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Organic carbon sequestration in mineral soil layers of cold-temperate mixed forests

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The aim of this study is to analyze the concentration of soil organic carbon (SOC) and C stocks in cold-temperate mixed forests in southern Québec, Canada. More specifically, the analysis deals with SOC concentrations and C stocks with respect to other key soil properties and environmental factors (such as soil pH, nitrogen, texture, structure, bulk density, litter thickness, drainage), including vegetation data (such as stems density, tree diameter and basal area). There are a total of 68 sampling sites across the various study sectors, including the collection of 109 soil mineral samples. The results indicate that SOC concentration and soil C stocks are high on average, ranging from 3.31 ±1.49 to 5.88 ±3.95% (SOC) and 70 to 114 t ha^{-1} C stocks, respectively. The results of the Principal Component Analysis (PCA) reveals that the texture of soils is the variable with the greatest differentiation among the sites, as well as soil acidity, nitrogen, litter thickness and topography. According to the multiple linear regression analysis, the two variables that result from the model are soil acidity (pH) and sand (%), which account for 33.2% of C stock variance.

Key words: Soil Organic Carbon (SOC), C stocks, soil properties, environmental factors.

INTRODUCTION

In the context of global climate warming, there is growing interest in the scientific literature on soils and their capacity to retain and store organic carbon (Pan et al., 2011; Powlson et al., 2011; Scharlemann et al., 2014). In fact, soil as a carbon reservoir is one of the solutions being considered by the scientific community to reduce atmospheric CO_2 and global warming (IPCC, 2018). It is estimated that global soil C stocks are approximately 1500 × 10^9 t (FAO, 2017), more than twice the quantities measured in the atmosphere. It is known that soil organic carbon (SOC) is the principal carbon pool in several terrestrial ecosystems (Fan et al., 2016; Joseph et al., 2018), and it is believed that close to 40% of the world's SOC is found in forest ecosystems (De Marco et al., 2016). In this regard, forest ecosystems constitute high-potential sites for soil carbon sequestration.

Different studies show that SOC concentrations are controlled by multiple soil properties and environmental

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parameters (Gabriel and Kellman, 2014; Ramage et al., 2019) that can vary depending on the ecosystems and environments. Parental material, soil type, texture and structure, and soil acidity, drainage, slope, for instance, may constitute key elements that explain SOC concentrations (Gray et al., 2016). Under a forest canopy, organic matter mainly comes from vegetation, which provides over 75% of the soil litter (Mao et al., 2019). This forest biomass is often highly varied and consists of dead leaves, twigs, needles, moss, herbaceous plants, branches and dead fallen trees, not to mention the belowground biomass made up of fine roots, humus and various soil microorganisms (Nielsen et al., 2011; Tu et al., 2020). The decomposition rate of the organic matter depend on a multitude of factors, including site conditions, litter quality and quantity (Bradford et al., 2016), and microbial activity (Cleveland et al., 2014). It is known that these organic compounds break down more or less rapidly depending on their composition, and that microbial activity is itself subject to site conditions (Paul et al., 2016; Smyth et al., 2015; Yang et al., 2019). Litter quality is often the determining factor in the decomposition rate of organic matter (Bradford et al., 2016; Ge et al., 2013). Also, it has been noted that the highest concentrations of SOC are generally found in surface mineral layers and tend to progressively decrease toward the base of the profile (Chai et al., 2015). The breakdown of this organic material will evolve in the form of humus forming aggregates of various sizes (macro- and microaggregates) that help stabilize the humic colloids in the soil (García-Palacios et al., 2013; Djukic et al., 2018). These aggregates, often qualified as organo-mineral complexes, are generally more abundant in forest soils. Microorganisms and earthworms also contribute to the cohesion of these aggregates by producing sticky mucilage that increases their adherence (Krause et al., 2019; Redmile-Gordona et al., 2020).

To better understand the interactions between soils and environmental factors that affect SOC concentrations and C stocks, a set of physical and chemical soil properties often need to be considered, along with the associated environmental conditions (Gabriel and Kellman, 2014; Nielsen et al., 2011). A study of these parameters on a local or subregional scale appears to be necessary to determine indicators and characterize the key factors related to soil organic carbon (Conforti et al., 2016; Hou et al., 2020). The aim of this study is to analyze SOC in the mineral soils of cold-temperate mixed forests located in southcentral Québec (Canada). The study area covers the Coaticook (COA), Massawippi (MAS) and Saint-François (STF) river watersheds. More specifically, the analysis deals with variations in SOC concentrations and C stocks with respect to other key soil properties and environmental factors (such as soil pH, nitrogen, texture, structure, bulk density, litterfall layer thickness, parent material, drainage, slope inclination), including vegetation data (such as stem density, tree diameter and basal area), in order to better characterize all the environmental conditions of the sites under study. The relationship between SOC concentrations and C stocks with edaphic and environmental variables will enable the key factors to be identified that best explain variations in SOC in mineral soil layers under a mixed forest cover.

MATERIALS AND METHODS

Description of the study area

The study area is part of a vast drainage basin that extends from the south shores of the St Lawrence River to northern Vermont in the United States. The St Lawrence Lowlands and the Appalachian Mountains are the two major physiographic divisions that characterize this drainage basin (COGESAF, 2014). The basin is crossed by many rivers, the main ones being the Coaticook, Massawippi and Saint-François rivers. The mean annual flow of these rivers can attain a maximum average discharge of 67, 131 and 1087 m^3/s, with peak discharges of 135, 223 and 2018 m^3/s, respectively (MDDELCC, 2019). Large plains or low terraces made up of ancient or recent alluvial sediments, and glacial deposits, glaciolacustrine sediments or reworked glacial tills and rocky outcrops are found at higher elevations (MERN, 1976; 1984). Glaciolacustrine sediments are mainly found in the Coaticook, Massawippi, Richmond and Windsor sector, followed by glacial till and rocky outcrops. The Drummondville sector contains more fluvial deposits and deltaic sediments on high terraces. All the parental materials were determined from the maps of superficial deposits produced by the Ministry of Energy and Natural Resources (MERN, 1976; 1984). Forest soils mainly consist of Orthic Dystric Brunisol (O.DYB) and Orthic Sombric Brunisol (O.SB), and podzol soils such as Humo-Ferric Podzol (O.HFP) and Orthic Ferro-Humic Podzol (O.FHP) (Lavoie et al., 2006). The region is characterized by a humid continental climate with average annual precipitation of 1113.5 mm, with deviations varying depending on the time of year (MDDELCC, 2019). The average annual temperature recorded between 1981 and 2010 ranges from 5.6 to 6.3°C based on the data recorded in the meteorological stations. Annual precipitation rates range from 1107 to 1185 mm (1981-2010). Temperature and precipitation values are comparable and do not show large variations between the various stations (Table 1).

