth in French grasslands and reported that surface layer was dominated by young fast-cycling carbon compared to subsoil dominated by ancient slow-cycling carbon (passive) suggesting that decomposition was strongly reduced at depth. Fang et al. (2005) investigated the impact of climate change (global warming in particular) on soil-stored carbon and concluded that both labile and resistant soil organic matter will have similar response to changes in temperature. Lehmann and Kleber (2015) argue that traditional view of soil organic matter pools should be replaced with viewing SOM as a continuum of progressively decomposing organic compounds.

3.5. Correlation of SOC with soil depth class, pH, and land use

Based on the results of a mixed linear nested model only depth class (top and subsoil) was found to be significant ($p \leq 0.0001$) in explaining SOC distribution in Entisols, Inceptisols, and Alfisols (Table 5). This is supported by results from Fig. 2 that show definite differences in SOC content with depth. Land use and pH were not significant in explaining SOC distribution with depth, despite the fact that previous research found land use to be significant in predicting SOC distribution and storage (Li et al., 2013; Gardi et al., 2016). The vertical variability of SOC may provide more detailed functions, since active SOC is often found within the top soil and passive SOC found within the subsoil (Trumbore, 1997). The top soil is of great importance for provisional services since it provides habitat, food, fiber, and raw materials (Brady and Weil, 2002). Subsoils contains significant fraction of SOC, but have a greater role in carbon sequestration which falls under regulating ecosystem services (Trumbore, 1997; Wiesmeier et al., 2012). Incorporation of soil depth into SOC ecosystem services framework will benefit the land management and decision making. For example, Comerford et al. (2013) reports that the protection of the soil surface with plant residue and SOC will help to control erosion, increase rainfall infiltration, enhance particle aggregation, increase nutrient supply and biodiversity.

3. Conclusions

This study analyzed differences in SOC and N distribution with depth in glaciated soils of the Upstate New York in the context of ecosystem services. Existing frameworks of ecosystem services for SOC were integrated with organizational hierarchy of soil systems. The vertical SOC distribution was examined quantitatively by soil order and depth class (top soil versus subsoil). Soil organic carbon decreased with depth in all soil orders. Bulk SOC concentration did not statistically differed from SOC with coarse fraction (CF) correction. Top soil (A horizon) contained more SOC and was highly variable compared to the subsoil (below A horizon). Depth class was statistically significant in explaining SOC distribution in all three soil orders. Ecosystem services provided by SOC are depth-dependent because of the types of SOC within the soil: top soil having more active or labile SOC and subsoil having more slow/passive SOC which is chemically stable (e.g. humus). Top soil SOC plays an important role in provisional (e.g. food, feed, fiber etc.), regulatory (e.g. atmospheric CO2 exchange), and supporting (e.g. soil structure, nutrient retention) services. Meanwhile, subsoil SOC plays a more dominant role in regulatory (e.g. carbon sequestration) services, and somewhat less important in provisional and supporting services.

