

2014

Effect of sugarcane residue management on soil organic carbon in a Louisiana agricultural system: implications for carbon sequestration

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EFFECT OF SUGARCANE RESIDUE MANAGEMENT ON SOIL ORGANIC CARBON IN A
LOUISIANA AGRICULTURAL SYSTEM: IMPLICATIONS FOR CARBON SEQUESTRATION

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of
requirements for the degree of
Master of Science

in

The School of Plant, Environmental, and Soil Sciences

by
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May 2014

Acknowledgements

Many individuals contributed to this work. First I would like to thank my major professor and committee chair, Dr. Magdi Selim, who envisioned this study as an extension of ongoing sugarcane yield studies with conservation management and who had the foresight and experience to properly design the depth and spacing of samples. Additional members of the team who designed and executed the sampling were Dr. Brenda Tubaña , Dr. Lewis Gaston, Marilyn Dalen, Dr. Yumiko Kanke, and Liyun Zhang. Liyun also sorted, cataloged, dried, and performed soil moisture and bulk density measurements on 600 samples, which was no small feat. I would also like to thank Dr. Jim Wang and Dr. Ole Wendroth for providing expertise in soil chemistry and spatial analysis, respectively. Dr. Clint Willson and Dr. Louis Thibideaux contributed substantially to my interpretation of results. Additionally, the field assistance and regional knowledge offered by Allen Arceneaux was invaluable.

I am grateful to have been a part of the cohesive and productive soil science group at LSU, whose success is driven not only by its faculty but also by its students and staff. Both Dr. Maud Walsh and Dr. Don Labonte were especially supportive of my professional development during my time at SPESS. Dr. Syam Dodla was ever-ready with technical expertise. Fellow students who were particularly helpful were Dr. Tamer Elbana, Chang Liu, Sara Nuss, Nazanin Akrami, Samantha Swanhart, Payton Dupree, Brittany Dupre, and Andrew Hewett. Many others, too numerous to name, provided support in the form of friendship, and I hope they recognize the value of that type of support. I would also like to thank the SPESS staff, who were always helpful with travel procedures, forms, and miscellaneous needs: Connie Dubois, Sheila Rohwer, Jere Townsend, and Becky Jolibois.

This work was funded by the Louisiana Agricultural Experiment Station: USDA-ARS Grant #59-626-2-058.

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Abstract

The soil organic carbon (SOC) pool is an important component of the global carbon budget. Agricultural systems in particular have been identified as an area in which SOC may be increased appreciably when managed for carbon sequestration. In the southern climate region of the United States, potential rates of carbon sequestration in soils are largely unquantified. The aim of this study was to quantify SOC and its spatial variability under two long-term residue management systems, burn and no-burn, for sugarcane (*Saccharum Spp. Hyb.*). Soil cores to a depth of 1 m were collected using a Giddings probe. Thirty soil cores per treatment were collected along a transect with 1.8-m spacing. Parameters measured were SOC, soil nitrogen, bulk density, gravimetric water content, CEC, and pH. Comparisons between treatments were conducted using paired t-tests. Geostatistical analyses were used to investigate 2-D vertical and lateral spatial trends. In a subsequent sampling, soil cores were collected from depths up to 2.7 m, and SOC, soil nitrogen, and gravimetric water content were measured. Differences in SOC between the two treatments were significant ($t = 2.35$, $p = 0.019$) and indicated that the no-burn treatment contained more SOC than the burn treatment. Variogram models indicated that the no-burn treatment (range = 10.19 m) had higher spatial variability than the burn treatment (range = 18.95 m), and kriging illustrated that the burn treatment had a SOC content that was more evenly distributed with depth. Some 70 % of SOC was in the 20-100 cm soil depth, and the greatest differences between the treatments occurred at depths below 60 cm. Estimated carbon sequestration was 0.56 Mg/ha/yr. A major finding from this study is that soil carbon sequestration in the burn and no-burn managements was consistent with other studies in the region; however, significant quantities of SOC may be present at depths below the typical 20-cm sampling depth, and ignoring deeply distributed carbon may result in the underestimation of carbon sequestration.

1. Introduction

In the southern climate region of the United States, potential rates of carbon sequestration in soils are largely unquantified. Recently, the soil organic carbon (SOC) pool has been recognized as an important contributor to global carbon sequestration, and agricultural systems in particular have been identified as an area in which SOC may be increased appreciably when managed for that objective (Lal, 2004; West and Post, 2002). Although a growing body of work has emerged to quantify the carbon sequestration potential of various cropping systems in the southeastern US, there have been no studies in Louisiana (Franzluebbers, 2010). Because controls on SOC dynamics vary with climate, vegetation, and soil type, regional sequestration potentials vary, and to understand the soil carbon sequestration potential of the unique southern Louisiana environment, studies of this specific region are needed.

Carbon sequestration is difficult to quantify. It is defined as the transfer of CO₂ from the atmosphere to the soil through incorporation into plants, plant residues, and other organic solids (Olson, 2013). Linking carbon sequestration to a specific management practice requires an increase in SOC with a concomitant decrease in atmospheric CO₂ during the period of study. Because these measures are not always available or practical, several studies have inferred sequestration potential by comparing soil organic carbon among various management practices (e.g. Thorburn et al., 2012; Venkatesh et al., 2013). Such results are commonly reported on a mass per area basis to control for differences in bulk density among treatments (Galdos et al., 2009).

In sugarcane (*Saccharum Spp. Hyb.*) cropping systems, burning either before or after harvest is a common practice worldwide, as is the case in Louisiana where 428,000 acres were harvested in 2012 (USDA, 2013). Burning of residues directly reduces the amount of surface organic matter available for incorporation into the soil, so a cessation of burning typically results in increased SOC. However, several years may be required before changes are evident. For example, total soil carbon was 30% higher in an unburned compared to a burned treatment in the first 10 cm of a clayey Oxisol after 8 years (Galdos et

al., 2009), but no difference was detected in soil carbon after the first ratoon in the upper 7.5 cm of a Spodosol (Ball-Coelho et al., 1993).

The spatial distribution of SOC is an important consideration when estimating carbon sequestration. Although studies of SOC typically focus on the upper 10-20 cm of soil (Franzluebbers, 2010), appreciable amounts of soil carbon can exist in deeper soil layers (Jobbagy and Jackson, 2000). There is evidence that SOC can accumulate in the subsoil. For example, a study of a sugarcane cropping system in Australia found that older, more established sites had higher levels of organic carbon at the 50-80 cm depth relative to new sites (Skjemstad et al., 1999). This suggests that carbon accumulation may occur below shallow soil depths. Mechanisms of subsoil accumulation of new carbon include integration of plant roots and root exudates, vertical transport of dissolved organic matter (David and Zech, 1990), and bioturbation (Rumpel and Kögel-Knabner, 2011). Subsoil carbon may be particularly relevant to carbon sequestration, because deeper soil carbon tends to have a longer residence time (Rumpel et al., 2002; Schöning and Kögel-Knabner, 2006).

2. Objectives

The aim of this study is to quantify SOC and its spatial variability and to infer implications for carbon sequestration in long-term sugarcane management systems in Louisiana. Here, two management systems were investigated. One was a burn treatment where the residue from the combine harvester was burned after harvest, and the other was a no-burn (or no-till) treatment in which the residue remained on the soil surface after harvest. The following soil properties were measured and compared between the burn and no-burn treatment to a depth of 1 m: soil carbon content, nitrogen content, moisture content, bulk density, pH, and cation exchange capacity (CEC). We used geostatistical analyses to investigate vertical and lateral spatial patterns of carbon, nitrogen, soil moisture, and CEC in both treatments. Additionally, we compared SOC, soil nitrogen, and initial moisture content in soil samples taken from depths up to 2.7 m to assess the potential for carbon accumulation at lower depths.

3. Literature Review

3.1 Conservation Management

In recent decades, the scientific community has identified soil carbon sequestration as an important and viable strategy to combat increased greenhouse gas concentration in the Earth's atmosphere. Conversion of conventional agricultural practices to conservation practices such as conservation tillage could sequester 15-25 Tg of carbon previously lost to tillage and erosion within a 30 year period (Lal et al., 2003). Numerous long-term studies have documented differences in SOC among various traditional and conservation management practices in an attempt to more accurately quantify regionally based estimates. Minimal or no-till agriculture is a well-accepted conservation practice for increasing SOC in agricultural land in various soil types, climates, and cropping systems. The role of no-till practices in promoting SOC is almost unequivocally positive. The term "no-till" is defined as any management practice that leaves at least 30% of crop residue on the field after harvest, so in addition to the absence of mechanical disturbance, it is characterized by a layer of mulch that affects soil temperature and moisture.

In a review of 147 comparisons of the effect of no-till versus conventional systems on SOC in the southeastern United States, Franzluebbers (2010) found that an average of $0.45 \pm 0.04 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ of carbon was added through no-till management when comparative studies of all crops in the region were considered. . Similarly, Johnson and Richard (2005) summarized research in the central United States, and found carbon sequestration rates of $0.40 \pm 0.61 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ when conventional tillage was converted to no-till. In the southern piedmont and coastal plain of the United States, Causarano (2008) found that for a variety of crops, primarily soybean, corn, cotton, and wheat, farms using conservation management had 5.7 Mg/ha more organic carbon in the upper 20 cm of soil than those using conventional management

In Louisiana sugarcane cropping systems, minimal tillage is already commonly practiced, largely because sugarcane crops are produced in multiple ratoons in which plants re-sprout after harvest and are

only tilled and replanted every 4-6 years. However, burning of post-harvest residue, which has been shown to decrease SOC in other systems (e.g. Galdos et al., 2009), is commonly practiced on an annual basis. In Brazil where burning of standing cane prior to harvest has been the standard practice for many decades, cessation of burning led to an average SOC accumulation of $1.24 \pm 0.09 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, but measurements taken immediately after sugarcane was replanted showed no change or even a loss of SOC (Cerri et al., 2011). This suggests that gains in SOC which occur during the multi-year planting cycle are vulnerable to loss when soil is disturbed.

There are two primary processes by which no-till management favors SOC sequestration. The first is a physical process in which tilling disrupts the integrity of soil aggregates, which protect SOC from oxidation by microorganisms. Large soil aggregates are composed of a conglomeration of smaller aggregates primarily held together by relatively labile organic substances such as polysaccharides that are quickly digested by microorganisms when disturbed and exposed (Blair, 2000; John et al., 2005). This mechanism of physical protection accounts for as much as half of the organic matter found in soil (Elliott, 1986); therefore, SOC is highly correlated to aggregate size. For example Kong et al. (2005), in a study considering a gradient of C inputs in silt loam and silty clay loam, found a positive linear relationship between SOC and aggregate stability ($r^2 = 0.62$, $p = 0.006$) and also found that carbon associated with microaggregates within macroaggregates (mM) accounted for a large portion (40-68 %) of the stabilized carbon. The physical dispersal of aggregates via tillage is considered a primary mechanism by which carbon is lost from natural systems when they are converted to agriculture, either by processes described above or through decreased resistance to erosion.

The second process by which no-till management enhances SOC sequestration is by buffering of soil temperature fluctuations due to the presence of a surface layer of mulch. Temperature is potentially an important control on SOC oxidation, but the exact relationship between soil temperature and organic matter degradation rate is still debated (Conant et al., 2011). As a rule of thumb, the degradation rate of soil organic matter (SOM) increases by a factor of two for every ten degree increase in temperature, and

this is commonly referred to as the Q10 of SOM. The Q10 for SOM tends to decrease with increased temperature and tends to increase with increased recalcitrance of SOM (Davidson and Janssens, 2006). There is strong evidence that residue left on the soil affects soil temperature regime; for example, Duiker and Lal (2000) found significant differences in soil temperature (14° C) at 5 cm depths between mulched and bare plots, yet temperature differences among different depths of mulch were negligible. This suggests that the presence or absence of a mulch layer has the potential to affect the amount of SOC in the first few centimeters by a factor of approximately two.

Effects of a mulch layer may also extend deeper into the soil profile by changing soil moisture regimes and consequently root growth. Because sugarcane is grown as a perennial, root systems can be extensive (Smith et al., 2005), therefore management strategies that affect root growth are likely to have an influence on the amount and distribution of SOC. Generally, high soil moisture leads to a shallow rooting system of sugarcane plants (Van Dillewijn, 1952). Specifically, by maintaining higher soil moisture content near the soil surface, no-till management can be expected to result in more SOC near the soil surface. In fact, no-till management in sugarcane has been found to increase crop yields in many cases (e.g. Ball-Coelho et al., 1993), which would be expected to increase both below-ground (root) above-ground (crop residue) carbon. In Louisiana sugarcane systems, the opposite is true: cessation of burning was found to decrease yield significantly (Arceneaux et al., 2011; Kennedy and Arceneaux, 2006). Decreased yield, in theory, should be a confounding factor for carbon sequestration in our soils, but no studies to date have measured this effect.

In general, no-till management practices affect SOC both by increasing the amount of carbon that is protected within aggregates and by altering the temperature and moisture regimes of the underlying soil. The relative importance of these two factors in controlling total soil carbon depends on climate, soil type, and vegetation. Importantly, decreased sugarcane yield in unburned versus burned treatments implies that in Louisiana, gains in SOC under no-burn management may be less than those in other regions. In order to better understand the effect of a given management on SOC and ultimately on carbon

sequestration, we must understand the mechanisms by which carbon is stored in soil. These mechanisms are discussed in the following section.

3.2 Mechanisms of Stabilization

Addition of organic matter to soil only leads to carbon sequestration when newly introduced carbon is immobilized or stabilized within the soil, and the amount of carbon that may be stabilized in a given soil is limited by soil properties. In a steady state system, carbon input rate is balanced by carbon degradation rate, so that the amount of SOC reaches a state of equilibrium. When the input rate changes, through conservation practices for example, the amount of SOC approaches a new equilibrium (Figure 1). Stewart et al. (2009) described and tested three common theoretical models of carbon sequestration using a large data set gathered from long-term agricultural studies from around the world. They found that the combined data were best fit by a C-saturation model which included an upper limit of carbon stabilization. Although some of the individual cases considered were best fit by a linear model, which does not consider an upper limit of C-saturation, these had very low carbon inputs and thus did not exhibit saturation behavior. The C-saturation model is corroborated by Six (2002) for forest and grassland as well as agricultural soils.

The upper limit of C-saturation is determined by soil properties, and there are three main processes by which soil organic matter (SOM) is stabilized: 1) physical, 2) chemical, and 3) biochemical. Physical stabilization occurs when SOM is protected within aggregates as described in the previous section.

Chemical stabilization occurs when particulate SOM forms complexes with clay-sized particles by cation and/or anion exchange and specific sorption mechanisms (Jardine et al., 1989). SOC is well-correlated with soil clay content (Causarano et al., 2008); therefore, existing models of soil carbon

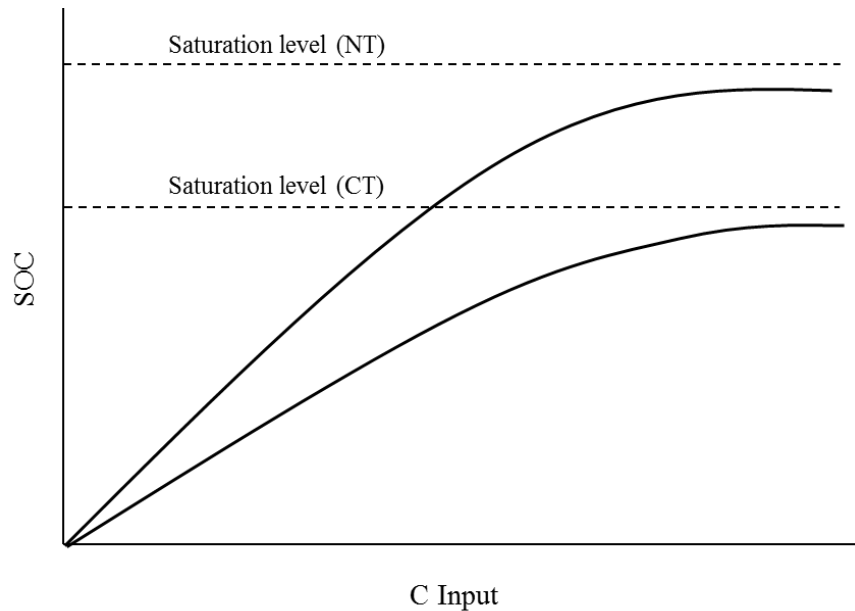


Figure 1: Conceptual diagram of C-saturation model for no-till (NT) management and conventional-till management (CT).

dynamics such as CENTURY (Metherell, 1993) and EPIC (Williams, 1995) include particle size distribution as a controlling factor. Because the amount and types of clay present in a soil strongly affect aggregation properties, the correlation between soil clay content and soil carbon content may be indirect. Clays of the 1:1 type flocculate more readily than those of the 2:1 type, so soils dominated by clays such as kaolinite tend to be more aggregated than those dominated by montmorillonite or vermiculite. This suggests that in 2:1-clay-dominated soils, chemical mechanisms of stabilization have a larger role, and therefore soil carbon content is more directly correlated to specific surface area of clay particles. In 1:1-clay-dominated soils, aggregation of clay particles reduces available surface area, but carbon that is stabilized is more protected and may remain in the soil longer. Therefore both the type and amount of clay are important controlling factors on the maximum amount of organic carbon that can be stabilized within a soil.