In this region characterized by a cold temperature climate, the forest areas are mainly characterized by mixed stands made up of sugar maple (*Acer saccharum* L.), red maple (*A. rubrum* L.), black ash (*Fraxinus nigra* Marsh.), yellow birch (*Betula alleghaniensis* L.), balsam fir (*Abies balsamea* Mill.), white cedar (*Thuja occidentalis* L.), and eastern hemlock (*Tsuga canadensis* L.) (MRNFF, 2007). Roughly the same species of trees were found in so-called pre-colonial forests (PRDIRT, 2015). Present-day forests have regenerated naturally following tree felling that occurred at the turn of the last century (1880-1920), which affected several regions in southcentral Québec (PRDIRT, 2015). These forests now cover 75% of the land (COGESAF, 2014) and are part of the agroforestry landscape that characterizes this region.

Sampling sites

The sampling sites were located in natural forests in the Coaticook, Massawippi and Saint-François river watersheds (between 45° 17`N; 71°50`W; 45°49`N; 72°15`W). There are a total of 68 sampling sites (surface unit 10 × 20 m) in various study sectors, including 109 mineral soil samples (Table 2). The geographical coordinates for the sampling sites were recorded on digital maps using GPS points (Universal Transverse Mercator coordinates), and

Table 1. Temperature and precipitation based on Climate Normal Data (1981-2010) in the study area, southern Québec, Canada.

Meteorological stations[1]	Annual temperature (°C)(1981-2010)			Annual precipitation (mm) (1981-2010)
	Min	Max	Mean	Total
Caoticook (7021840)	0.8	10.6	5.7	1181.4
Drummondville (7022160)	1.6	11.1	6.3	1107.3
Richmond (7026465)	0.2	11.0	5.6	1185.0

1Source: MDDELCC (2019).

Table 2. Distribution of sampling sites in the study area in southern Québec, Canada.

River	Sector	Code	Number of sites and soil samples [1]
Coaticook	Coaticook	COA	27 (n = 27)
Massawippi	Massawippi	MAS	10 (n = 20)
Saint-François	Drummondville	DRU	8 (n = 16)
Saint-François	Richmond	RIC	17 (n = 34)
Saint-François	Windsor	WIN	6 (n = 12)
Total			68 (n = 109)

[1]Sampling sites include double soil samples, excluding COA sector.

digital photographs were taken at each site. Soils were collected and trees identified and measured in the same sampling sites during the summer (2012 and 2016 in COA sector). The soil samples were collected to a depth of 0-20 cm using a one-piece metal auger (Edelman-Eijkelkamp model) and placed in numbered Ziploc® bags. Besides the soil samples, data on topographic characteristics and edaphic conditions were recorded (such as microtopography, slope (%), drainage class, soil texture and structure, litter thickness (cm), and Munsell color). The data were gathered and recorded using the Canadian System of Soil classification (CSSC, 1998).

Soil bulk density (BD)

To measure bulk density, soil samples were collected in the uppermost layer of the profile at a depth of 0-20 cm. The samples were collected using a rigid metal tube. The soil samples were weighed in the laboratory wet and then dry. The dry weight of a unit volume of soil provides the bulk density (BD), with the proportion of solid particles and porous spaces (Rawls, 1983).

Soil analysis

Soil samples were analyzed in the soil laboratories to characterize their physical and chemical parameters (such as particle size, soil pH, SOC). For the particle size analyses, the dry sandy fraction (>2 mm) was obtained by sieving, and the fine particles (<2 mm) were analyzed using a laser particle sizer (Fritsch "Analysette 22" MicroTec Plus), with an interval class ranging from 0.08 to 2,000 microns. The texture classes are those found in the Canadian System of Soil Classification (CSSC, 1998), and correspond to those of the FAO international system (FAO, 2015). Chemical analyses were performed in an external laboratory (Université Laval, Québec), including acidity (pH), total soil organic carbon (SOC), and total nitrogen (TN), in accordance with the analytical standards of the Soil Sampling and Methods of Analysis (Carter and Gregorich, 2008). A 1:2 soil-solution ratio ($CaCl_2$ 0.01 M) was used to determine the pH of the soil samples, and the liquid solution was measured with pH meter electrodes (Carter and Gregorich, 2008). SOC and TN were determined with a TruMac Series (Leco) analyzer, which allows for fast readings with minimum quantities of soil. In the laboratory, the soil sample (~1.5 gr) was placed on a ceramic plate and loaded into the purge chamber. After the entrained atmospheric gas was purged from the sample, the ceramic plate was introduced into the furnace controlled at a temperature of 1100° to 1450°C. The remaining combustion gases were collected and equilibrated in ballast, where an aliquot was taken for carbon and nitrogen determination. The whole procedure is described in leaflet 11/12-REV9 (Leco Corporation, 2012).

Soil organic carbon (SOC) and C stocks

SOC concentrations and bulk density (BD) were used to determine the C stocks for the samples collected in the mineral layers. The method developed by Tremblay et al. (2002) was used, which was applied to forest stands. The equation is:

$$Q = C \times Bh \times Th \tag{1}$$

where, Q = Quantity of organic C in the horizon ($t\ ha^{-1}$); C = Concentration of organic C in the horizon (%); Bh = Bulk density of the horizon ($g\ cm^{-3}$); Th = Thickness of the horizon (20 cm), excluding coarse particles >2 mm.

Litterfall layers and tree measurements

To assess the ground biomass in the sampling sites, litter thickness was measured using a metal ruler (cm) at the four corners and litter composition was characterized (such as dead leaves, twigs, moss). Branches or dead tree trunks on the ground were excluded from the measurements. The tree inventory included the identification and number of tree species and their diameters at breast height (dbh: 1.3 m) in each sampling site. The diameter of the trees was measured with a circumferential tape (Forestry Supplies Inc, Jackson, MS), and stems over 1 m in height were included in the total number of trees in each sampling site. To determine the age of the trees, cores were collected from two or three individuals with the largest diameters in each sampling site. Tree cores were analyzed in an external laboratory (Tree-ring Laboratory, Université Laval, QC).