APPENDICES

Appendix A

Figures

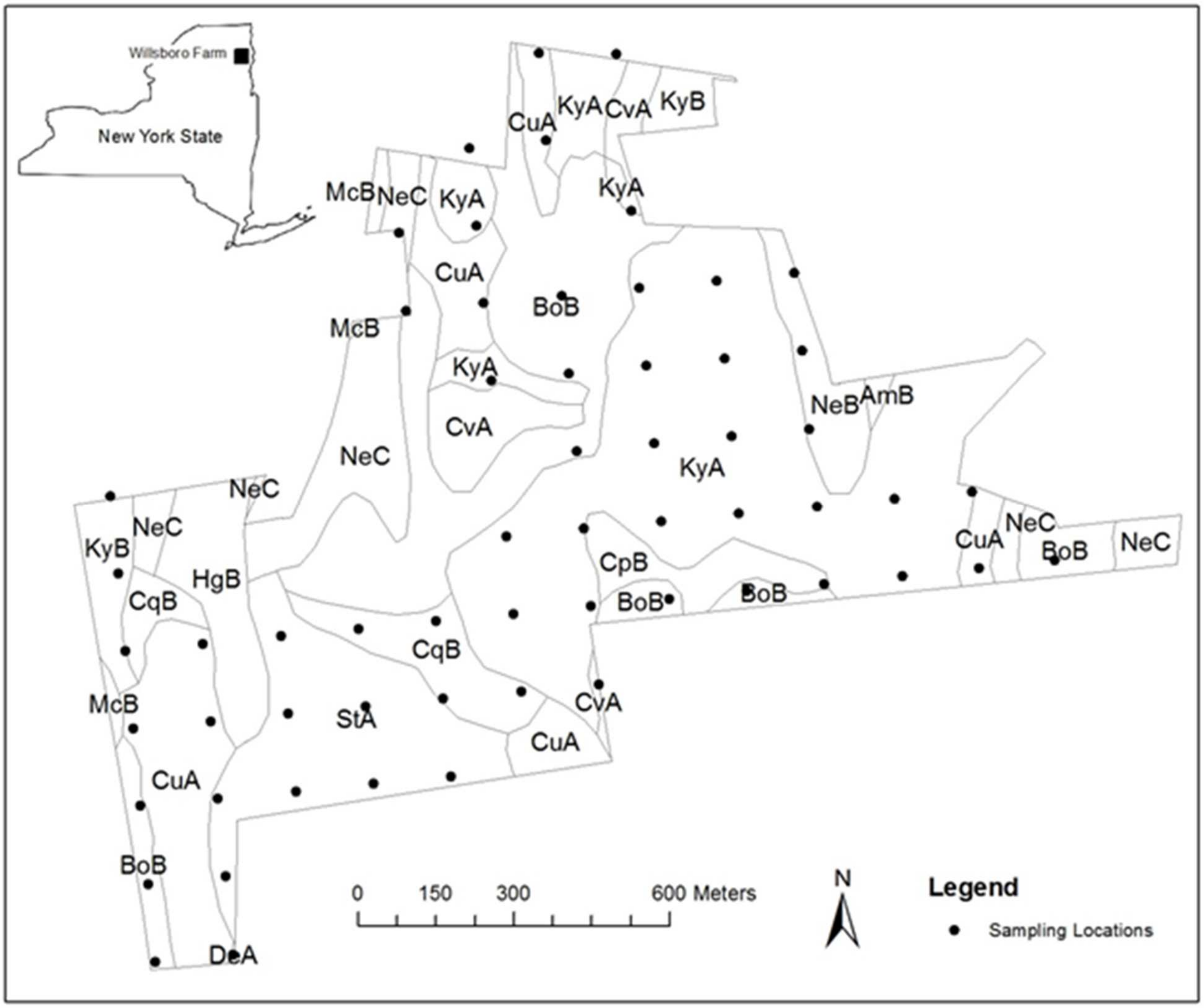

Fig. 1. Map of Willsboro Farm, NY with the following soil types: Howard gravelly loam, 2 to 8 percent slopes (HgB); Bombay gravelly loam, to 8 percent slopes (BoB); Kingsbury silty clay loam, 0 to 3 percent slopes (KyA); Kingsbury silty clay loam, 3 to 8 percent slopes (KyB); Covington clay, 0 to 3 percent slopes (CvA); Churchville loam, 2 to 8 percent slopes (CpB); Cosad loamy fine sand, 0 to 3 percent slopes (CuA); Claverack loamy fine sand, 3 to 8 percent slopes (CqB); Deerfield loamy sand, 0 to 3 percent slopes (DeA); Stafford fine sandy loam, 0 to 3 percent slopes (StA); Amenia fine sandy loam, 2 to 8 percent slopes (AmB); Massena gravelly silt loam, 3 to 8 percent slopes (McB); Nellis fine sandy loam, 3 to 8 percent slopes (NeB); Nellis fine sandy loam, 8 to 15 percent slopes (NeC) (Mikhailova et al., 2016).