The third mechanism of stabilization is biochemical, which is a concept related to carbon quality. Some forms of SOM are naturally more resistant to degradation; for example, higher lignin content

generally causes slower decomposition (e.g. Six et al., 2001). Other forms of organic matter enter the soil carbon cycle as readily degradable substances but after being recycled and redigested numerous times, become recalcitrant. Recalcitrant SOC is defined as the fraction of organic matter that is resistant to degradation because of its inherent properties, whether those properties are initially present or acquired through microbial degradation. The recalcitrant portion of SOC is commonly referred to as the ‘passive’ fraction, because it remains in the soil for a very long time regardless of environmental conditions. Kleber (2010) argued that this perceived property is in fact a combination of other factors including microbial ecology, enzyme kinetics, environmental factors, and physical protection, and future work may clarify this concept.

Carbon that is not stabilized is subject to vertical or lateral transport and potential loss from the soil. Dissolved organic matter (DOM) is defined operationally as organic molecules small enough in size to pass through a 0.45 μm sieve. Therefore the only distinguishing feature of DOM as compared to bulk soil organic matter is size. Nevertheless, this size difference has a direct effect on the mobility of carbon in the soil. As such, DOM may behave like a solute in soil solutions and has been found to compete with anions of phosphate and sulfate for sorption sites (Guppy et al., 2005). DOM is retained by soil through physical adsorption and anion exchange (Jardine et al., 1989), and this is evidenced by the increased anion retention capacity that has been found to correlate well with decreases in soil organic matter with depth (Blank et al., 1994). Additionally, oxides and hydroxides of Fe, Al, and Mn have high sorption capacity for DOM and are important sources of variable charge in soils (Kalbitz et al., 2000), and sorption may be essentially irreversible at a given pH (Gu et al., 1994).

3.3 Effect of Burning

Burning of harvest residues has specific effects on soil properties that may affect carbon stabilization mechanisms, and these effects are primarily apparent in the upper few centimeters of the soil. Oxidation during burning decreases soil organic matter content and consequently increases bulk density which decreases water retention (Stoof et al., 2010). Ash created by burning has been found to increase

soil water retention and decrease hydraulic conductivity and infiltration rates (Chang et al., 1977). Several scientists have postulated that decreased infiltration rates after burning are a result of pore-filling by fine ash particles (Gabet and Sternberg, 2008; Mallick et al., 1984). However, increased hydrophobicity of soils, which is ubiquitous in wildfire-affected landscapes (Certini, 2005; Mataix-Solera et al., 2013), is another potentially important factor, because it can reduce hydraulic conductivity by as much as 40% (Robichaud, 2000). During low-intensity burning, hydrophobic substances in the near-surface soil are gasified (Doerr et al., 1998) and move downward along temperature gradients (Huffman et al., 2001), creating a low-permeable layer. As with other effects of burning, hydrophobicity is typically restricted to the first few centimeters (Huffman et al., 2001). Therefore, it likely has as large an effect on decreased infiltration as pore-filling by ash. Additionally, hydrophobic substances have been shown to increase the stability of soil organic matter because they are resistant to dissolution, so their presence may enhance carbon sequestration (Spaccini et al., 2002).

Pyrogenic changes in soil chemistry can have important implications for SOC retention as well. Potentially most important is a change in soil pH. Burning increases soil pH primarily by releasing base cations into solution (Arocena and Opio, 2003; Ulery et al., 1993). Khanna et al. (1994) found that the capacity of ash to neutralize acid was well correlated with the total amount of basic cations in the ash. In general, functional groups are protonated when pH is low, and at higher pH, the functional groups dissociate and become negatively charged. It follows that carbon stabilization is greater at lower pH, and indeed several studies document increased sorption at lower pH (Evans et al., 2012; Jardine et al., 1989; Kennedy et al., 1996). Burning generally removes external oxygen-containing functional groups (González-Pérez et al., 2004; Henig-Sever et al., 2001) and effectively reduces the capacity of soil to retain organic matter. Any soil property that decreases sorption potential of SOC allows for increased mobility, which may lead to vertical redistribution or loss through runoff.

3.4 Vertical Distribution of SOC

Soil organic carbon typically decreases sharply with depth and is well-predicted by a negative exponential function for most reported measurements. For example, Mishra et al. (2009) found that a negative exponential distribution satisfactorily described the vertical distribution of SOC to a depth of 1 m in a large dataset of soil profiles in Indiana. Both Franzluebbers (2010) and Causarano et al. (2008) found that a majority of carbon gained by no-till management was in the upper 5 cm of the soil profile. For this reason, the vast majority of SOC studies only measure and consider the upper 20-30 cm of the soil profile at most and either ignore carbon accumulation below that depth or model it with a negative exponential function. However, there are reasons to question this methodology, the most obvious of which is an extensive rhizosphere that extends to depths greater than 1 m in many crops. Baker (2007) emphasized that the upper 30 cm of the soil profile encompasses only a small fraction of the *Zea mays* L. root system. Given that approximately 50 % of carbon incorporated into plant biomass is stored below ground (Wilts et al., 2004) carbon accumulation should be expected within the extent of the rhizosphere, and in sugarcane crops, this zone can extend as deeply as 6 m (Evans, 1935) with most of the biomass occurring in the upper 1.5 m (Smith et al., 2005).

The rhizosphere includes not only roots but also root exudates, soil microbes, and fungi. Microbes are a major control on decomposition rates of soil organic matter, so their abundance and composition affect carbon residence time and thus carbon sequestration. Soil microbes typically account for a small fraction of total organic carbon, approximately 2-4 %; however, their metabolites may constitute a significant portion of dissolved carbon (Guggenberger et al., 1998). In sugarcane specifically, Graham and Haynes (2006) reported that although there were no differences in total organic carbon between burned and unburned treatments, microbial biomass was significantly greater in the unburned treatments at all depths (0-30 cm). Notably, mycorrhizal fungi may contribute as much organic carbon to the soil as fine roots (Wallander et al., 2004), and burning can affect the spatial distribution of soil fungi by vertically stratifying species (Anderson et al., 2007).

Even if the amount of total carbon stored at depths below 30 cm is small relative to that stored near the soil surface, this “deep” carbon is important in terms of carbon sequestration because it tends to contain a high fraction of recalcitrant forms of carbon with residence times on the order of 1000 years or more (Rumpel et al., 2002). On a global scale, carbon stored in the second and third meter of the soil profile may account for a 56% increase in estimated SOC (Jobbagy and Jackson, 2000). Therefore, any attempt to quantify carbon sequestration should consider SOC beyond the zone of tillage.

4. Materials and Methods

In order to quantify SOC and its spatial variability under different management systems, this investigation took advantage of an existing study of sugarcane yield to compare the long-term effects of two treatments: burn and no-burn. In the burn treatment, either standing sugarcane or post-harvest residue was burned annually; in the no-burn treatment, residue remained on the plot. Both treatments involved minimal tillage and were in place from 2001-2012. Two sets of soil samples were collected for this study. The first set of samples was collected on 30 April and 1 May 2012, and the second set of samples was collected on 1 August 2013.

4.1 Field Site

Research plots were at the Louisiana Agriculture Experiment Station's Sugar Research Station located 19 km south of Baton Rouge, LA and approximately 500 m from the east levee of the Mississippi River. Each plot was 0.25 ha in size (138 m long and 16 m wide). Soil at the research site is Commerce silt loam, a fine-silty, mixed, superactive, nonacid, thermic, Fluvaquentic Endoaquept. Three cycles (ratoons) of sugarcane were planted and harvested during the study period with tillage to approximately 12 cm between each; no tillage occurred between ratoons. The following sugarcane varieties were hand planted with whole stalks: HoCP 91-555 on September 19, 2001, L97-128 on August 15, 2006, and L01-283 on August 29, 2011.

4.2 Field Sampling

Sampling was designed to provide a dataset to support geostatistical analyses of soil parameters. Soil cores were collected with a Giddings probe on a center-row transect of one burn and one no-burn plot at a spacing of 1.8 m (6 ft) and a depth of 1 m. Each of the thirty soil cores per transect were divided into 10 cm segments for a total of 10 samples per core and a grand total of 300 samples per plot. Each sample was oven dried, ground, and analyzed for gravimetric soil water content and bulk density. Samples were further analyzed for percent total carbon and percent total nitrogen using the dry combustion method (Elementar Americas Inc., Mount Laurel, NJ). Select soil samples were tested for inorganic carbon

according to the pressure calcimeter method (Loeppert and Suarez, 1996). Half of the samples, every other core along the transect, were analyzed for CEC using the ammonium acetate replacement method (Sparks et al., 2006). Half of those samples were analyzed for soil pH using a 1:1 ratio of deionized water to soil and a benchtop pH electrode. Percentages of total carbon and nitrogen were converted to mass of total carbon and nitrogen per hectare for each 10 cm segment using mean bulk density of each treatment, and mean total carbon per depth (Mg ha^{-1}) was used to determine total carbon and nitrogen per treatment for the entire 1 m depth.

A second set of samples was collected on 1 August 2013 for the purpose of investigating the trend in soil carbon at depths greater than the initial 1 m. As in the first sampling, a Giddings probe was used to collect soil cores, and 3 cores per treatment were collected. Lengths of each core varied between 1.4 and 2.7 m according to soil wetness, which affected the ability of the equipment to penetrate the subsoil. These cores were divided into 10 cm increments, dried, ground, and analyzed for total carbon and nitrogen content, initial moisture content, and pH according to the methods described above.

4.3 Statistical Analyses

Paired t-tests were used to determine if differences between treatments were significant. Assumptions for the paired t-test include data that is normally distributed and equal variance of the two populations. Assumptions were tested with the Shapiro-Wilk test for normality and the f-test for equal variance. T-tests were completed for the complete dataset for each treatment and also for each soil depth and treatment. Descriptive statistics were computed for all variables by treatment which included mean, minimum, maximum, standard deviation, variance, skewness, and kurtosis. All basic statistics were computed with the software package SigmaPlot (Systat Software, Inc.).

Geostatistical methods, which included semivariogram analysis and kriging, were used to investigate spatial trends of measured parameters. These methods have been used widely in soil science for several decades to model spatial variability of environmental data (e.g. Warrick et al., 1986). In

typical soil science applications, variables are measured and modeled in a two-dimensional plane at the soil surface (x and y directions) (e.g. Goovaerts, 1999). In the analysis presented here, the two dimensions are distance along the transect and sampling depth (x and z directions). All geostatistical analyses were computed using the software package GS+ (v9, Gamma Design Software, Plainwell, Michigan).

Semivariograms of SOC, soil nitrogen, soil moisture, and CEC were computed for each 10-cm depth increment and for the complete dataset of each treatment. Semivariance (γ) for each lag distance (h) was computed as

$$\gamma(h) = \frac{1}{2 N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i - h)]^2 \quad (1)$$

where $N(h)$ is the number of pairs separated by a specific lag distance, $z(x_i)$ is the measured variable at point x_i , and $z(x_i + h)$ is the measured variable at point $x_i + h$. Plotting semivariance as a function of lag distance provided a semivariogram, which is a graphical representation of spatial auto-correlation.

Semivariograms were modeled using one of two functions that are commonly used in soil geostatistical applications: spherical and exponential. The best-fitting model was selected using a least squares fitting routine according to the highest coefficient of determination (R^2); each model contained three parameters: nugget, sill, and range. The range provides a particularly useful metric for comparing spatial structure of variables between treatments, because it represents the maximum distance at which spatial autocorrelation is present.

To further illustrate spatial patterns and make inferences about processes controlling the distribution of measured variables, we used best-fit isotopic semivariogram model parameters to interpolate unknown values using the ordinary point kriging method. In this method, the estimated point value (z^*) at an unsampled location (x_0, y_0) is

$$z^*(x_0, y_0) = \sum_{j=1}^m \lambda_j z(x_j, y_j) \quad (2)$$

where $z(x_i, y_i)$ are known values, and $\lambda_1, \lambda_2, \dots, \lambda_m$ are weights obtained by solving a system of linear equations known as the kriging system (Goovaerts, 1997). Kriging was done by lag distances, which were 1.8 m in the x direction and 10 cm in the z direction. To aid comparison of spatial trends among variables, data were grouped into quintiles in the final kriging maps.

5. Results and Discussion

5.1 Field Sampling

Total carbon content ranged from 0.20 - 1.1 % in the burn treatment and from 0.34 - 1.4 % in the no-burn treatment (Figure 2). Overall averages were 0.61 and 0.65 % for the burn and no-burn treatments, respectively (Tables 1 and 2). Overall variances were 0.029 and 0.027 % for the burn and no-burn treatments, respectively (Tables 1 and 2). Inorganic carbon was undetectable in all samples tested, therefore all total carbon measurements were interpreted as representing SOC. Values of SOC in our system were somewhat lower than those found in other soils in the region which ranged from 1.0 to 2.4 % in South Louisiana sugarcane fields (Johnson and Richard, 2005) and from 1.1 to 22.6 % in non-agricultural floodplain soils of the Atchafalaya River Basin, Louisiana (Scaroni et al., 2010). Differences in SOC between the burn and no-burn treatments were significant ($t = 2.35$, $p = 0.019$) and indicate that at the time of sampling, the no-burn treatment contained more organic carbon than the burn treatment (Table 3).

Nitrogen content ranged from 0.03 - 0.14 % in the burn treatment and from 0.03 - 0.13 in the no-burn treatment (Figure 3). Overall averages were 0.07 and 0.08 % for the burn and no-burn treatments, respectively (Tables 4 and 5). Overall variances were 2.6×10^{-4} and 3.0×10^{-4} % for the burn and no-burn treatments, respectively (Tables 4 and 5). Differences between the two treatments were significant ($t = 4.73$, $p < 0.001$) and indicate that at the time of sampling, the no-burn treatment contained more nitrogen than the burn treatment (Table 6).