Statistical analysis

Descriptive statistics and analyses as well as statistical tests were applied to the soil data and environmental variables. All the data were compiled in Excel files and processing and statistical analysis were done using R statistical software (R Development Core Team, 2014), with a confidence interval of 95% (p = 0.05). A principal component analysis (PCA) was performed on soil properties and environmental variables on the correlation matrix to show the most significant variables that differentiate the sites. The Pearson coefficient was used to measure the level of correlation between SOC concentrations and C stocks in soil samples. Multiple linear regression analysis was applied to attempt to explain C stock variations using several variables (such as pH + TN% + C:N + clay% + silt% + sand% + slope% + drainage + litter thickness + stem density + basal area). The forward selection of variables was applied, and at each stage of the analysis, the variable most closely related to the C stocks was added to the model, provided that the variable was statistically significant. The model was validated through the normality of residuals, the homogeneity of the residual variance, and the lack of observations that could skew the model (Distance de Cooks; *in* Cook, 1977).

RESULTS

Parent material and soil properties

The soils that were sampled in the COA sector are mainly found on steep terrain with a prevalence of glaciolacustrine sediments (Table 3) over till or bedrock (MERN, 1984). More than 70% of the soils collected in the COA sector are found on steep slopes (~30-45%). For the other sectors, close to half the sites are on moderately to steeply sloped terrain (~15-30%), and the soil is most often made up of fine materials (such as glaciolacustrine sediments). Soils in the DRU sector mainly consist of fluvial or deltaic deposits (MERN, 1976). The pH values obtained for the soils (0-20 cm in depth) show some differences between the sectors. The soil pH ranged from strongly to moderately acidic, with values of 2.66 to 5.71. The soils in the DRU sector had the highest acidity levels, and the least acidic soils were found in the COA sector (Table 3). The minimum and maximum values of the TN concentration in the mineral layer ranged from 0.19 ± 0.1% to 0.30 ± 0.2%. The TN values were equivalent (0.21 ± 0.12 to 0.26 ± 0.11%) in the DRU, RIC and WIN sectors, with the largest differences (0.19 ± 0.07 to 0.30 ± 0.16%) found between the MAS and COA sectors. The C/N ratio was equivalent between the different sectors. The most marked differences ranged from 13.67 to 19.26 for the RIC and COA sectors, respectively. In terms of texture, most of the soil samples analyzed were made up of sandy loam or loamy sand. The dominant matrix mainly consisted of silt and fine to very fine sand (Table 3), with a very small proportion of clay fraction (mean of ~3 %). The mean bulk density of the soils ranged from 0.65 ± 0.11 to 0.14 ± 0.20 g cm^{-3}. The highest values were found in the soils in the DRU, RIC and WIN sectors.

Litterfall composition

The litterfall composition is determined by the dominant tree species; in this instance the hardwoods that provide most of the soil biomass for the sites. This litter can reach maximum thicknesses of 10 and 13 cm, although mean thickness values of about 4 to 6 cm were measured (Table 3). The litter thickness values were relatively comparable from one sector to another. The litter mainly consists of an initial layer of dead leaves showing little or no decomposition (L layer). Under this first layer, there is usually a fabric layer (F layer) that is partially decomposed and found over a thin humic layer (H layer) that rarely exceeds one centimetre in thickness. Besides the layer of dead leaves that constitutes most of the organic debris on the ground, litter can contain twigs, a few needles, dry herbaceous plants, ferns and mosses.

SOC concentration and C stocks

The highest SOC concentrations in mineral layers were found in the COA sector (mean value of 5.88 ± 3.95%), followed by the WIN sector (mean value of 4.26 ± 1.61%) (Table 4). For the coefficient of variation (CV%), which indicates the dispersion of values around the mean, the highest SOC value came from the COA sector (67%) and the lowest from the WIN sector (41%). For the coefficient of skewness and kurtosis, the highest values are found in the COA and MAS sectors (Table 4). The soil C stocks in surface layers (0-20 cm depth) ranged from 70.49 ± 35.17 to 114.33 ± 56.36 t ha^{-1}. Except for the COA and MAS sectors, the values are comparable (from 70.49 ± 35.17 to 98.00 ± 57.60 t ha^{-1}). A high correlation was noted (r = 0.729) between the SOC (%) and C stock variables for most of the soils in all the sectors, except for a few extreme values (Figure 1).

Tree data compilation

Table 5 presents a compilation of the dominant trees inventoried for all the sectors. Balsam fir (*Abies balsamea* (L.) Mill.), maple red (*Acer rubrum* L.), maple sugar (*Acer saccharum* L.), yellow birch (*Betula alleghaniensis* L.), black ash (*Fraxinus nigra* Marsh.), and eastern helmlock

Table 3. Properties of soil mineral layers and environmental variables of the sampling sites.

Sector /Variables	COA	MAS	DRU	RIC	WIN
Clay (%)	4.73 ± 5.56	3.09 ± 2.39	2.52 ± 5.57	1.71 ± 0.53	2.05 ± 0.68
Silt (%)	47.89 ± 11.52	53.56 ± 19.34	43.28 ± 11.53	45.03 ± 12.30	43.89 ± 7.55
Sand total (%)	47.39 ± 13.44	43.35 ± 21.54	54.20 ± 13.34	52.75 ± 13.91	54.06 ± 8.19
Very fine sand (50-100 µm)	28.51 ± 5.42	23.83 ± 3.52	30.64 ± 7.79	28.62 ± 5.64	30.81 ± 3.93
Fine sand (100-250 µm)	16.21 ± 8.32	17.79 ± 5.95	20.45 ± 11.41	21.51 ± 8.83	20.90 ± 5.80
Medium + coarse sand (>250 µm)	2.67 ± 4.44	1.73 ± 4.83	3.11 ± 2.57	2.62 ± 3.50	2.35 ± 3.66
Soil acidity (pH)	4.21 ± 0.86	4.03 ± 0.65	3.43 ± 0.42	4.11 ± 0.74	3.88 ± 0.34
Soil organic carbon (%)	5.88 ± 3.95	3.31 ± 1.49	3.66 ± 2.16	3.51 ± 1.66	4.24 ± 1.74
Soil total nitrogen (%)	0.30 ± 0.16	0.19 ± 0.07	0.21 ± 0.12	0.26 ± 0.11	0.24 ± 0.09
C/N ratio	19.26 ± 4.13	17.04 ± 2.90	16.27 ± 4.31	13.67 ± 2.72	17.76 ± 4.53
Bulk density (g cm^{-3})	0.69 ± 0.22	0.65 ± 0.11	1.11 ± 0.17	1.12 ± 0.17	0.14 ± 0.20
Soil structure	Granular	Granular	Granular/particular	Granular	Granular/particular
Surface drainage	1 to 4	1 to 5	3 to 4	3 to 4	3 to 4
Slope (%)	1 to 6	1 to 5	1 to 4	3 to 4	1 to 5
Material parental	GS, GS/R	GS, GS/R	DS, FD	GS, UT, UT/R	GS, GS/R
Litter thickness (cm)	3.74 ± 2.31	3.46 ± 2.18	2.60 ± 2.03	3.34 ± 2.93	4.45 ± 2.13
Litter composition (death leaves represent >80% in all sites)	Dead leaves, twigs needles	Dead leaves, twigs, mosses	Dead leaves, twigs, needles	Dead leaves, twigs, mosses, needles	Dead leaves, twigs
Mean tree density (trees/ha)	3600	2200	3400	2800	1800
Mean basal area (m^2/ha)	209	308	129	280	398