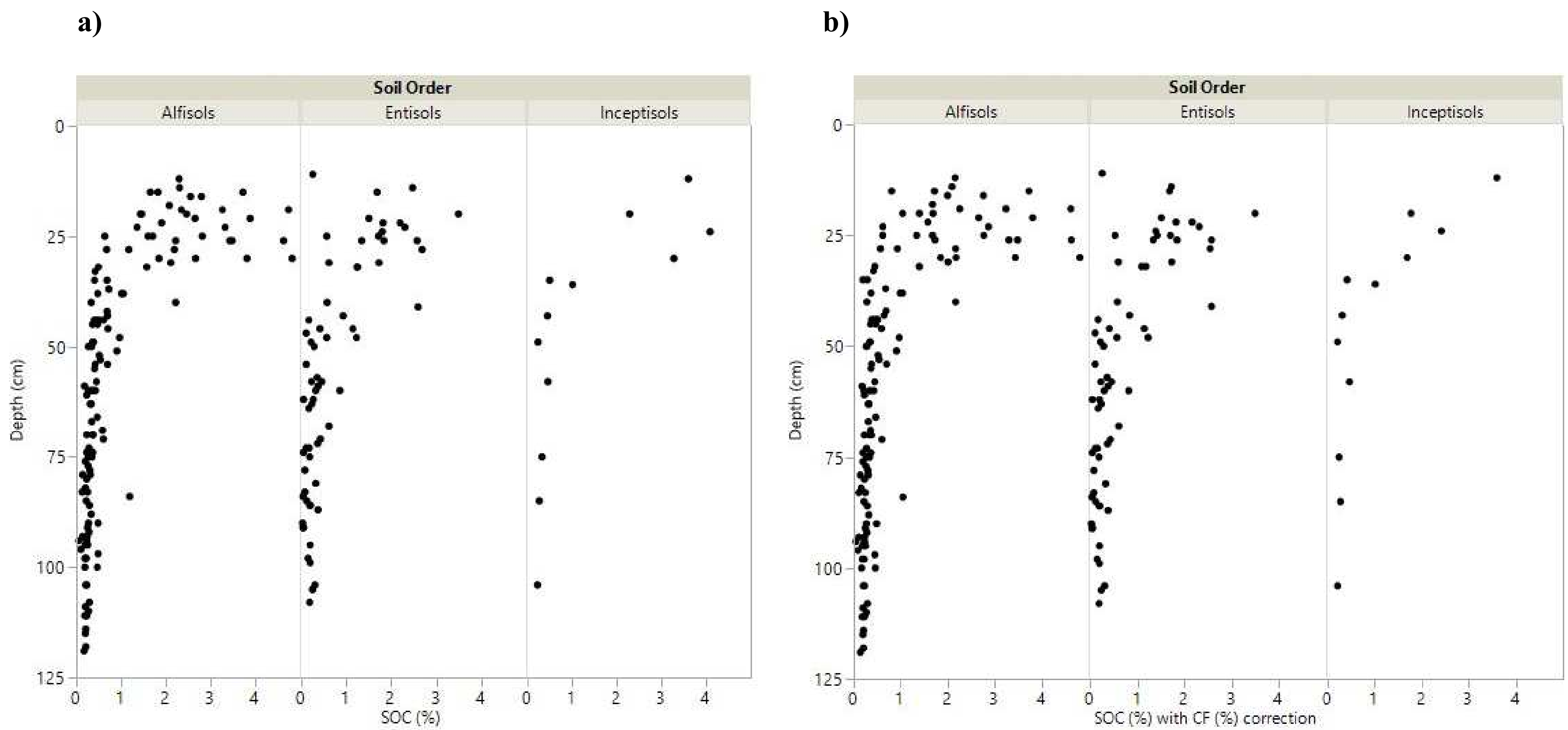

Fig. 2. Soil organic carbon (SOC) distribution with depth (values are reported for the low boundary of sampled horizon) in Entisols, Inceptisols, and Alfisols at polypedon level: a) not corrected for coarse fraction (CF); b) corrected for CF.