The ratio of C:N ranged from 5.9 to 11.7 in the burn treatment with an average of 8.8 and from 4.4 to 13.9 in the no-burn plot with an average of 8.6. Differences between treatments were significant ($t = 2.108$, $p = 0.035$), and vertical distribution of C:N ratio varied between treatments (Figure 4). Differences in C:N ratio may indicate differences in the nature of SOC between treatments or differences

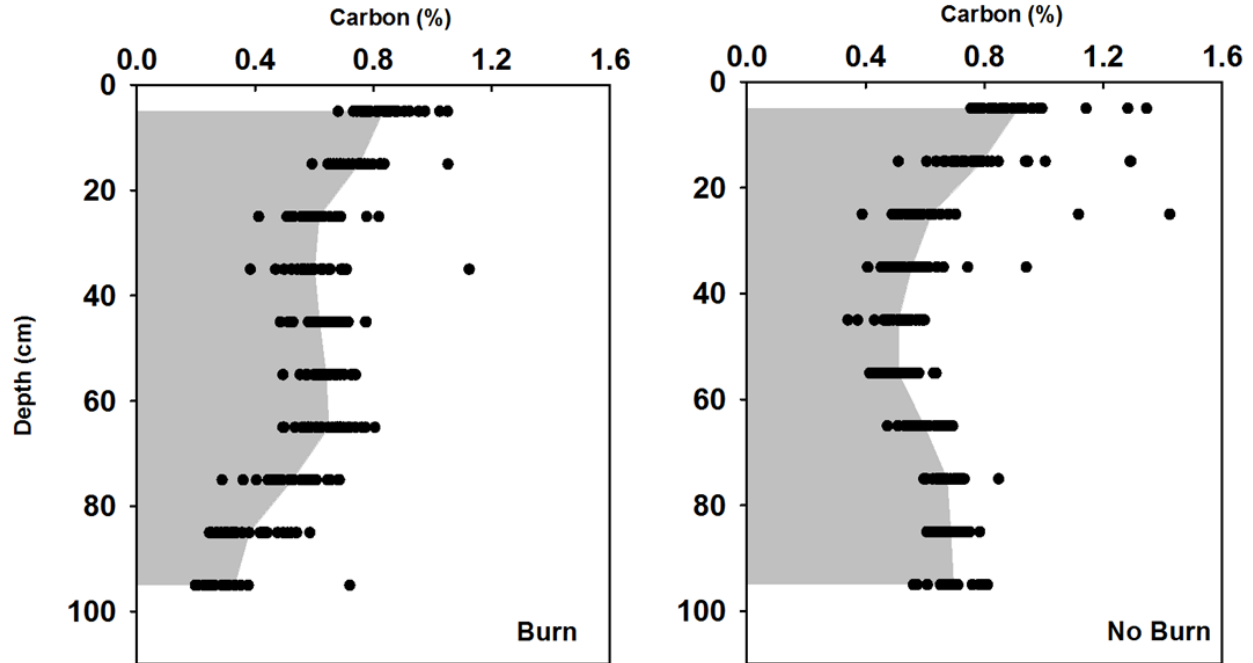


Figure 2: Each SOC measurement is represented by a point, and shaded grey area delineates the mean percent carbon for each mean depth.

Table 1. Statistical parameters for percent SOC by depth in the burn plot. S-W indicates the results of the Shapiro-Wilk test for normality where N is normal and NN is not normal ($\alpha = 0.1$).

Mean Depth (cm)	Mean (%)	Max (%)	Min (%)	Std Dev	Variance	Skewness	Kurtosis	S-W
5	0.83	1.05	0.68	0.09	0.008	0.90	0.588	N
15	0.75	1.05	0.59	0.09	0.008	1.10	3.007	NN
25	0.62	0.82	0.41	0.08	0.006	0.17	1.282	N
35	0.60	1.12	0.29	0.13	0.018	1.80	8.764	NN
45	0.62	0.78	0.49	0.13	0.017	-3.51	16.116	N
55	0.64	0.74	0.49	0.06	0.003	-0.26	0.551	N
65	0.65	0.81	0.49	0.08	0.006	-0.17	-0.297	N
75	0.53	0.69	0.29	0.09	0.009	-0.42	0.351	N
85	0.38	0.59	0.25	0.10	0.010	0.45	-1.081	NN
95	0.33	0.72	0.20	0.13	0.017	1.51	1.935	NN
Total	0.61	1.12	0.20	0.16	0.027	-0.19	0.476	NN

Table 2. Statistical parameters for percent SOC by depth in the no-burn plot. S-W indicates the results of the Shapiro-Wilk test for normality where N is normal and NN is not normal.

Mean Depth (cm)	Mean (%)	Max (%)	Min (%)	Std Dev	Variance	Skewness	Kurtosis	S-W
5	0.91	1.35	0.75	0.14	0.019	1.93	4.003	NN
15	0.79	1.29	0.51	0.17	0.028	1.76	0.028	NN
25	0.62	1.42	0.39	0.19	0.038	3.21	0.038	NN
35	0.55	0.94	0.41	0.10	0.011	1.91	0.011	NN
45	0.51	0.60	0.34	0.06	0.004	-0.86	0.004	N
55	0.51	0.64	0.41	0.06	0.003	0.31	0.003	N
65	0.60	0.69	0.47	0.05	0.003	-0.12	0.003	N
75	0.67	0.85	0.60	0.05	0.002	1.35	0.002	NN
85	0.69	0.78	0.61	0.05	0.002	0.05	0.002	N
95	0.70	0.93	0.56	0.08	0.007	0.54	0.007	N
Total	0.65	1.42	0.34	0.16	0.029	1.58	4.221	NN

Table 3. Results for SOC of paired t-tests for each depth. Negative t values indicated that the mean of values in the burn plot was greater than in the no-burn plot. S-W indicates results of the Shapiro-Wilk test for normality where N is normal and NN is not normal. HOV indicates the results of the homogeneity of variance test where E is equal variance and NE is not equal variance.

Mean Depth (cm)	Depth (cm)	t	p	S-W	HOV
5	0-10	2.690	0.009	NN	E
15	10-20	1.153	0.254	NN	E
25	20-30	0.139	0.890	NN	E
35	30-40	-2.040	0.046	NN	E
45	40-50	-7.797	< 0.001	N	E
55	50-60	8.597	< 0.001	N	E
65	60-70	-3.104	0.003	N	E
75	70-80	7.739	< 0.001	N	NE
85	80-90	14.899	< 0.001	N	NE
95	90-100	11.267	< 0.001	NN	E

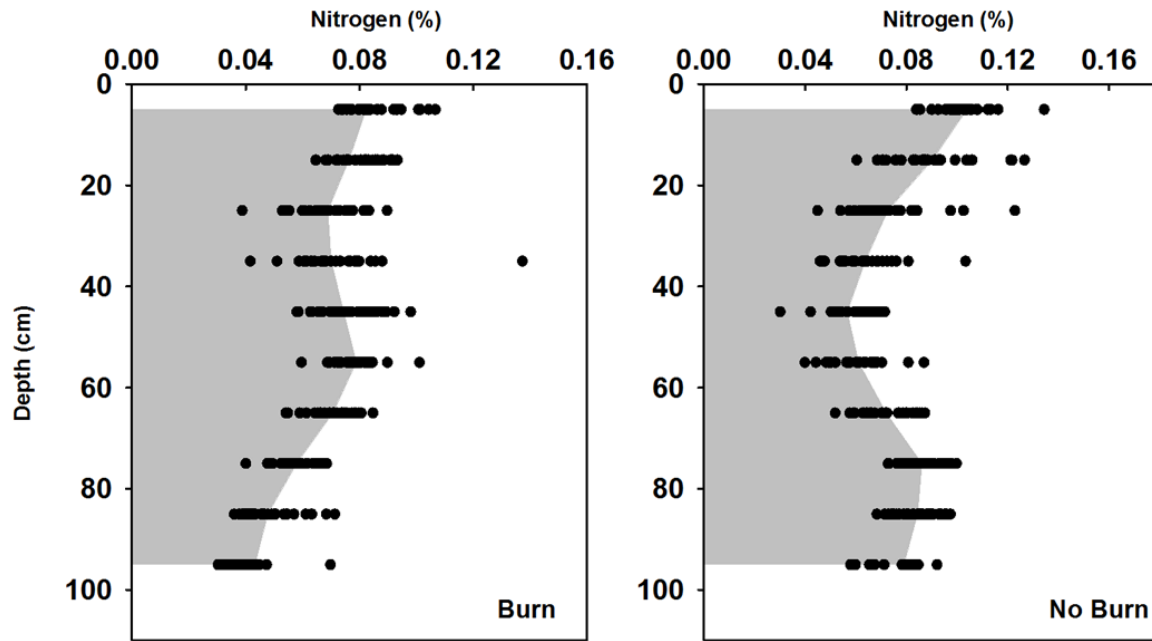


Figure 3: Each soil nitrogen measurement is represented by a point, and shaded grey area delineates the mean percent nitrogen for each mean depth.

Table 4. Statistical parameters for percent soil nitrogen by depth in the burn plot. S-W indicates the results of the Shapiro-Wilk test for normality where N is normal and NN is not normal ($\alpha = 0.1$).

Mean Depth (cm)	Mean (%)	Max (%)	Min (%)	Std Dev	Variance	Skewness	Kurtosis	S-W
5	0.085	0.107	0.073	0.010	9.6E-05	0.744	-0.452	NN
15	0.079	0.093	0.065	0.009	8.3E-05	0.001	-1.272	N
25	0.069	0.090	0.039	0.011	1.2E-04	-0.522	0.645	NN
35	0.071	0.137	0.042	0.017	2.7E-04	2.287	9.143	NN
45	0.077	0.098	0.058	0.010	9.8E-05	-0.153	-0.268	N
55	0.079	0.101	0.060	0.007	5.5E-05	0.304	3.217	N
65	0.071	0.085	0.054	0.007	5.2E-05	-0.525	0.271	N
75	0.058	0.068	0.040	0.007	4.6E-05	-0.504	0.379	N
85	0.048	0.071	0.036	0.009	8.7E-05	0.992	0.370	NN
95	0.041	0.070	0.030	0.009	8.1E-05	2.195	6.855	NN
Total	0.069	0.137	0.030	0.016	2.6E-04	-0.105	0.540	NN

Table 5. Statistical parameters for percent soil nitrogen by depth in the no-burn plot. S-W indicates the results of the Shapiro-Wilk test for normality where N is normal and NN is not normal.

Mean Depth (cm)	Mean (%)	Max (%)	Min (%)	Std Dev	Variance	Skewness	Kurtosis	S-W
5	0.102	0.134	0.084	0.010	9.6E-05	1.15	3.69	NN
15	0.090	0.127	0.060	0.015	2.4E-04	0.64	0.67	N
25	0.073	0.123	0.045	0.016	2.5E-04	1.39	3.13	N
35	0.064	0.103	0.046	0.012	1.4E-04	1.39	4.06	NN
45	0.059	0.071	0.030	0.009	8.7E-05	-1.41	2.84	NN
55	0.060	0.087	0.040	0.011	1.1E-04	0.48	0.69	N
65	0.072	0.087	0.052	0.010	9.6E-05	-0.03	-1.05	N
75	0.086	0.100	0.073	0.007	5.2E-05	-0.05	-0.68	N
85	0.084	0.097	0.068	0.008	6.0E-05	-0.30	-0.70	N
95	0.075	0.092	0.058	0.010	1.0E-04	-0.44	-0.89	N
Total	0.077	0.134	0.030	0.017	3.0E-04	0.31	0.04	NN

Table 6. Results for percent soil nitrogen of paired t-tests for each depth. Negative t values indicated that the mean of values in the burn plot was greater than in the no-burn plot. S-W indicates results of the Shapiro-Wilk test for normality where N is normal and NN is not normal. HOV indicates the results of the homogeneity of variance test where E is equal variance and NE is not equal variance.

Mean Depth (cm)	t	p	Norm	HOV
5	6.311	<0.001	NN	E
15	3.425	0.209	N	E
25	1.062	0.293	NN	E
35	-1.887	0.065	NN	E
45	-6.829	<0.001	N	E
55	-7.442	<0.001	NN	NE
65	0.422	0.674	N	NE
75	15.473	<0.001	N	E
85	16.362	<0.001	N	E
95	10.666	<0.001	N	E

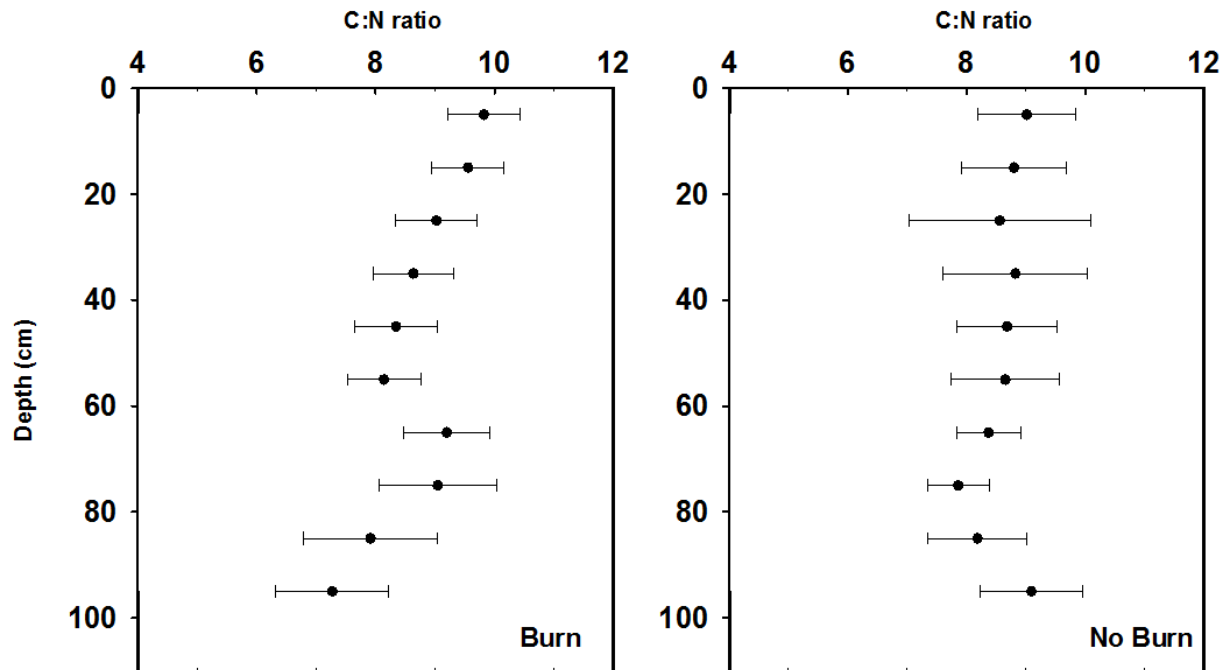


Figure 4: Vertical distribution of carbon to nitrogen ratios differed between treatments.

in fertilizer application. Particularly for depths below 60 cm, these differences may be from pre-existing heterogeneity in the alluvial soil.

Gravimetric water content ranged from 0.09 - 0.44 g g⁻¹ in the burn treatment with an average of 0.25 g g⁻¹, and the peak of water content occurred at 40-60 cm below the surface (Figure 5). In the no-burn treatment, soil moisture content ranged from 0.06 - 0.50 g g⁻¹ with a mean of 0.28 g g⁻¹ and a peak occurring at 60-90 cm below the surface (Figure 5). Soil moisture was significantly greater in the no-burn compared to the burn treatment ($t = 3.61$, $p < 0.001$). Higher organic matter likely contributed to the higher moisture content in the no-burn treatment, as organic matter has high water holding capacity. Differences in water content between treatments were not apparent at shallow depths where the highest presence of soil organic matter was observed (Figures 2 and 3). This suggests that some factor besides soil organic matter is important in controlling soil moisture, possibly soil texture or structure. In South

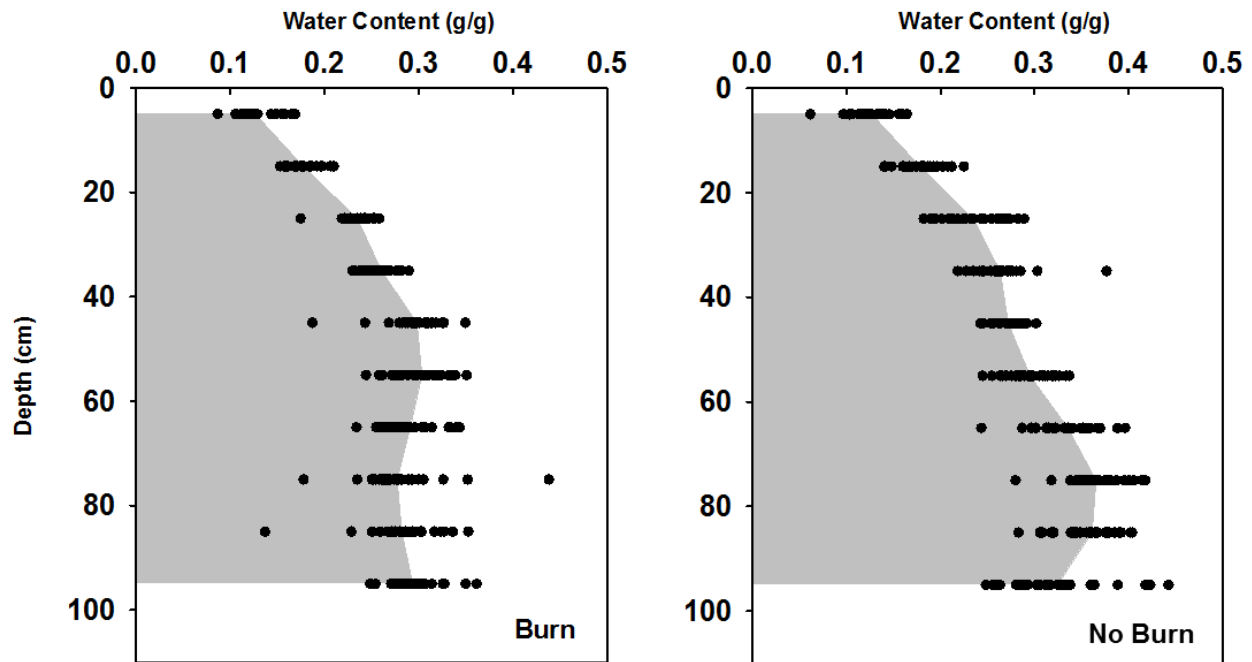


Figure 5: Each water content measurement is represented by a point, and shaded grey area delineates the mean water content for each mean depth.