Soil samples collected at depth of 0-20 cm (total n = 109). Values represent means ± SD.
Drainage: 1=Excessive; 2=Excellent; 3=Good; 4=Moderate.
Slope: 1=0.0-0.5%; 2=0.5-2%; 3=5-10%; 4=10-15%; 5=15-30%; 6=30-45%.
Material parental: DS: Deltaic sediments; FS: Fluvial deposits; GS: Glaciolacustrine sediments; GS/R: Glaciolacustrine sediments on rock; UT: Undifferentiated tills; UT/R: Undifferentiated tills on rock. (Note: All of these variables were used for statistical analyzes).

(*Tsuga canadensis* L.) are the dominant species. Most of the inventoried sites consist of small- to medium-diameter trees (<30 cm dbh), with a low number of mature trees. The largest individuals (>30 cm dbh) are mainly represented by species such as Tsuga canadensis and Acer saccharum, and trees less than 30 cm are mainly represented by Abies balsamea, Fraxinus nigra, and Thuya occidentalis. The oldest individuals that were inventoried are between 83 and 102 years of age. With respect to tree density and mean basal area (BA) measurements, the mean values vary between 1800 to 3600 trees/ha and 209 to 398 m2/ha, respectively. The highest density values were found in the COA sector and the lowest in the WIN sector. Conversely, the highest mean BA values are in the WIN sector and the lowest in the DRU sector. Lastly, the diameter structure shows an overabundance of stems under 30 cm (dbh), which is attribuable to overfelling in 1880-1920, as well as natural disturbances such as windthrow (PRDIRT, 2015).

Multivariate analysis on soil and environmental data

The principal component analysis (PCA) results that were obtained on the correlation matrix for soil and environmental data show that the principal

Table 4. Descriptive statistics of soil organic carbon (SOC) concentrations and C stocks in mineral soil layers (0-20 cm).

Sector	SOC (%)	CV%	Coefficient of skewness	Coefficient of kurtosis	Soil C stocks (t ha^{-1})	Soil C stocks (t ha^{-1}) (min-max)
COA	5.88 ± 3.95	67.15	1.83	2.73	70.49 ± 35.17	4.10-177.63
MAS	3.31 ± 1.49	45.32	1.56	3.85	114.33 ± 56.36	62.00-174.01
DRU	3.51 ± 5.85	59.06	0.51	-0.94	98.00 ± 57.60	36.01-162.00
RIC	3.51 ± 1.66	47.29	0.99	1.74	77.66 ± 34.28	24.03-166.60
WIN	4.26 ± 1.61	41.04	0.49	-0.64	81.42 ± 24.38	56.14-120.54

Values represent mean ± SD, and percentage.

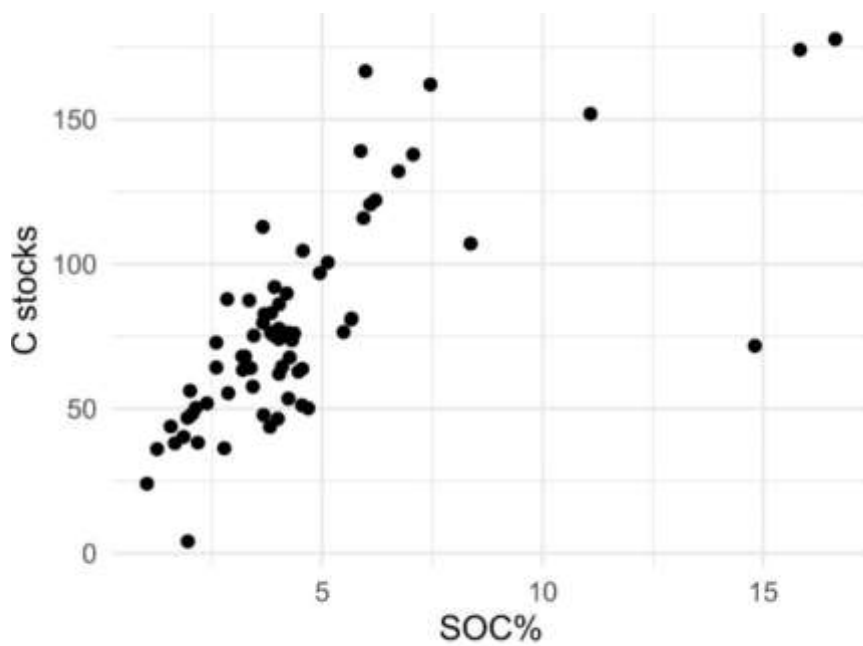

Figure 1. Pearson correlation graph between SOC% and C stocks t ha^{-1} in mineral soil layers at a depth of 0-20 cm (r = 0.729).

Table 5. Data on dominant tree species inventoried in the sampling sites in all sectors.