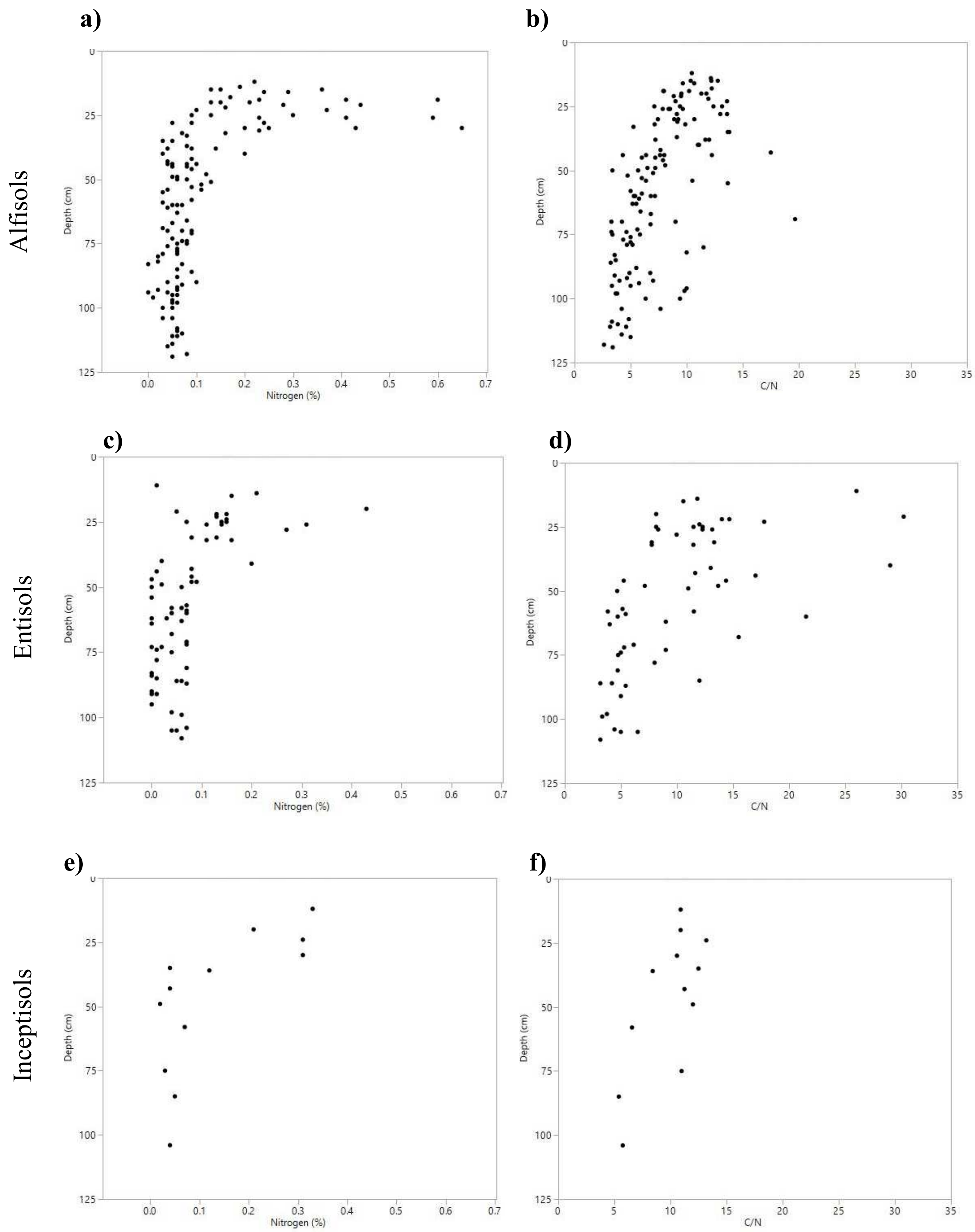

Fig. 3. Total nitrogen (%) concentration with depth and carbon-to-nitrogen (C/N) ratios with depth by soil order: Alfisols (a, b), Entisols (c, d), and Inceptisols (e, f).