Louisiana, shallow water tables are common, and soil moisture typically increases with depth. At the time of sampling, a water table was not observed in the top 1 m depth.

Cation exchange capacity varied from 9.2 to 55.8 meq 100g⁻¹ in the burn treatment with a mean of 28.6 meq 100g⁻¹, and the peak of CEC occurred at 40-60 cm below the surface (Figure 6). In the no-burn treatment, CEC varied from 12.9 to 61.0 meq 100g⁻¹ with a mean of 29.8 meq 100g⁻¹, and the peak CEC occurred between 60 and 90 cm. The peak CEC for each treatment generally corresponded with the second peak of both SOC and soil nitrogen, the first peak occurring within 20 cm of the soil surface. Notably, CEC values were relatively low in the shallow depths even though both SOC and soil nitrogen were relatively high.

Cation exchange capacity is commonly correlated with soil organic matter content, so CEC measurements would be expected to correlate well with both SOC and soil nitrogen (e.g. Parfitt et al., 1995). However, such correlations were not apparent for either variable in our dataset, and coefficients of

determination for linear regressions of CEC as a function of SOC and soil nitrogen were low ($R^2 < 0.05$) in all cases. One potential reason for this is an observed threshold of CEC, below which both SOC and soil nitrogen were uncorrelated to CEC and above which correlations were notably stronger. When CEC values below 20 meq/100 g were excluded from the regression, correlation increased significantly, and this effect was stronger in the no-burn treatment (Figure 7). In the burn treatment, approximately 68 % of the area of the mean CEC curve fell under the 20 meq/100 g threshold and approximately 63 % of the area of the mean CEC curve fell under this threshold in the no-burn treatment (Figure 6). Therefore, in the upper 20 cm of the soil profile, a large proportion of the CEC was due to a factor other than organic matter. Conversely, in depths where most of the CEC values were above the threshold, soil organic matter was a contributing factor to CEC.

The CEC of soil organic matter increases as it decomposes from newly added plant matter to humic substances (Butler et al., 2001). This means that areas of the soil having stronger correlations of CEC with SOC and soil nitrogen may be interpreted as having older, more degraded organic substances than areas where the correlation is weaker. The soil depths having strongest correlation between SOC and CEC were 55 and 65 cm in the no-burn treatment ($R^2 = 0.57$ and 0.39 , respectively) and 45 and 95 cm in burn treatment ($R^2 = 0.37$ and 0.51 , respectively). The depths with the highest correlation between soil nitrogen and CEC were 35 cm in the no-burn treatment ($R^2 = 0.16$) and 25, 45, and 95 cm in burn treatment ($R^2 = 0.42$, 0.49 , and 0.59 , respectively). Weaker correlations of CEC with SOC and soil nitrogen in the upper 20 cm of soil in both treatments suggest that soil organic matter in the shallow depths is relatively new compared that found deeper in the profile. This agrees with evidence from other studies that residence time of SOC tends to increase with depth (Rumpel et al., 2002; Schöning and Kögel-Knabner, 2006).

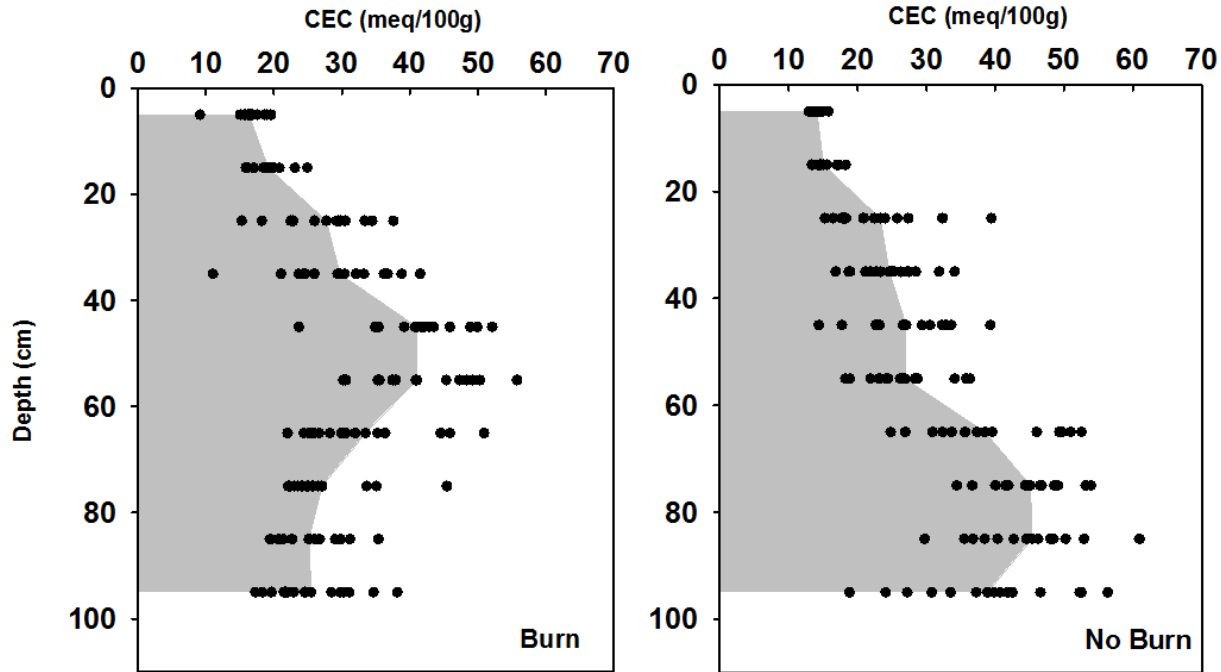


Figure 6: Each CEC measurement is represented by a point, and shaded grey area delineates the mean CEC for each mean depth.

Correlations between CEC and gravimetric water content were stronger than those between CEC and both SOC and soil nitrogen, and the relationship between CEC and soil moisture content displayed a positive log-linear relationship (Figure 8). Because water content and CEC are not directly related, this result suggests a third factor which is associated with soil water and also contributes to CEC. Most likely, this third factor is clay content, which is a strong control on both organic matter stabilization and water holding capacity. Differences in clay content with depth may be from soil formation processes, which are discussed further in section 5.3. Another possible contributor to this relationship is dissolved organic carbon. This hypothesis is supported by findings of relatively low CEC in the near-surface profile despite relatively high SOC and soil nitrogen, because soil moisture content was also relatively low in this zone.

Soil pH was lowest near the soil surface and increased with depth in both treatments (Figure 9). In the burn treatment, soil pH varied from 6.17 to 8.23 and increased sharply within the first 30 cm from the surface. Similarly, in the no-burn treatment soil pH varied from 5.57 to 8.08 and increased sharply

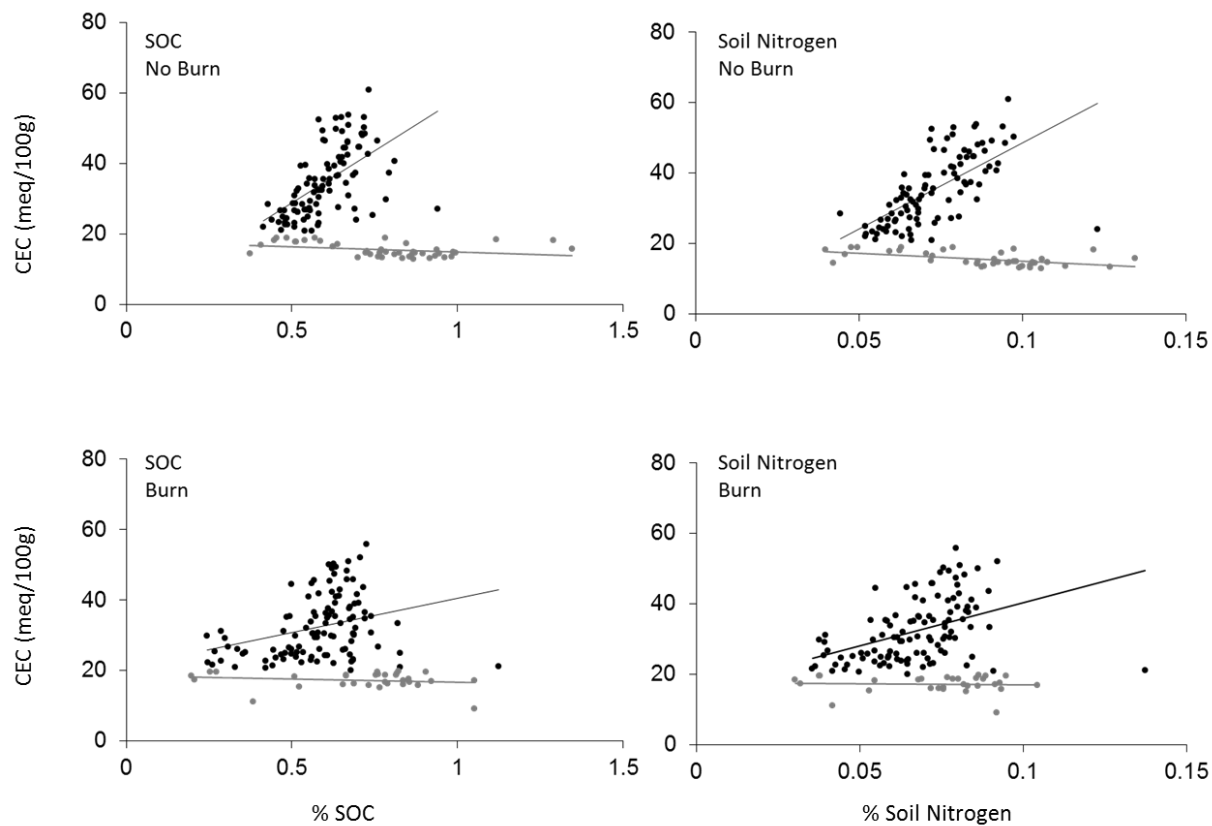


Figure 7. A threshold of correlation between CEC and SOC and between CEC and soil nitrogen occurred at approximately 20 meq/100g. This phenomenon was more apparent in the no-burn treatment.

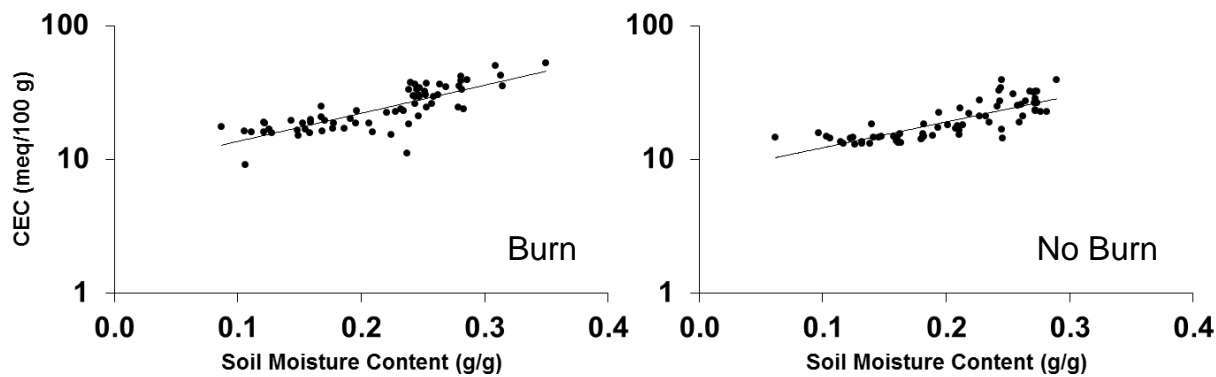


Figure 8: A strong, positive, log-linear relationship existed between CEC and soil moisture content.

within the first 30 cm from the surface. Loss of base cations during burning generally causes a drop in pH (Arocena and Opio, 2003; Ulery et al., 1993), but in this study, mean pH was higher at the soil surface in the burn treatment (6.55) compared with the no-burn treatment (5.94). Differences between the two treatments were significant in the upper 20 cm ($t = 3.9$, $p < 0.001$), and pH in the no-burn treatment was lower within this zone. For the full depth profile, the mean pH of the burn treatment (7.38) was in fact lower than the mean pH of the no burn treatment 7.56, but the differences were not significant ($t = -1.7$, $p = 0.08$). This suggests that the loss of base cations from burning does not have a strong effect on soil pH and that other factors such as nitrogen fertilization may play a larger role.

The series description for the Commerce soil notes that reactivity varies from medium acid to moderately alkaline and that horizons below approximately 40 cm contain “shell fragments”, which would suggest the presence of inorganic carbon (NRCS, 2014). The Commerce soil series is widely distributed across the Mississippi River alluvial valley; therefore, soil heterogeneity within the series is likely. Harrell and Wang (2006) found pH values of 7.4 to 7.5 in the upper 45 cm of a Louisiana Commerce soil and measured a calcium carbonate equivalent of 11.1 to 12.5 cmol/kg (0.11 – 0.12 %). In our study however, inorganic carbon was not detectable, therefore relatively high pH values are likely the result of the presence of base cations such as sodium or potassium, but this hypothesis is untested.

Although soil bulk density was measured for each sample, mechanical core sampling is a highly inaccurate method of quantifying soil bulk density. This is due to compaction, which is often observed at various depths as the core penetrates into the soil profile. Although an overall bulk density of the entire depth of sampling can be calculated, bulk densities for individual depths are unreliable. The mean bulk densities were 1.23 and 1.22 g cm⁻³ for the burn and no-burn treatments respectively, and these values were used for carbon sequestration estimates which are given in section 5.4.