Tree species (n = 1433) and sectors	COA	MAS	DRU	RIC	WIN	<30 cm	>30 cm
Abies balsamea L. (Mill.)	83	43	129	36	14	300	5
Acer rubrum L.	87	85	22	17	36	239	8
Acer saccharum L.	125	29	5	2	5	150	16
Betula alleghaniensis L.	164	2	5	8	6	173	12
Fraxinus nigra Marsh.	162	66	15	0	0	241	2
Thuja occidentalis L.	81	7	0	0	7	91	4
Tsuga canadensis L.	97	44	47	2	2	175	17
Number of tree species	799	276	223	65	70	1369	64
Mean tree density (trees/ha)	3600	2200	3400	2800	1800	–	–
Mean basal area (m^2/ha)	209	308	129	280	398	–	–
Tree diameter <30 cm (dbh in cm)	739	263	208	57	59	1326	–
Tree diameter >30 cm (dbh in cm)	60	13	15	8	11	–	107
Age of oldest trees (yrs)	91	98	83	102	92	–	–

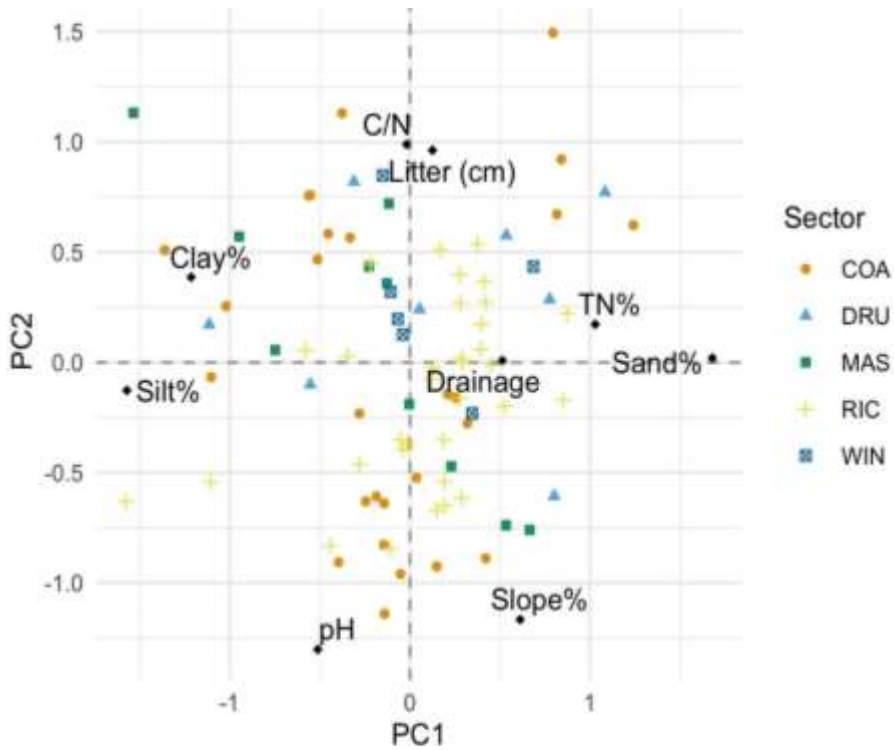

Figure 2. Graph of the principal component analysis (PCA) based on soil properties and environmental variables (Litter thickness (cm), Slope, Drainage). The two main axes (PC1 and PC2) explain 51% of the variation.

axis (PC1) is represented by the silt%+clay% variables on one side of the graph and the sand% variable on the other side (Figure 2). This shows that surface soil grain size composition is a key variable for explaining the most marked differences between the sites. The second axis (PC2) is represented by the C/N + litter thickness (cm) variables on one side of the graph and the pH + slope (%) variables on the other. The two axes (PC1 and PC2) represent 51% of variability. To represent 95% of data variability, a total of seven axes were required (not illustrated). According to the multiple linear regression analysis performed on the matrix containing the soil and environmental data, two variables resulted from the model, that is soil acidity (pH) and sand (%) (Figure 3). These two variables account for 33.2% of C stock variance. Note that these two variables are the same as those obtained from the first two PCA axes carried out on the data matrix, which supplements the accuracy of the analysis results.

DISCUSSION

Variability of soil properties

The main soil properties that show some variability between the various study sectors are texture, acidity, organic carbon and nitrogen. The PCA results on the data correlation matrix reveal that the principal axis (PC1) is represented by the texture variables (silt + clay and sand), which indicates that grain size composition is the variable that differentiates one site from another the most. The textural variations that were observed in the soils of the different sectors are mainly due to the type of parent material that provides a predominantly loamy or sandy mineral matrix. For the COA sector, for instance, surface deposits mainly come from glaciolacustrine sediments characterized by sandy loam with slightly higher clay content (mean of 4.73 ± 5.56%). However, for all the soils that were analyzed, the sandy matrices contain a very high proportion of fine and very fine sand. Fine matrices have a greater capacity for retaining organic particles and humic colloids than coarse matrices (Conforti et al., 2016). These particles and colloids are mainly found in the surface soil layers that contain residues of organic matter, humus, rootlets, and debris from soil fauna and microorganisms (De Marco et al., 2016; Gray et al., 2016). We also noted that fine matrix soils with a high proportion of sand (fine and very fine sand) contained more SOC (such as 174 to 177 t ha^{-1} in COA sector). The second axis in the graph (PC2) reveals that the variables resulting from the data analysis are C/N ratio + litter (cm) (top of the graph) and soil pH + slope% (bottom of the graph). Litter biomass helps provide