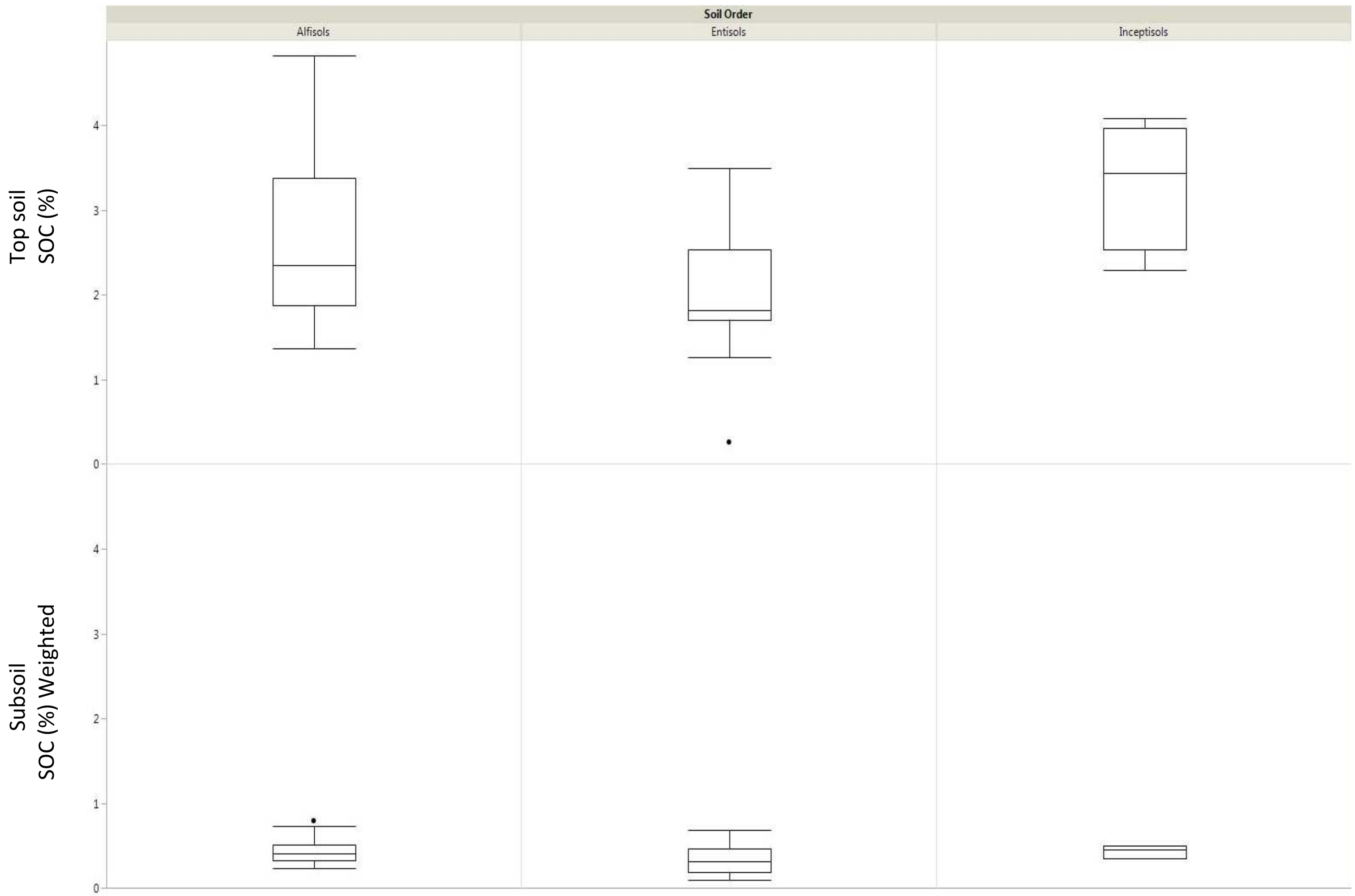

Fig. 4. Soil organic carbon (SOC) distribution by soil order in top soil (A horizon), and subsoil (weighted average).