Isotropic semivariogram analyses of SOC and soil nitrogen were completed for each individual depth increment (Appendices A and B). Most of these semivariograms did not exhibit spatial

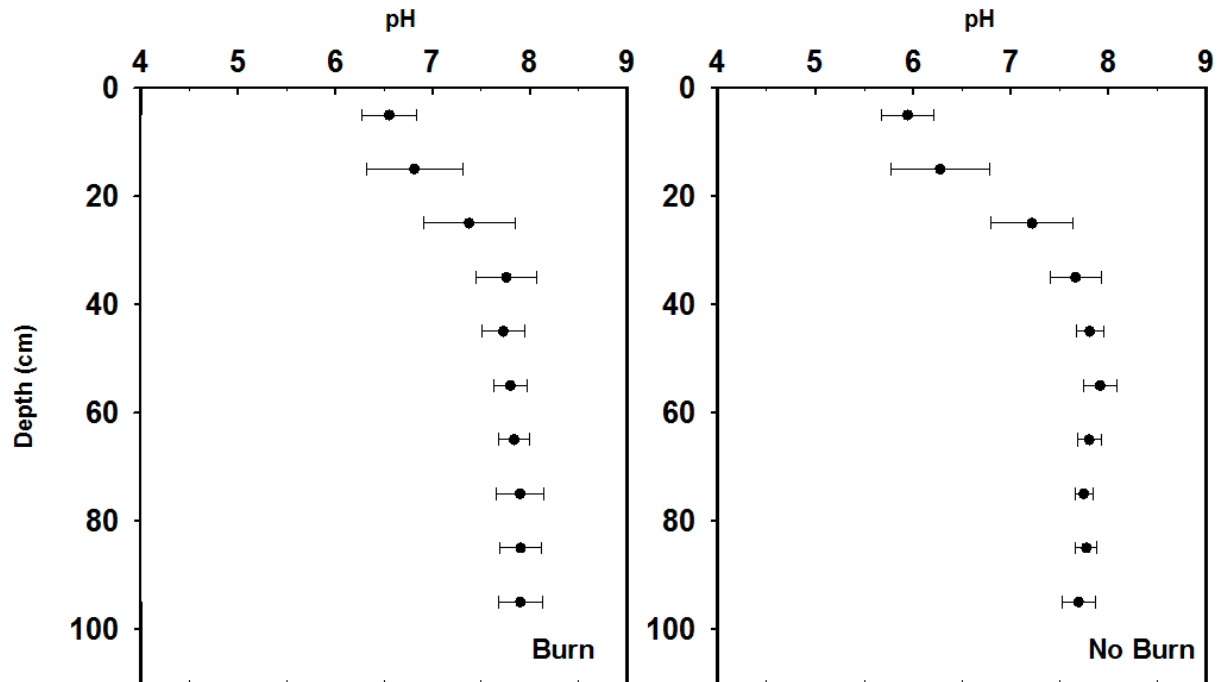


Figure 9: Mean pH is represented by each point, and error bars are one standard deviation from the mean.

autocorrelation, and modeling was not feasible. Using the entire dataset, spatial autocorrelation was present for SOC, soil nitrogen, soil moisture, and CEC. Therefore, variogram modeling and kriging were performed (Table 7 and Figures 10-18). Semivariograms of SOC displayed strong autocorrelation for both treatments and a range of autocorrelation that was almost twice as large for the burn (range = 18.95 m) compared to the no-burn treatment (range = 10.19 m) (Figure 10 and Table 7), which suggests greater spatial heterogeneity of SOC in the no-burn treatment. Overall variance was low but was higher in the burn treatment for both the overall dataset and within lag classes, as indicated by the higher sill (3.88×10^{-2}) and higher overall variance (3.34×10^{-2}) as compared to the no-burn sill (2.50×10^{-2}) and overall variance (2.69×10^{-2}). This means that values for SOC are more similar to one another at shorter distances and have a more predictable spatial structure in the no-burn compared to the burn treatment. The ranges of spatial correlation were notably smaller in both treatments compared to those reported by Johnson and Richard (2005) for sugarcane cropping systems in Patoutville, LA, which were between 29.4 and 146.4

m. These differences may be the result of sampling scale; soil sampling was conducted at 10-15 m spacing in the Patoutville study compared to 1.8-m-spacing in this study.

Greater heterogeneity of SOC in the no-burn treatment was corroborated by kriging of SOC (Figure 11) where delineation of discrete areas of relatively high and low SOC contrasted with a comparatively smooth decreasing gradient of SOC with depth in the burn treatment. As expected, the highest amount of SOC was present near the soil surface in both treatments, and this layer of SOC was more pronounced in the no-burn treatment. An additional zone of relatively high SOC at the lower depth of the no-burn treatment was unexpected, because SOC typically decreases with depth (Mishra et al., 2009). Mobility of DOC is a likely contributing factor to this vertical distribution of SOC.

Semivariograms of soil nitrogen displayed strong autocorrelation for both burn and no-burn treatments and a range of autocorrelation that was almost twice as large for the burn (range = 17.87 m) compared to the no-burn treatment (range = 7.76 m) (Figure 12 and Table 7. The range of autocorrelation for soil nitrogen was comparable to those of SOC discussed previously. Overall variance was lower in the burn (variance = 2.61×10^{-4}) compared to the no-burn treatment (variance = 2.89×10^{-4}), but the sill was slightly higher for the burn (sill = 3.75×10^{-4}) compared to the no-burn treatment (sill = 3.26×10^{-4}).

Overall, spatial trends of soil nitrogen were similar to those of SOC, and kriging illustrated a greater heterogeneity of soil nitrogen in the no-burn treatment (Figure 13). The highest amount of soil nitrogen was present near the soil surface in both treatments, and this layer of soil nitrogen was more pronounced in the no-burn treatment. As with SOC, an additional zone of relatively high soil nitrogen below 0.6 m in the no-burn treatment may be related to DOC.

Water content was strongly spatially autocorrelated in both treatments (Figure 14 and Table 7). The range of spatial autocorrelation for soil moisture content was similar for both treatments, but the variance and sill were notably higher in the no-burn (variance = 6.40×10^{-3} , sill = 7.47×10^{-3}) compared to the burn treatment (variance = 3.90×10^{-3} , sill = 4.38×10^{-3}). Kriging of soil moisture content indicated a

Table 7. Variogram model parameters for each variable and treatment.

Variable	Treatment	Model	R ²	Variance	Range (lags)	Range (m)	Sill	Nugget
SOC	Burn	Spherical	0.88	3.34E-02	10.53	18.95	3.88E-02	9.30E-03
SOC	No Burn	Spherical	0.97	2.69E-02	5.66	10.19	2.50E-02	2.00E-03
Soil N	Burn	Spherical	0.93	2.61E-04	9.93	17.87	3.75E-04	1.44E-04
Soil N	No Burn	Spherical	0.81	2.89E-04	4.31	7.76	3.26E-04	6.00E-05
SMC	Burn	Spherical	0.94	3.90E-03	8.85	15.93	4.38E-03	2.20E-04
SMC	No Burn	Spherical	0.92	6.40E-03	9.57	17.23	7.47E-03	1.00E-05
CEC	Burn	Spherical	0.81	9.92E+01	4.63	8.33	1.45E+02	1.26E+01
CEC	No Burn	Spherical	0.85	1.62E+02	8.94	16.09	1.86E+02	2.00E+00

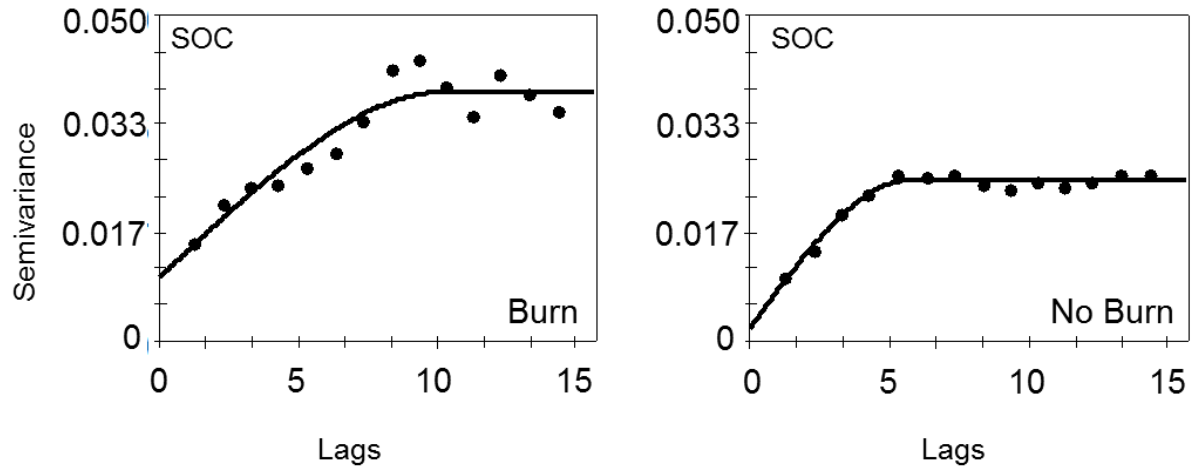


Figure 10: Variograms and best-fit models of percent SOC for all combined depths. 1 lag = 1.8 m.

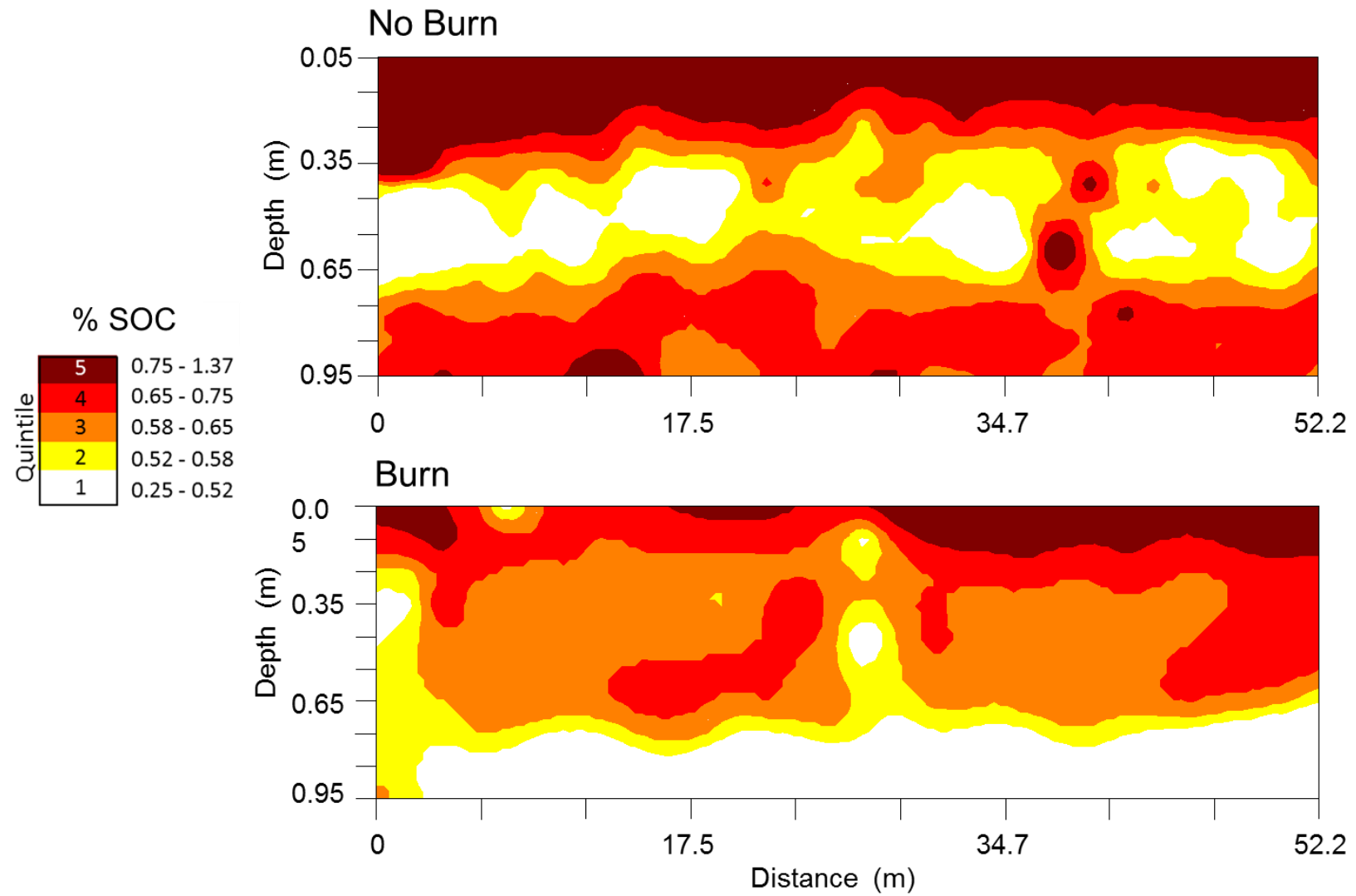


Figure 11: Kriging plots of SOC showed greater heterogeneity in the No Burn treatment..

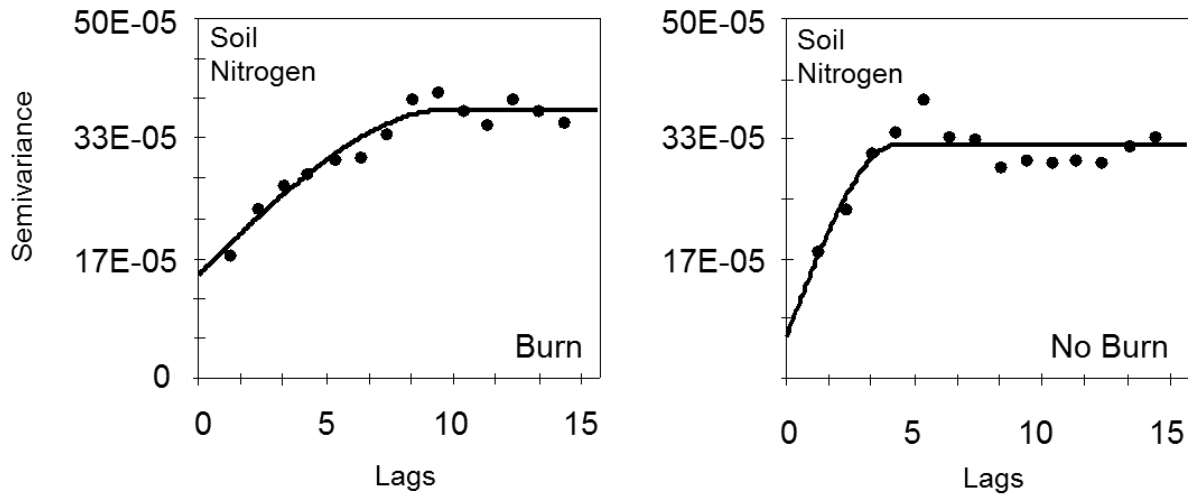


Figure 12: Variograms and best-fit models of percent soil nitrogen for all combined depths. 1 lag = 1.8 m.

general decrease with depth in both treatments (Figure 15), and this trend was more pronounced in the no-burn treatment, which also had overall higher soil moisture content. A zone of relatively high soil moisture content at 0.65 to 0.95 m in the no-burn treatment corresponded to a zone of relatively high SOC and soil nitrogen content, providing additional evidence for the hypothesis of mobility of DOC as an important factor in the vertical distribution organic matter in this system.

Similar to soil properties previously presented, spatial autocorrelation of CEC was apparent (Figure 16 and Table 7). In contrast to the other variables, the range of autocorrelation was greater in the no-burn treatment (range = 16.09 m) as compared to the burn treatment (range = 8.33 m), which suggests more spatial heterogeneity of CEC in the burn treatment. Kriging of CEC illustrated an area of lowest CEC in both treatments within the 0 to 0.2 m zone nearest to the soil surface (Figure 17). In the no-burn treatment, CEC generally increased with depth, and the area of highest CEC was at 0.65 to 0.95 m. In the burn treatment, CEC decreased with depth to approximately 0.65 m which was the area of highest CEC, then decreased toward the bottom of the sampled profile. Spatial trends in CEC were most reflective of those of soil moisture content, which is in agreement with the high correlation found between those two variables. Similar to SOC, the ranges of spatial correlation were notably smaller in both treatments

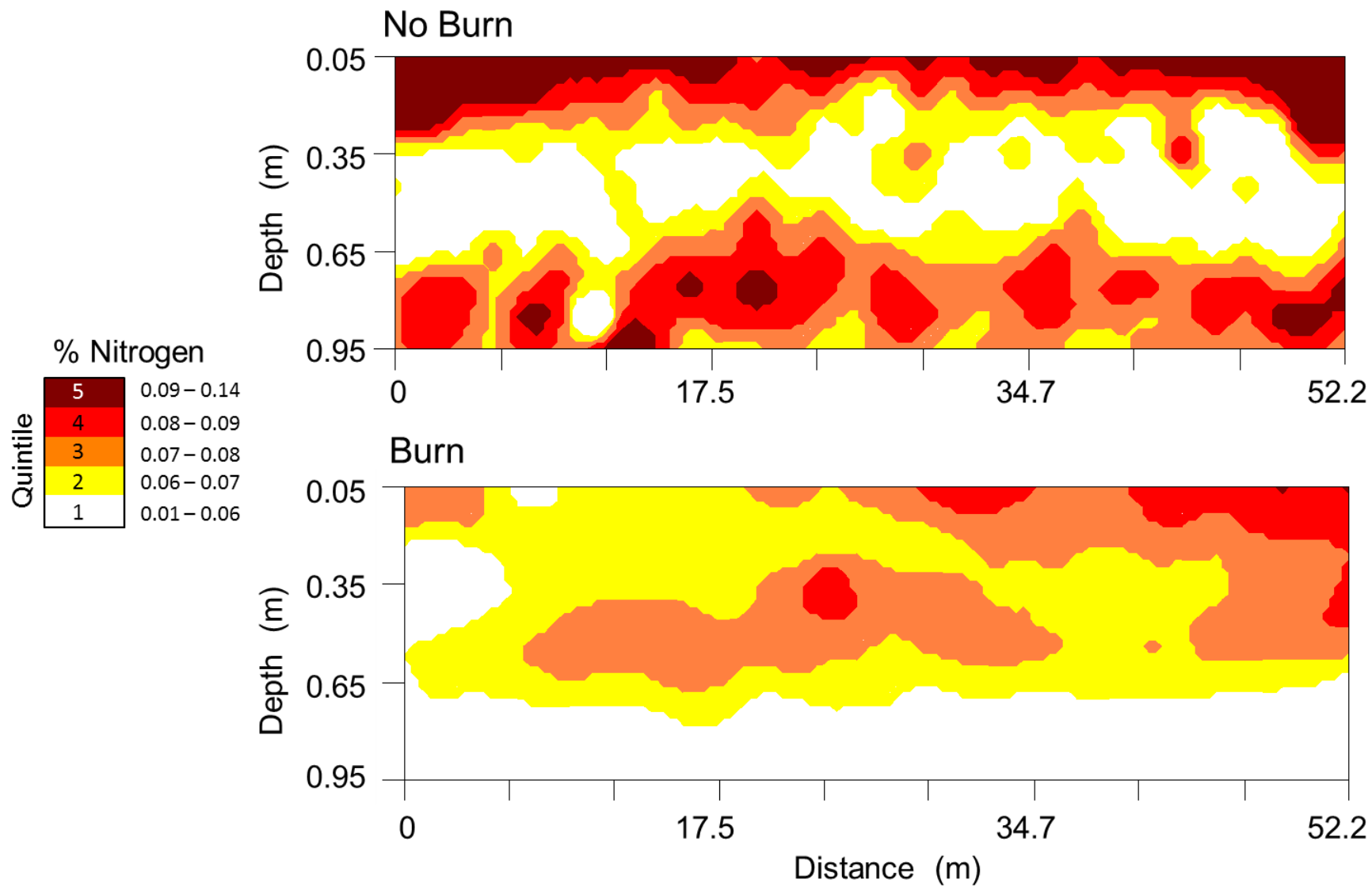


Figure 13: Kriging plots of soil nitrogen showed greater heterogeneity in the No Burn treatment.

compared to those reported by Johnson and Richard (2005) for sugarcane cropping systems in Patoutville, LA, which were between 30.9 and 127.0 m. These differences may be the result of sampling scale; soil sampling was conducted at 10-15 m spacing in the Patoutville study compared to 1.8-m-spacing in this study.