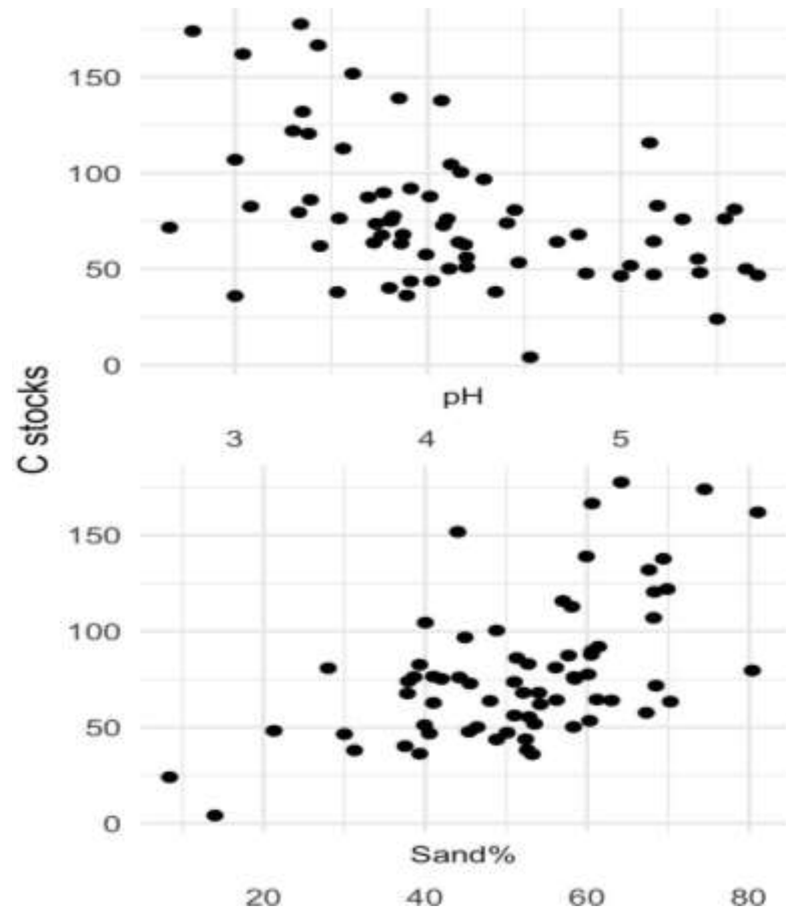

Figure 3. Stepwise multiple linear regression showing two key variables (soil pH and Sand%) resulting from the analysis based on the concentration of soil C stocks. These two soil variables account for 33.2% of the variance.

organic carbon to the soil and nitrogen, which explains why the two variables (C/N ratio and litter) are closely linked (Becker et al., 2015; Ge et al., 2013). For its part, the relationship between the soil pH and slope variables can be explained by the slope effect, which accentuates internal soil leaching, which can affect soil acidity *in situ* (Fan et al., 2016). Note that SOC concentrations are highest in the most acidic soils (such as pH 2.78 - SOC 15.83%; pH 3.34 - SOC 16.63%).

Concentration of SOC and C stock in mineral soils

The highest concentrations of SOC and C stocks are found in fine matrix soils with a high level of acidity (pH 2.66 to 3.61). Soils made up of loam and very fine sand promote the formation of aggregates, which contain a high concentration of organic C that remains stable in the soil matrix. These are mainly found in surface layers (O, Ah horizons), which are directly supplied by the breakdown of organic matter. These aggregates may progressively migrate to the illuvial horizons, especially if soil acidity increases, which favours leaching, depending on the size of the particles and aggregates (Weil and Brady, 2017). Sandy or loamy soils generally enable better drainage and facilitate particle migration. These aggregates are therefore concentrated in the topsoil (0-20 or 0-30 cm), depending on site conditions (Chai et al., 2015). No marked differences were noted between soils with higher clay content and C stocks (Figure 4), and soils with clay content greater than 10% have not been found to contain more organic C than other soils.

The C stock concentrations measured at our sites are comparable to the values obtained for other studies conducted in Québec (Marty et al., 2015; Tremblay et al., 2002). The studies by Marty et al. (2015), for instance, show C stocks ranging from 70 to 226 t ha^{-1} for mineral soils, compared to 24 to 177 t ha^{-1} for our sites (excluding the value of 4.10). These studies were carried out in central Québec under a mixed forest cover or dominated by coniferous species. The work by Tremblay et al. (2002) in central and northern Québec under a hardwood or coniferous forest cover shows values comparable to ours, with differences ranging from 22 to 186 t ha^{-1} for

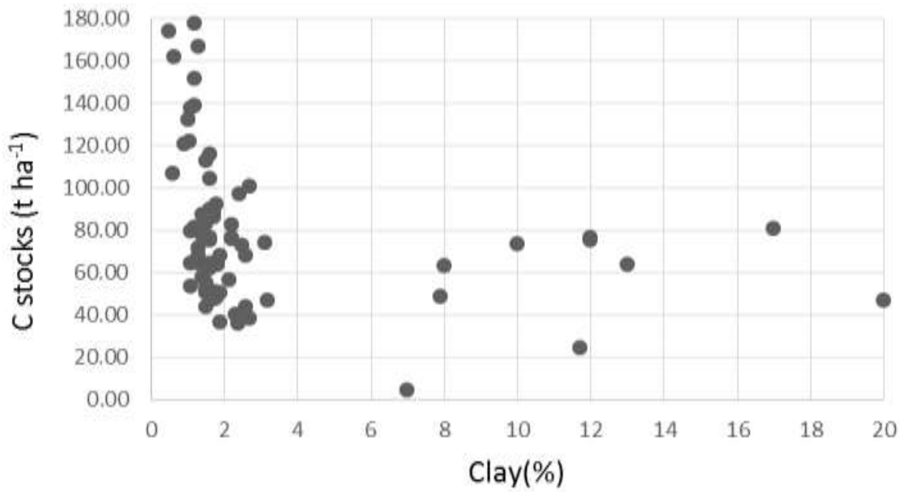

Figure 4. Correlation between C stocks and clay(%) proportion in mineral layers (0-20 cm) for all the sectors. The increase in clay content (>10%) does not appear to affect the C stocks.

mineral soils. Studies by Marty et al. (2015) show higher C stock levels (177 t ha^{-1}) for soils under a mainly coniferous forest cover, while the work done by Tremblay et al. (2002) shows the reverse, with higher levels for soils under a hardwood forest cover. These studies in fact mention that the lowest C stock value was measured in pine forest stands, whereas the highest value came from hardwood stands (Tremblay et al., 2002). For our part, there is an absence of relationship between vegetation data and soil C stocks, excluding litter thickness. The authors also mention that litter thickness, soil acidity and textural classes appear to be the best indicators for determining C stocks in the forest soils that were studied (Tremblay et al., 2002). Lastly, other studies conducted across Canada for sites under mixed forest covers or dominated by coniferous species (Arevalo et al., 2009; Hazlett et al., 2005; Moroni et al., 2010) show mineral layer values ranging from 16 to 179 t ha^{-1}. According to these authors, these variations may depend on several factors, including particle-size fractions, moisture content, and soil pedogenic processes associated with geographical variables. Soil type and macrofauna activity are also mentioned to explain soil C sequestration on a local or regional scale.