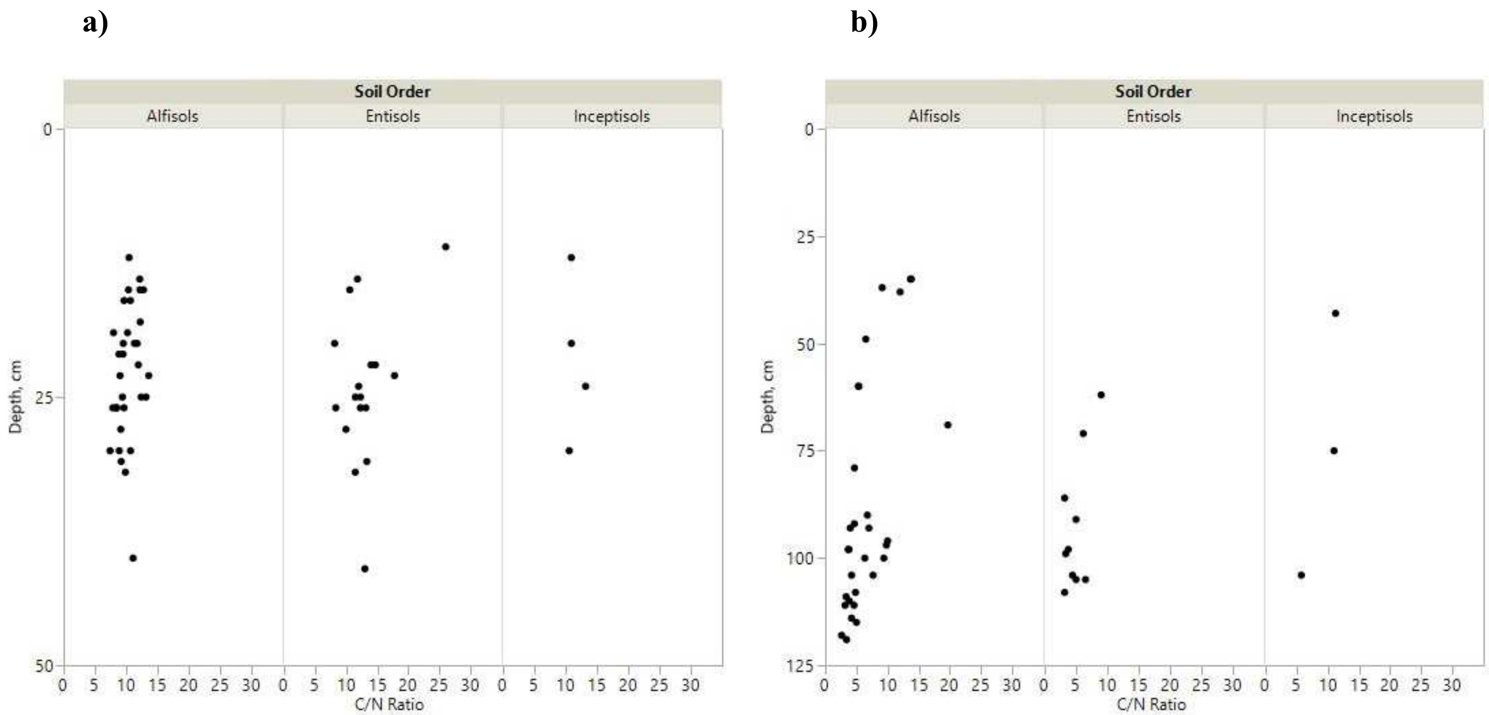

Fig. 5. Carbon-to-nitrogen ratios distribution by soil order in a) top soil (A horizon) and b) subsoil (weighted).

Table 1

Classification of Willsboro soil organic carbon study with depth as it is relates to ecosystem services, scale hierarchy and knowledge type diagram (Dijkerman, 1974; Hoosbeek and Bryant, 1992; Adhikari and Hartemink, 2016).

Organizational hierarchy of soil systems					Framework for ecosystem services			
			Degree of …		Ecosystem services			
System	Scale hierarchy	Time	Computation (qualitative or quantitative)	Complexity (mechanistic or empirical)	Provisional	Regulating	Cultural	Supporting
World	i+6							
Continent	i+5							
Region	i+4							
Watershed	i+3							
Catena	i+2							
Polypedon	i+1	variable	quantitative	both	x	x	x	x
Pedon	i	variable	quantitative	both	x	x	x	x
Soil horizon	i-1	variable	quantitative	both	x	x	x	x
- Top soil (A horizon)		variable	quantitative	both	x	x	x	x
- Subsoil (below A horizon)		variable	quantitative	both	x	x	x	x
Soil structure	i-2							
Basic structure	i-3							
Molecular interaction	i-4							

Table 2

Average A horizon values for thickness, percent soil organic carbon (SOC), soil texture, and percent coarse fraction by soil type and soil order[a] from detailed field study (original core data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol), number of soil cores	Total area	A horizon thickness	SOC[b]	Sand[b]	Silt[b]	Clay[b]	Texture class (number of cores)	Coarse fraction
	m^2	cm	%	-------------------- % --------------------				%
Alfisols (total), n=33	**937940**	**23 ± 6[c]**	**2.7 ± 1**	**45 ± 23**	**23 ± 7**	**32 ± 21**	**LS(2), SCL(5), FSL(5), SL(2), CoSL(3), C(13), CL(1), L(1)**	**11 ± 14**
Bombay gravelly loam, 3 to 8 percent slopes (BoB), n=10	270615	21 ± 5	1.9 ± 0.4	65 ± 11	20 ± 5	14 ± 8	LS(1), SCL(2), FSL(2), SL(2), CoSL(3)	23 ± 18
Churchville loam, 2 to 8 percent slopes (CqB), n =1	36900	18	2.1	59	22	19	SL(1)	19

Covington clay, 0 to 3 percent slopes (CvA), n=1	49076	26	4.6	13	13	74	C(1)	0
Howard gravelly loam, 2 to 8 percent slopes (HgB), n/a[d]	58680	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA), n=19	480679	23 ± 6	3.1 ± 0.9	35 ± 20	26 ± 7	39 ± 16	C(12), CL(1), SCL(2), FSL(2), L(1), LS(1)	6 ± 7
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB), n=2	41990	30 ± 14	1.8 ± 0.6	59 ± 18	21 ± 5	20 ± 13	FSL(1), SCL(1)	2 ± 0
Entisols (total), n=17	**378691**	**24 ± 7**	**2.0 ± 0.7**	**69 ± 27**	**17 ± 13**	**14 ± 19**	**SiL(1), SL(2), L(1), FS(5), FSL(1), LS(2), C(2), S(1), LFS(2)**	**6 ± 10**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB), n=3	64230	31 ± 9	2.3 ± 0.5	62 ± 32	28 ± 21	10 ± 10	SiL(1), SL(1), L(1)	3 ± 3