Results of deep sampling addressed the question of whether an apparent increasing trend in SOC and soil nitrogen, which was present in the 0.65 to 0.95 m depths of the initial sampling (Figures 2 and 3), persisted at depths below 1 m. Vertical distribution of SOC and soil nitrogen was characterized by a general decreasing trend in both treatments (Figures 18-23); however, values were relatively high and confirmed the presence of substantial amounts of soil organic matter at depths below the typical sampling depth of 20 to 30 cm. In the burn treatment, SOC varied between 0.15 and 0.84 % with a mean of 0.46 %. In the no-burn treatment, SOC varied between 0.18 and 1.31 % with a mean of 0.48 %. Soil nitrogen in the burn treatment varied between 0.02 and 0.11 % with a mean of 0.06 %, and soil nitrogen in the no-burn treatment varied between 0.03 and 0.13 % with a mean of 0.06 %. Neither SOC ($p = 0.545$, $t = 0.606$) nor soil nitrogen ($p = 0.547$, $t = 0.603$) differed significantly between treatments.

Gravimetric water content for the deep sampling increased in both treatments for the first meter and varied little below that point. In the burn treatment, water content varied from 0.15 to 0.38 g g⁻¹ with a mean of 0.23 g g⁻¹. In the no-burn treatment, water content varied from 0.06 to 0.28 g g⁻¹ with a mean of 0.21 g g⁻¹. At the time of deep sampling, the water table was approximately 1 m below the soil surface in both treatment plots, but mean gravimetric water content was lower in both treatments in comparison to the initial sampling which had mean water contents of 0.25 and 0.28 g g⁻¹ for the burn and no-burn treatments respectively. This difference is likely because of the timing of the sampling events: the initial sampling took place in spring when plants were growing, and the deep sampling occurred in late summer when the field was fallow. Additionally, the deep samples were collected after a prolonged rain-free period to facilitate removal of soil from the Giddings probe. In contrast to the initial sampling, soil water content was poorly correlated to SOC and soil nitrogen.

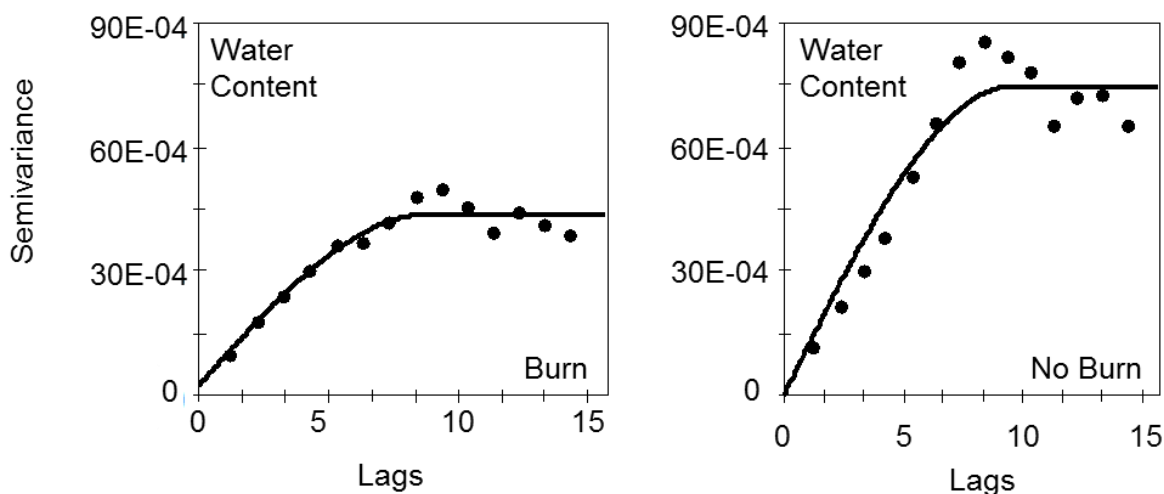


Figure 14: Variograms and best-fit models of soil moisture content (g/g) for all combined depths. 1 lag = 1.8 m

5.2 Carbon Sequestration Estimates

On a mass per area basis, there were 73.1 Mg ha^{-1} SOC in the burn treatment and 79.8 Mg ha^{-1} SOC in the no-burn treatment for the entire 1-m sampling depth. These figures are substantially greater than the total SOC reported for other agricultural soils in the region, which are between $20\text{--}40 \text{ Mg ha}^{-1}$ (Franzluebbers, 2010); however, estimates from these previous studies only considered SOC in the upper 10 to 20 cm of soil. In our study, the amount of SOC in the upper 20 cm of soil was 20.1 and 23.4 Mg ha^{-1} for the burn and no-burn treatments, respectively. Thus, SOC in the upper 20 cm accounts for only 28 to 29 % of SOC that is present in the first 1 m of soil. A comparison of SOC between the two treatments provided an estimate of the carbon sequestration potential of the no-burn treatment compared to the burn treatment. For the entire 1-m soil profile, SOC was greater in the no-burn treatment by 6.69 Mg ha^{-1} , an increase of 8.4 %. Averaged over the 12-year study period, this equates to $0.56 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, which is slightly larger than the amount of sequestration estimated by Franzluebbers (2010) of $0.45 \pm 0.04 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for conservation versus conventional tillage in the southeastern region of the United States. It is

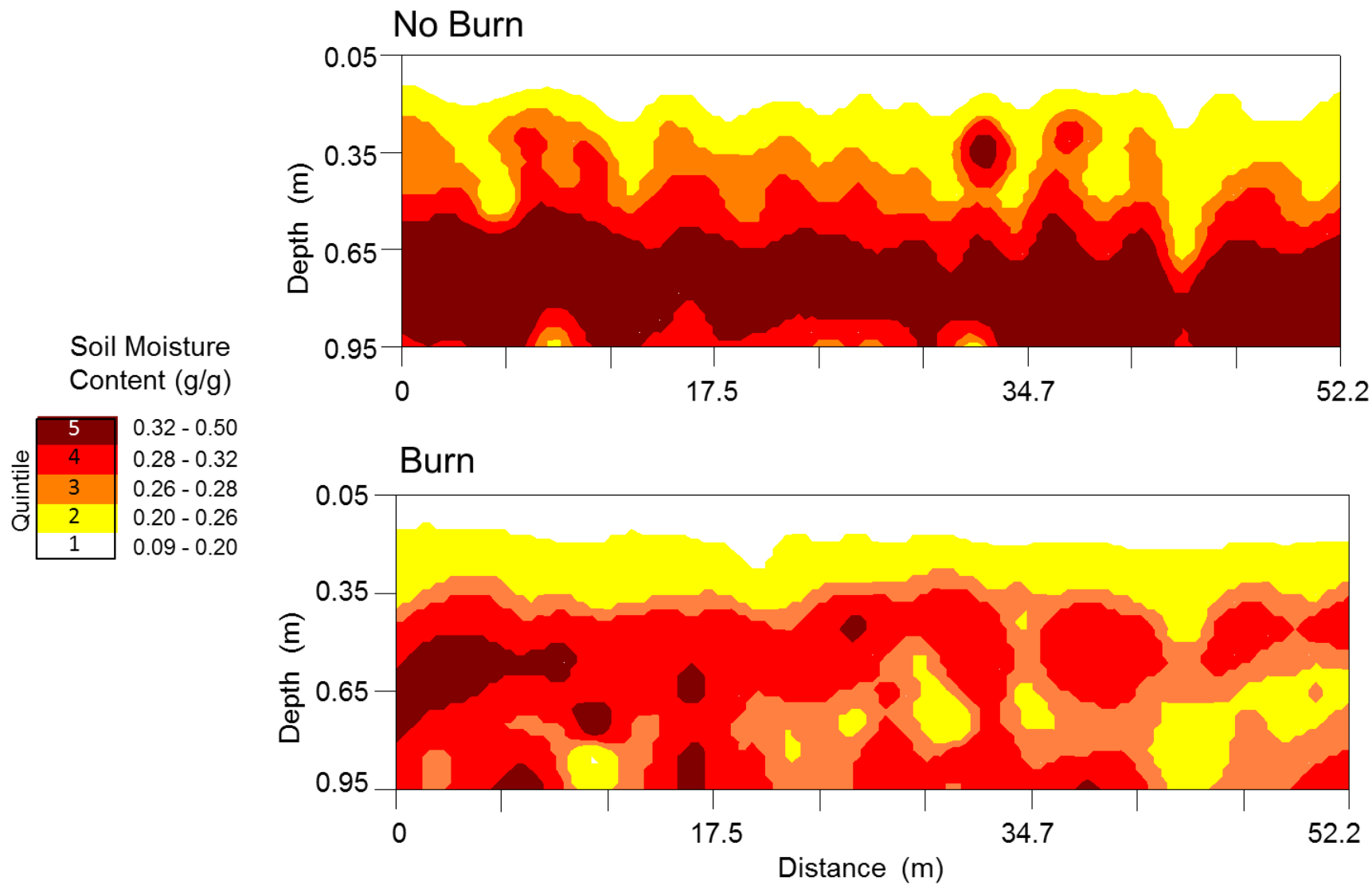


Figure 15: Kriging plots of soil moisture content showed an increase with depth for both treatments.

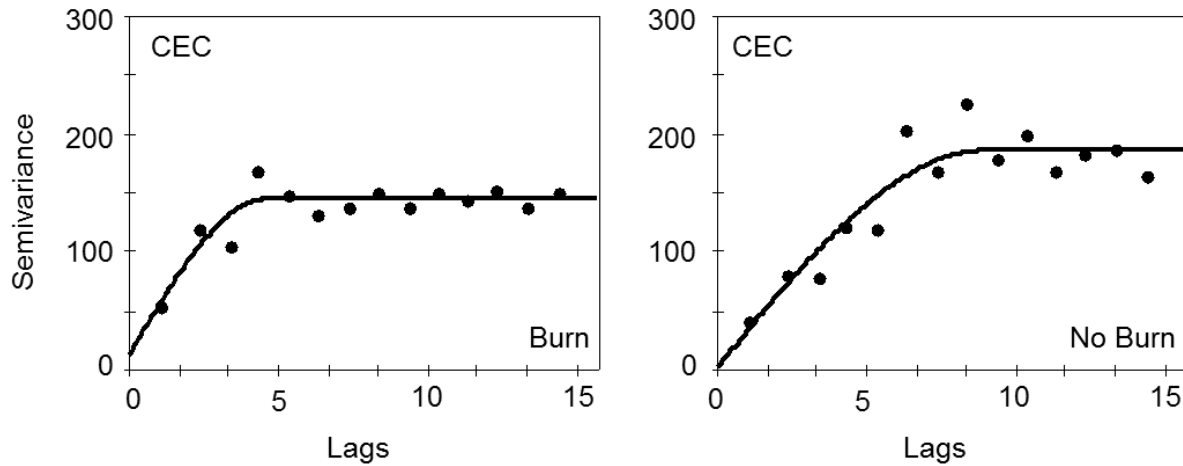


Figure 16: Variograms and best-fit models of cation exchange capacity (CEC) for all combined depths. 1 lag = 1.8 m.

notably smaller than the amount of sequestration estimated by Cerri (2011), which was $1.24 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the upper 30 cm for no-burn versus burned sugarcane-cropped soils in Brazil.

Because our study included the upper 1-m of the soil profile compared to the upper 10-30 cm of soil in the Franzluebbers (2010) and Cerri (2011) studies, our sequestration rates were markedly less than either of these when considering a comparable soil depth ($0.28 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in the upper 20 cm). One reason for this may be the timing of the soil sampling, which occurred shortly after stalks had been planted, and measurements may reflect loss of shallow soil organic matter from tillage and replanting as evidenced by the Cerri (2011) study. Another potential factor is the decreased yield in this region that is associated with the no-burn treatment (Arceneaux et al., 2011; Kennedy and Arceneaux, 2006). Decreased yield means less biomass overall that is available for incorporation into the soil, so this factor may have lessened the amount of carbon sequestration that occurred as a result of conservation management. Given the evidence for transport of DOC to greater depths, it is also possible that some new carbon was translocated from the 0 to 20 cm region to the 60 to 100 cm region.