SOC concentration, C stocks and environmental variables

The results of the stepwise multiple regression analysis show that soil acidity and texture are the two properties that best explain C stocks in the mineral soils. It was noted that the highest concentrations were only found in more acidic soils (pH 2.66 to 3.61). These results are consistent with several studies showing that soil acidity is one of the key factors that may account for the high C stock concentrations in soils, in addition to texture and drainage (Fan et al., 2016). Soil acidity can be explained by the properties of the parent material (such as low concentration of basic elements), concentration of organic acids (such as humic and fulvic acids) produced by the decomposition of soil organic matter, and by soil drainage and leaching, which in turn are dependent on texture and topography (Conforti et al., 2016).

The results also show that silty soils that are predominantly sandy (fine and very fine sand) contain higher C stock concentrations. A high SOC concentration is often associated with aggregate abundance (Fan et al., 2016; Zhang et al., 2017), and soils with a fine matrix favour the development of aggregates of all sizes (Conforti et al., 2016; Zhang et al., 2017). According to the studies by Zhang et al. (2017), macroaggregates (>25 mm) make a larger contribution to SOC accumulation than other aggregate fractions. The formation of these macro- or microaggregates namely depends on the original parent material, including mineral matrices with high concentrations of fine particles (such as silt or fine sand), and is also dependent on the quantity and quality of organic matter, a large part of which comes from litter, microbial residues and exudates (Krause et al., 2019; Redmile-Gordona et al., 2020). The leaching and migration of organic particles or aggregates may be facilitated based on the porosity and structure of the soil (Weil and Brady, 2017). Overly compact soil may significantly hinder soil drainage. Lastly, the equation could also include the topography factor (slope inclination), which influences the soil water regime and facilitates particle and humic colloid migration through the profile (Conforti et al., 2016; Krause et al., 2019). In short, two key soil properties resulted from the analysis: soil acidity and texture. These two variables are in fact often referenced to explain SOC concentrations, in particular in forest soils (Conforti et al., 2016; Nielsen et al., 2011). The two soil properties are themselves affected by a multitude of factors (such as parent material, slope, drainage, litter) that must be taken into account in the diagram that explains the dynamics of soil and soil-forming processes.

Conclusion

The findings of this study reveal that soils under mixed forest cover have comparable SOC stocks, consistent with the concentrations measured in forest ecosystems similar to this study (cold-temperate mixed forests). The results of the PCA on the correlation matrix for soil and environmental data reveal that grain size composition is the variable that differentiates one site from the other the most, which is largely attributable to the study sectors' respective parent material, with C/N ratio + litter thickness (cm) and soil pH + slope% constituting other discriminating variables. For the determination of C stocks in mineral subsurface soils, two key soil properties resulted from the analysis: soil acidity and texture. These soil properties can thus serve as key parameters for a better determination of C stocks under forest cover under the soil and environmental conditions specific to these sites. In the context of global warming, it can be concluded that mixed forests in a cold temperate climate have substantial soil C stocks, and preserving them is part of possible solutions being considered for climate change mitigation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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REFERENCES

Arevalo CBM, Bhatti JS, Chang SX, Sidders D (2009). Ecosystem carbon stocks and distribution under different land-uses in north central Alberta, Canada. Forest Ecology and Management 257(8):1776-1785.

Becker JN, Pabst H, Mnyonga J, Kuzyakov Y (2015). Annual litter fall dynamics and nutrient deposition depending on elevation and land use at Mt. Kilimanjaro. Biogeosciences 12(19):5635-5646.

Bradford MA, Berg B, Maynard DS, Wieder, WR, Wood SA (2016). Understanding the dominant controls on litter decomposition. Journal of Ecology 104(1):229-238.

Carter MR, Gregorich JM (2008). Soil sampling and methods of analysis. Canadian Society of Soil Science, Second edition, Taylor and Francis Group: Boca Raton, FL, USA.

Chai H, Yu G, He N, Wen D, Li J, Fang J (2015). Vertical distribution of soil carbon, nitrogen, and phosphorus in typical Chinese terrestrial ecosystems. Chinese Geographical Science 25(5):549-560.

Cleveland CC, Reed SC, Keller AB, Nemergut DR, O'Neill SP, Ostertag R, Vitousek PM (2014). Litter quality versus soil microbial community controls over decomposition: a quantitative analysis. Oecologia 174(1):283-294.

COGESAF (2014). Conseil de gouvernance de l'eau des bassins versants de la rivière Saint-François. Le Plan directeur de l'eau du bassin versant de la rivière Saint-François.

Conforti M, Lucà F, Scarciglia F, Matteucci G, Buttafuico G (2016). Soil carbon stocks in relation to soil properties and landscape position in a forest ecosystem in southern Italy (Calabria region). Catena 144:23-33.

Cook RD (1977). Detection of influential observation in linear regression. Technometrics 19(1):15-18.

Canadian System of Soil Classification (CSSC) (1998). Soil Classification Working Group, Research Branch, Agriculture and Agri-Food Canada, Publication 1646, Government of Canada, Ottawa, Canada.

De Marco A, Fioretto A, Giordano M, Innangi M, Menta C, Papa S, Virzo de Santo A (2016). C Stocks in forest floor and mineral soil of two Mediterranean beech forests. Forest 7(8):181.

Djukic I, Kepfer-Rojas S, Schmidt IK, Larsen KS, Beier C, Ber B., Verheyen K (2018). Early stage litter decomposition across biomes. Science of the Total Environment 628:1369-1394.

Fan S. Guan F, Xu X, David I, Forrester DI, Ma W, Tang X (2016). Ecosystem carbon stock loss after land use changing subtropical forests in China. Forests 7(7):142.

Food and Agriculture Organization (FAO) (2015). Universal Soil Classification.

Food and Agricultural Organization (FAO) (2017). Soil organic carbon: the hidden potential. Food and Agriculture Organization of the United Nations, Rome.

Gabriel CE, Kellman L (2014). Investigating the role of moisture as an environmental constraint in the decomposition of shallow and deep mineral soil organic matter of a temperate coniferous soil. Soil Biology and Biochemistry 68:373-384.

García-Palacios P, Maestre FT, Wall J, Kattge DH (2013). Climate and litter quality differently modulate the effects of soil fauna on litter decomposition across biomes. Ecology Letters 16(8):1045-1053.

Ge X, Zeng L, Xiao W, Huang Z, Geng X, Tan B (2013). Effect of litter substrate quality and soil nutrients on forest litter decomposition: A review. Acta Ecological Sinica 33:102-108. Gray JM, Bishop TFA, Wilson BR (2016). Factors controlling soil organic carbon stocks with depth in eastern Australia. Soil Science Society of America Journal 79:1741-1751.