Cosad loamy fine sand, 0 to 3 percent slopes (CuA), n=6	168530	19 ± 7	1.8 ± 0.8	61 ± 26	18 ± 12	20 ± 20	SL(1), L(1), FS(1), C(1), FSL(1), LS(1)	12 ± 13
Deerfield loamy sand, 0 to 3 percent slopes (DeA), n=1	331	22	2.2	87	10	3	FS(1)	2
Stafford fine sandy loam, 0 to 3 percent slopes (StA), n=7	145600	26 ± 4	2.0 ± 0.8	75 ± 29	12 ± 7	13 ± 22	C(1), LFS(2), FS(3), LS(1)	2 ± 5
Inceptisols (total), n=4	**157764**	**27 ± 8**	**3.3 ± 0.8**	**57 ± 22**	**33 ± 10**	**9 ± 16**	**CL(1), SL(1), CoSL(2)**	**41 ± 22**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB), n/a	3185	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Massena gravelly silt loam, 3 to 8 percent slopes (McB), n/a	8479	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Nellis fine sandy loam, 3 to 8 percent slopes (NeB), n=3	39030	19 ± 6	3.3 ± 0.9	56 ± 27	24 ± 10	19 ± 17	CL(1), SL(1), CoSL(1)	21 ± 20

Nellis fine sandy loam, 8 to 15 percent slopes (NeC), n=1	107070	30	3.3	58	36	6	CoSL(1)	48

[a] Mean values for soil orders are area-weighted averages. SMUs with no soil cores were omitted from the calculations.
[b] Values shown are for < 2 mm size fractions (i.e., not coarse-fraction corrected).
[c] Means $\pm$ standard deviations, unless only one soil core was taken from a specific SMU.
[d] n/a: not applicable. No soil core was taken from the specific SMU.

Table 3
Average subsoil (below A horizon) values for thickness, percent soil organic carbon (SOC), soil texture, and percent coarse fraction by soil type and soil order[a] from detailed field study (original core data from Mikhailova et al., 1996).

Soil order / Soil series (Map unit symbol), number of soil cores	Total area	Subsoil thickness	SOC[b] weighted	Sand[b]	Silt[b]	Clay[b]	Texture class (number of samples)	Coarse fraction
	m^2	cm	%	------------------ % ------------------				%
Alfisols (total), n=32	**937940**	**65 ± 26[c]**	**0.4 ± 0.3**	**25 ± 23**	**33 ± 11**	**42 ± 20**	**SL(2), SCL(1), FSL(10), SiL(1), SiC(19), CoSL(2), C(38), SC(1), CL(11), L(6), SiCL(4)**	**6 ± 10**
Bombay gravelly loam, 3 to 8 percent slopes (BoB), n=9	270615	52 ± 35	0.5 ± 0.2	42 ± 25	31 ± 12	26 ± 17	C(1), CL(2), CoSL(2), FSL(6), L(3), SC(1), SiC(4), SiCL(1), SL(1)	23 ± 18
Churchville loam, 2 to 8 percent slopes (CqB), n=1	36900	51	0.6	58 ± 5	24 ± 4	18 ± 1	FSL(2), SL(1)	22 ± 0

Covington clay, 0 to 3 percent slopes (CvA), n=1	49076	66	0.5	6 ± 4	29 ± 2	65 ± 4	C(4)	0
Howard gravelly loam, 2 to 8 percent slopes (HgB), n/a[d]	58680	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Kingsbury silty clay loam, 0 to 3 percent slopes (KyA), n=19	480679	71 ± 22	0.4 ± 0.1	17 ± 18	35 ± 12	48 ± 18	C(27), CL(9), SCL(1), FSL(2), L(3), SiL(1), SiC(14), SiCL(3)	4 ± 6
Kingsbury silty clay loam, 3 to 8 percent slopes (KyB), n=2	41990	75 ± 9	0.3 ± 0	7 ± 3	30 ± 8	64 ± 10	C(6), SiC(1)	1 ± 2
Entisols (total), n=16	**378691**	**65 ± 20**	**0.3 ± 0.3**	**50 ± 38**	**21 ± 13**	**30 ± 28**	**SiC(2), LS(1), FS(15), FSL(1), C(20), LFS(4), CL(3), S(1), CoSL(1), LVFS(1), VFLS(2)**	**2 ± 4**
Claverack loamy fine sand, 3 to 8 percent slopes (CqB), n=3	64230	57 ± 30	0.3 ± 0.1	39 ± 38	21 ± 10	40 ± 31	FSL(1), CL(1), LS(1), C(3), LFS(1)	2 ± 3