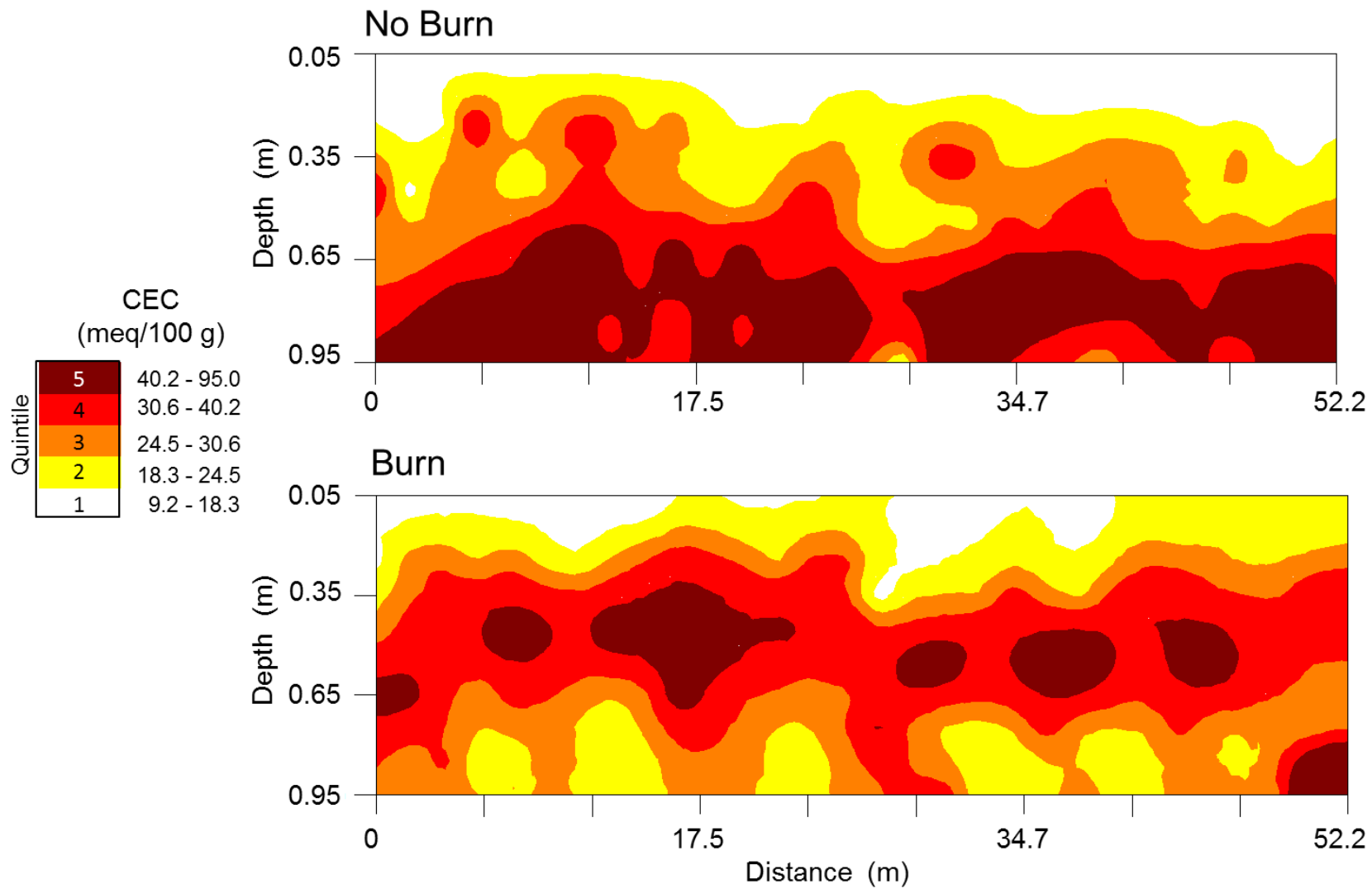


Figure 17: Kriging plots of cation exchange capacity (CEC) showed greater heterogeneity in the Burn treatment.

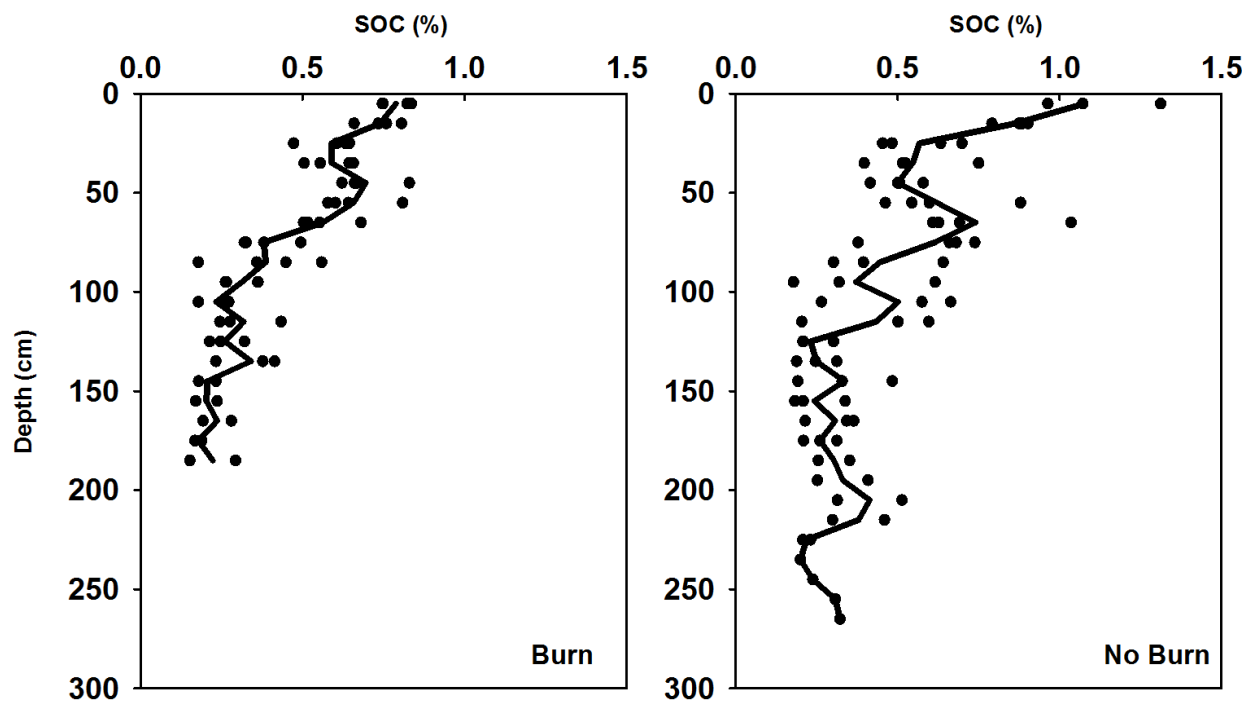


Figure 18: Each SOC measurement for the deep sampling is represented by a point, with a maximum of four points per depth per treatment. Black line indicates mean of each depth.

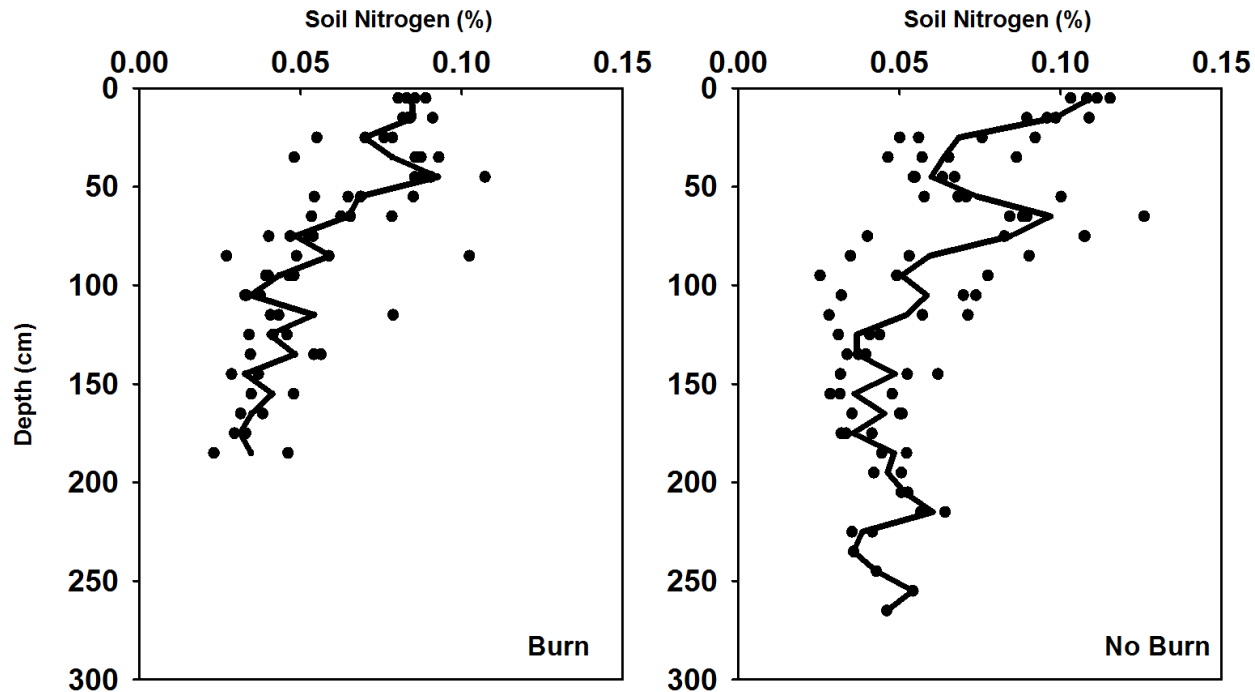


Figure 19: Each soil nitrogen measurement for the deep sampling is represented by a point, with a maximum of four points per depth per treatment. Black line indicates mean of each depth.

5.3 Vertical Distribution of SOC

Perhaps the most interesting result from this study was that the greatest differences between the two treatments did not occur near the soil surface as expected but instead occurred at depths well below the typical zone of measurement. This result may be particularly relevant to carbon sequestration, because not only is SOC at lower depths at risk of being vastly underestimated by methods which assume an exponential decrease in SOC with depth, but carbon stored deeper in the soil profile is more likely to remain there for long time periods. High heterogeneity of soil properties is typical in areas of fluvial deposition such as the Mississippi River alluvial valley (Aslan and Autin, 1999), and the possibility exists that one of the transects in this study lay in an area having higher clay content and associated higher organic matter. In the absence of control data, we cannot rule out the possibility of a pre-existing layer of organic matter in the no-burn treatment. However, the proximity of the treatment plots to one another as well as the total number of samples for each treatment allays this concern to some extent.

Assuming that there was not a pre-existing layer of organic deposition in the no-burn treatment plot, differences in SOC (and related properties) were from downward transport of soil water containing DOC and nutrients. This leaves the question of why the two treatments differ. Both treatments have relatively high pH below approximately 40 cm which favors transport over sorption of DOC. Two factors that are affected by burning and are discussed in section 3.3 may contribute to this phenomenon: pore-filling by fine ash particles and hydrophobicity of surface soils. Both of these factors act to inhibit percolation of water and nutrients into the deeper regions of the soil and therefore may inhibit the downward transport of DOC. Further, inhibition of downward flow may inhibit downward transport of nutrients. Deeper distribution of soil nutrients favors deeper distribution of plant roots (Robinson, 1996), and this effect may also contribute to the differences observed between treatments.

Because of specific hydrological conditions in this region, SOC in the subsoil may have extremely long residence times. In situations where the water table is near the soil surface, which is generally the case in wetlands and floodplains, degradation of organic matter occurs at a much slower rate

than in well-oxidized conditions. In South Louisiana croplands, a shallow water table is common, especially in areas adjacent to wetlands, and these conditions favor biogeochemical stabilization of soil carbon. Moerschbaeher (2012) monitored water table depth in a bottomland swamp near the Louisiana Agriculture Experiment Station's Sugar Research Station in St. Gabriel, LA, and found that the water table was within 2 m of the soil surface for approximately ten months of the year. Surface flooding at this site was recorded for 84 days of the year, and the lowest water levels occurred during the winter months. Therefore the warmest months, which would otherwise have the highest rates of microbial degradation, are also the time of greatest soil saturation, so degradation of organic matter is inhibited.

In the unique situation of the Southern Louisiana region, these hydrological conditions may affect the spatial and temporal distribution of both SOC and soil nitrogen. In areas of shallow water table and poor drainage, reduced conditions cause Fe and Al oxides to be released into solution, and the mobility of DOM increases accordingly. Because these compounds co-precipitate upon re-oxidation (Hagedorn et al., 2000), cycles of wetting and drying can lead to a transient zone of DOM that follows fluctuations in water table. Rising water table floods complexed organic matter that is otherwise highly stabilized (Guggenberger and Kaiser, 2003), and biogeochemical reduction causes DOM to be released into the soil water. As the water table drops, DOM moves downward accordingly. Water table rise from river forcing would then drive this DOC back upward in the soil profile, whereas water table rise from rainfall would bring more DOC from the surface downward.

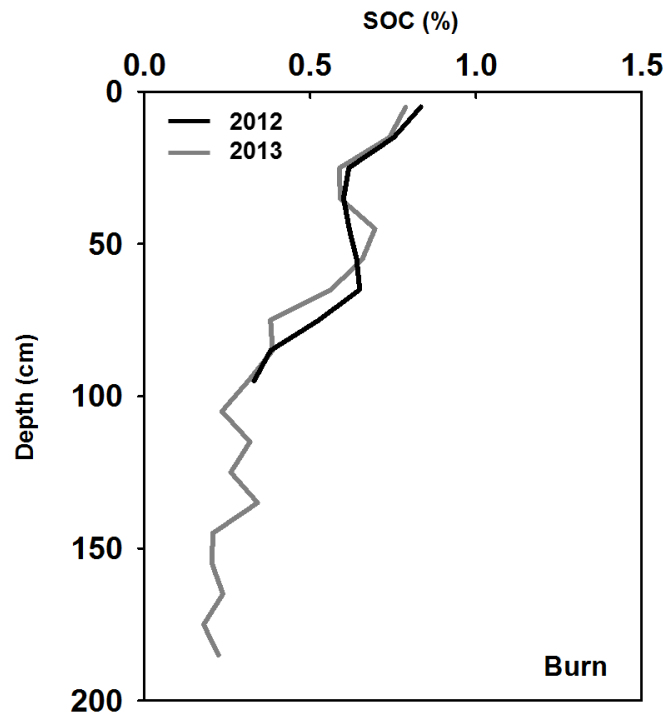


Figure 20: A comparison of mean SOC measurements for the Burn treatment for 2012 and 2013.

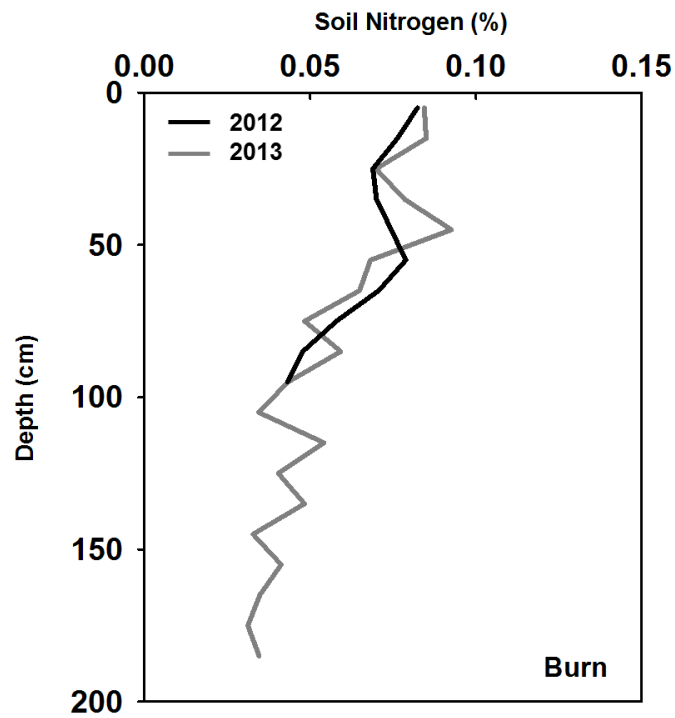


Figure 21: A comparison of mean soil nitrogen measurements for the Burn treatment for 2012 and 2013.

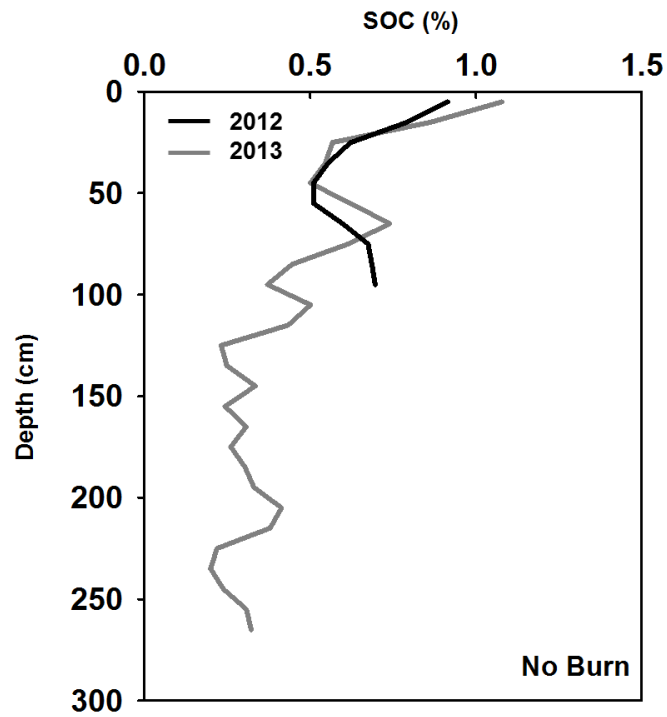


Figure 22: A comparison of mean SOC measurements for the No Burn treatment for 2012 and 2013.