Gray JM, Bishop, TFA, Wilson BR (2016). Factors controlling soil organic carbon stocks with depth in Eastern Australia. Soil Science Society of America Journal 79(6:1741-1751.

Hazlett PW, Gordon AM, Sibley PK, Buttle JM (2005). Stand carbon stocks and soil carbon and nitrogen storage for riparian and upland forests of boreal lakes in northeastern Ontario. Forest Ecology and Management 219(1):56-68.

Hou G, Delang CO, Lu GX, Gao L (2020). A meta-analysis of changes in soil organic carbon stocks after afforestation with deciduous broadleaved, sempervirent broadleaved, and conifer tree species. Annals of Forest Science 77(4):1-13.

Clare Nullis, Communications and Public Affairs, WMO (2018). Intergovernmental panel on climate change (IPCC) issues Special Report on Global Warming of 1.5 °C. Bulletin no. 67 (2). https://public.wmo.int/en/resources/bulletin/ipcc-issues-special-report-global-warming-of-15-%C2%B0c

Joseph A, Oluwakem A, Olanrewaju O (2018). Climate change effect and adaptation measures on selected soil properties. Journal of Soil Science and Environmental Management 9(10):154-163

Krause L, Biesgen D, Treder A, Schweizer SA, Klumpp E, Knief C, Siebers N (2019). Initial microaggregate formation: Association of microorganisms to montmorillonite- goethite aggregates under wetting and drying cycles. Geoderma 351:250-260.

Lavoie L, Saint-Laurent D, St-Laurent J (2006). Pedological and sedimentological analyses of alluvial soils and paleosols on floodplain terraces. Canadian Journal of Soil Science 86:1-14.

LECO Corporation (2012). TruMac Series Determinator. Document 11/12-REV9. http://www.naizaklab.com/docs/58ff3ab6409731b7bf10fe50d4dde5fc.pdf

Mao Z, Derrien D, Didio M, Liski J, Eglin T, Nicolas M, Jonar M., Saint-André L (2019). Modeling soil organic carbon dynamics in temperate forests with Yasso07. Biogeosciences 16(9):1955-1973.

Marty C, Houle D, Gagnon C (2015). Variation in stocks and distribution of organic C in soils across 21 eastern Canadian temperate and boreal forests. Forest Ecology and Management 345:29-38.

MDDELCC (2019). Ministère du développement durable, de l'Environnement et de la Lutte contre les changements climatiques. Normales Climatiques du Québec 1981-2010. Gouvernement du Québec, 2018.

Ministère de l'Énergie et des Ressources naturelles du Québec (MERN) (1976). Compilation de la géologie du Quaternaire (1:50 000). Gouvernement du Québec, Service de la géoinformation (31H/16).

Ministère de l'Énergie et des Ressources naturelles du Québec (MERN) (1984). Compilation de la géologie du Quaternaire (1 : 50 000). Gouvernement du Québec, Service de la géoinformation

Moroni MT, Shaw CH, Otahal P (2010). Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin: field study. Canadian Journal of Forestry Research 40(11):2135-2145.

Ministère des Richesses naturelles, de la Faune et des Forêts (MRNFF) (2007). Région écologique 2c - Coteaux de l'Estrie, Guide de Reconnaissance des types écologiques, Direction des inventaires forestiers et Direction des communications, Gouvernement du Québec.

Nielsen UN, Ayres E, Wall DH, Bardgett RD (2011). Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity-function relationships. European Journal of Soil Science 62(1):105-116.

Pan Y, Birdsey RA, Fan J, Houghton R, Kauppi PE, Kurz W, Phillips OL, Shvidenko A, Lewis SL, Canadell JG (2011). A large and persistent carbon sink in the world's forests. Science 333:988-993.

Paul E (2016). The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. Soil Biology and Biochemistry 98:109-126.

Powlson D, Whitmore AP, Goulding KWT (2011). Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. European Journal of Soil Science 62(1):42-55.

PRDIRT (2015). Plan régional de développement intégré des ressources naturelles et du territoire. Portrait de la forêt naturelle et des enjeux écologiques de l'Estrie.

R Development Core Team (2014). A Language and Environment for Statistical Computing. R Foundation for Statistical Computing; Vienna, Austria.

Ramage JL, Fortier D, Hugelius G, Lantuit H, Morgenstern A (2019). Distribution of carbon and nitrogen along hillslopes in three valleys on Herschel Island, Yukon Territory, Canada. Catena 178:132-140.

Rawls WJ (1983). Estimating soil bulk density from particle size analysis and organic matter content. Soil Science 135(2):123-125.

Redmile-Gordona M, Gregory AS, Whit RP, Watts CW (2020). Soil organic carbon, extracellular polymeric substances (EPS), and soil structural stability as affected by previous and current land-use. Geoderma 363:114143.

Scharlemann JP, Tanner EVJ, Hiederer R, Kapos V (2014). Global soil carbon: Understanding and managing the largest terrestrial carbon pool. Carbon Management 5(1):81-91.

Smyth CE, Macey D., Trofymow JA (2015). Long-term litter decay in Canadian forests and the influence of soil microbial community and soil chemistry. Soil Biology and Biochemistry 80:251-259.

Tremblay S, Ouimet R, Houle D (2002). Prediction of organic carbon content in upland forest soils of Quebec, Canada. Canadian Journal of Forestry Research 32(5):903-914.

Tu Q, Yan Q, Deng Y, Michaletz ST, Buzzard V, Weiser MD, Waide R, Ning D, Wu L, He Z, Zhou J (2020). Biogeographic patterns of microbial co-occurrence ecological networks in six American forests. Soil Biology and Biochemistry 148:107897.

Weil RR, Brady NC (2017). The Nature and properties of soils. Pearson, 15th Edition Columbus, OH, USA.

Yang S, Yao F, Ye J, Fang S, Wang Z, Wang R, Zhang Q, Ma X, Yang, Jiang, Y, Dorodnikov M, Li H, Zoua H (2019). Latitudinal pattern of soil lignin/cellulose content and the activity of their degrading enzymes across a temperate forest ecosystem. Ecological Indicators 102: 557-568.

Zhang X, Xin X, Zhu A, Zhang J, Yang W (2017). Effects of tillage and residue managements on organic C accumulation and soil aggregation in a sandy loam soil of the North China Plain. Catena 156:176-183.