Cosad loamy fine sand, 0 to 3 percent slopes (CuA), n=5	168530	76 ± 17	0.5 ± 0.2	35 ± 35	26 ± 13	39 ± 25	SiC(1), CL(2), FS(4), C(10), LFS(1)	2 ± 3
Deerfield loamy sand, 0 to 3 percent slopes (DeA), n=1	331	69	0.6	79 ± 13	18 ± 10	4 ± 4	FS(1), S(1), LFS(1), VFSL(1)	0
Stafford fine sandy loam, 0 to 3 percent slopes (StA), n=7	145600	60 ± 18	0.3 ± 0.1	60 ± 38	17 ± 13	23 ± 27	C(7), CoSL(1), LFS(1), FS(10), SiC(1), LVFS(1), VFSL(1)	2 ± 6
<u>Inceptisols (total), n=3</u>	**157764**	**55 ± 35**	**0.4 ± 0.1**	**37 ± 29**	**32 ± 13**	**31 ± 18**	**C(1), SiC(3), FSL(2), SCL(1), SL(1)**	**12 ± 13**
Amenia fine sandy loam, 2 to 8 percent slopes (AmB), n/a	3185	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Massena gravelly silt loam, 3 to 8 percent slopes (McB), n/a	8479	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Nellis fine sandy loam, 3 to 8 percent slopes (NeB), n=3	39030	**55 ± 35**	0.4 ± 0.1	37 ± 29	32 ± 13	31 ± 18	C(1), SL(1), FSL(2), SCL(1), SiC(3)	12 ± 13

Nellis fine sandy loam, 8 to 15 percent slopes (NeC), n/a	107070	n/a	n/a	n/a	n/a	n/a	n/a	n/a

[a] Mean values for soil orders are area-weighted averages. SMUs with no soil cores were omitted from the calculations.
[b] Values shown are for < 2 mm size fractions (i.e., not coarse-fraction corrected).
[c] Means ± standard deviations, unless only one soil core was taken from a specific SMU.
[d] n/a: not applicable. No soil core was taken from the specific SMU.

Table 4

Pearson correlation (r) of SOC (%) with SOC (%) corrected for CF (%) across the total site depth, the upper depth class, the lower depth class, and by soil order (p-values in parentheses).

Parameter	SOC (%) vs. SOC (%) corrected for CF (%)
Total soil profile	
Alfisols	0.99 (<0.0001)
Entisols	0.99 (<0.0001)
Inceptisols	0.93 (<0.0001)
All soil orders	0.98 (<0.0001)
Upper soil class (top soil)	
Alfisols	0.98 (<0.0001)
Entisols	0.96 (<0.0001)
Inceptisols	0.51 (0.4983)
All soil orders	0.93 (<0.0001)
Lower soil class (subsoil)	
Alfisols	0.98 (<0.0001)
Entisols	0.99 (<0.0001)
Inceptisols	0.98 (<0.0001)
All soil orders	0.99 (<0.0001)

Table 5

ANOVA results for final mixed linear nested model.

Dependent variable	Independent variable	Df[a]	F value[b]	Pr (>F)
		Alfisols		
SOC (%)	Soil depth (depth class)	54	102.77	<0.001
	pH	54	0.65	0.4234
	Land use	54	1.24	0.2931
		Entisols		
SOC (%)	Soil depth (depth class)	17.7	55.01	<0.001
	pH	9.7	0.50	0.4951
	Land use	6.7	0.58	0.7834
		Inceptisols		
SOC (%)	Soil depth (depth class)	3	22.55	0.0177
	pH	3	0.22	0.6725
	Land use	3	0.10	0.7718

[a] The degrees of freedom are using an approximation method accounting for heterogeneity of variances.
[b] Numerator degrees of freedom are always 1.

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