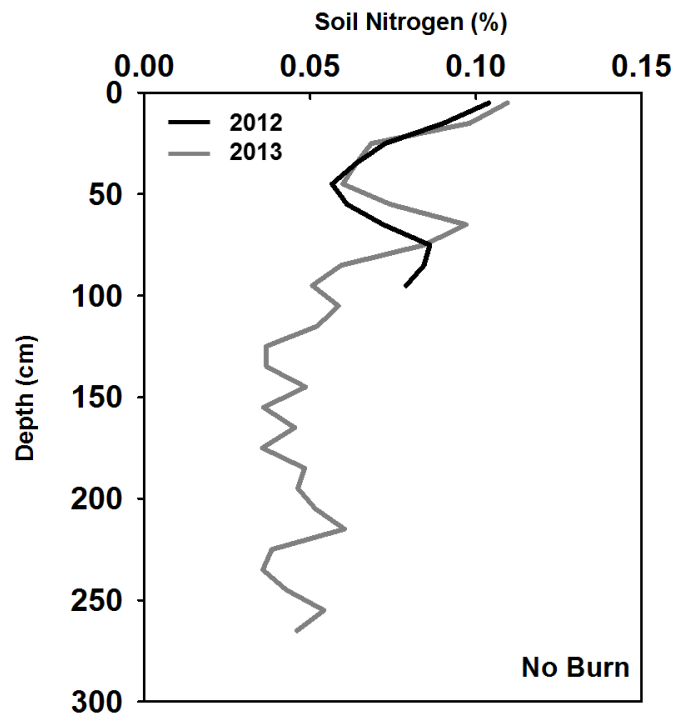


Figure 23: A comparison of mean soil nitrogen measurements for the No Burn treatment for 2012 and 2013.

6. Conclusions

In Southern Louisiana, soil carbon sequestration resulting from the conversion of conventional management of sugarcane in the form of annual burning to conservation management by leaving crop residues on the field was similar to that of other studies in the region when a comparable depth of soil was considered. This study differed from others in the region, and from most soil carbon sequestration studies overall, by considering spatial distribution of SOC to a depth of 1 m and by measuring SOC and soil nitrogen to depths beyond 2 m. The vertical distribution of SOC differed between treatments, with greater differences between treatments at depths below 60 cm. Although the pre-existence of a fluvial deposit of organic matter at this depth cannot be ruled out, a strong relationship between CEC and both SOC and soil nitrogen suggests and specific hydrological conditions in this environment support a zone of DOC at this depth which is potentially transient. Further studies are needed to determine the role of DOC in this and similar systems. Importantly, future studies of soil carbon sequestration and estimates of soil carbon stocks should consider SOC below the typical depth of measurement, because neglect of deeply distributed SOC may result in large underestimation.

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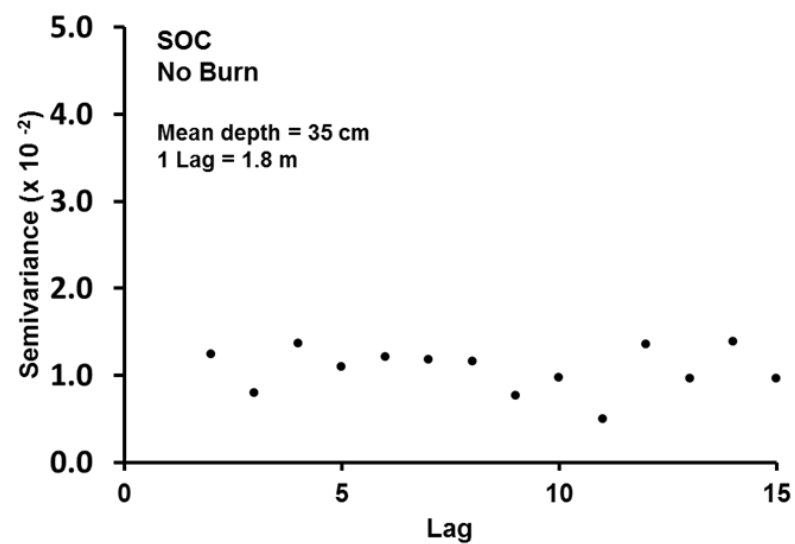
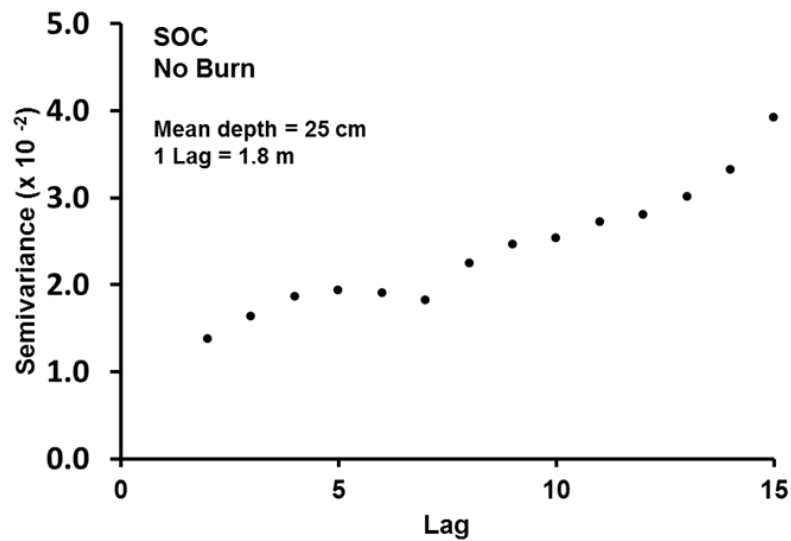
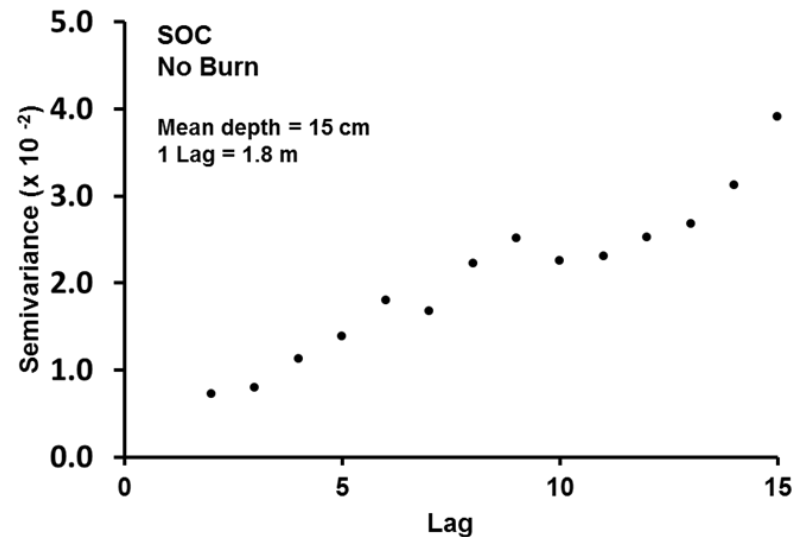
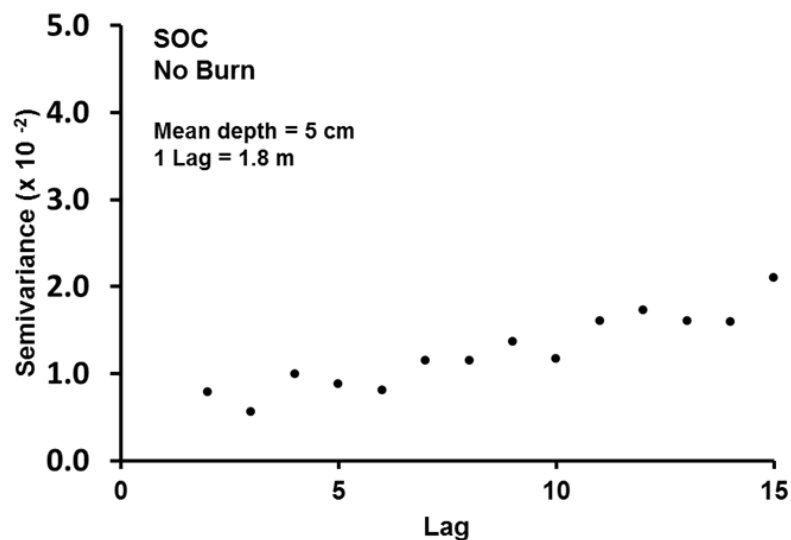
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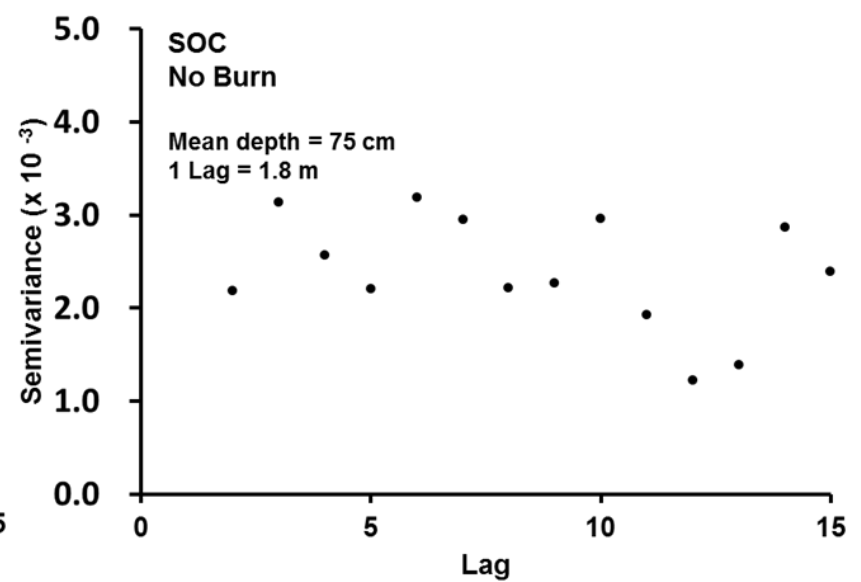
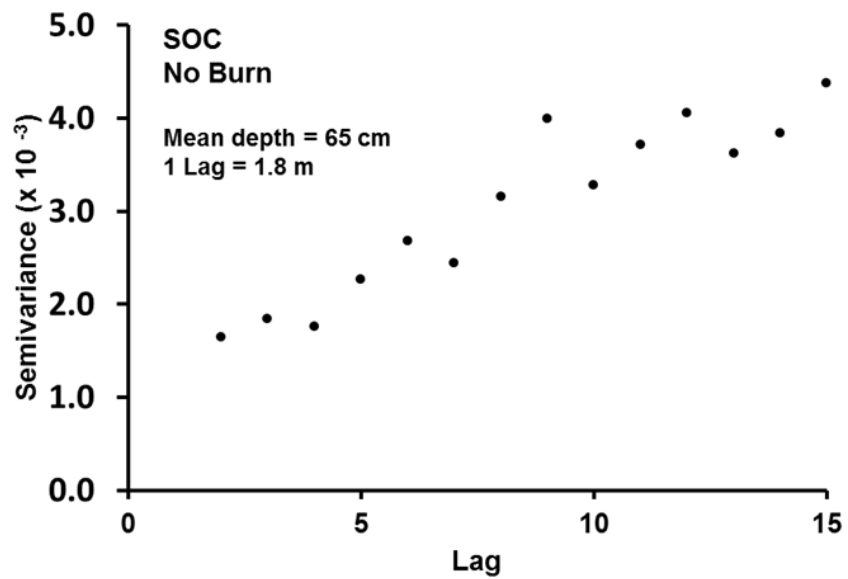
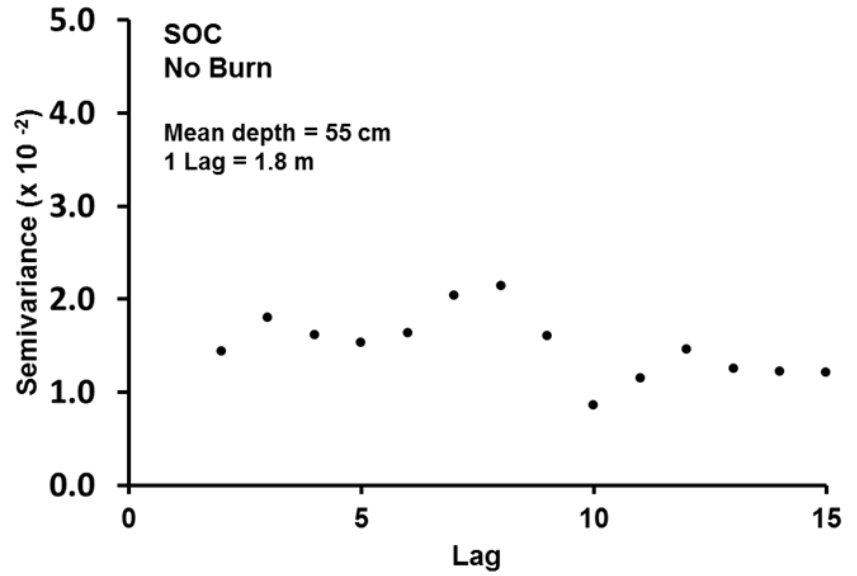
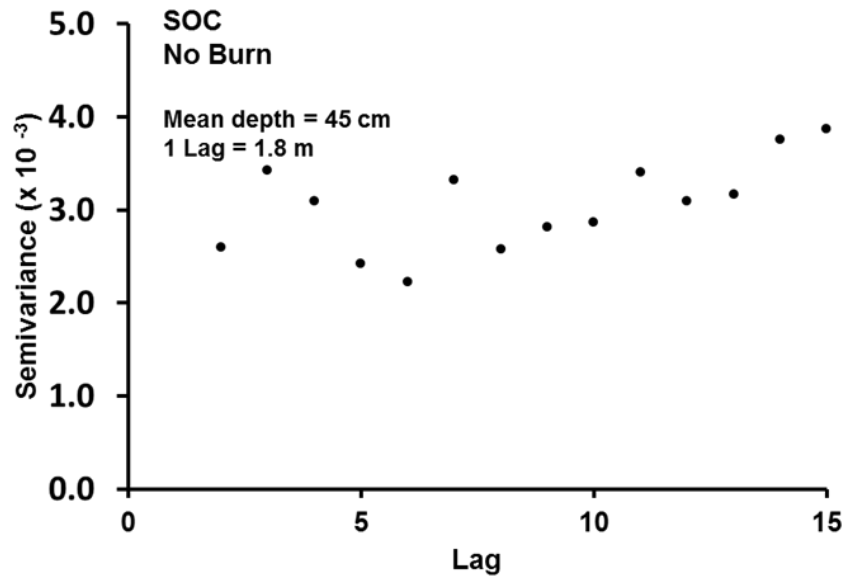
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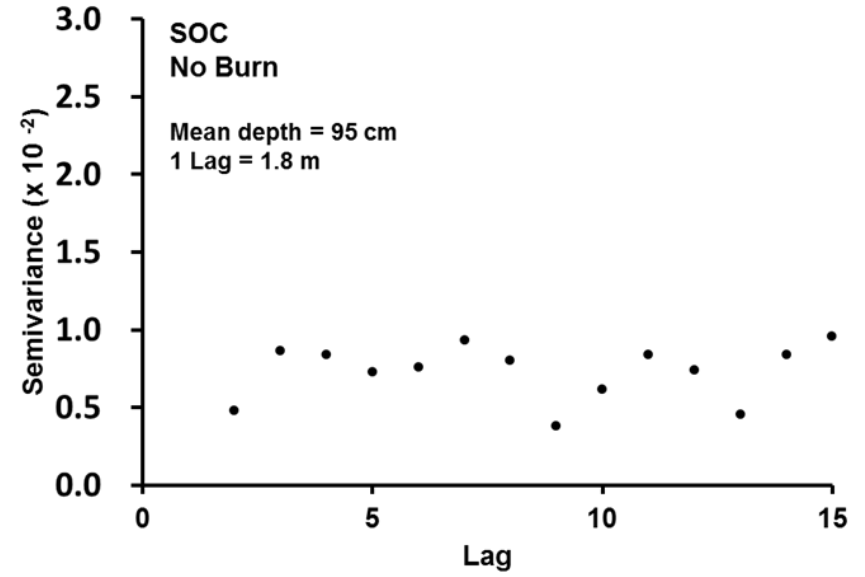
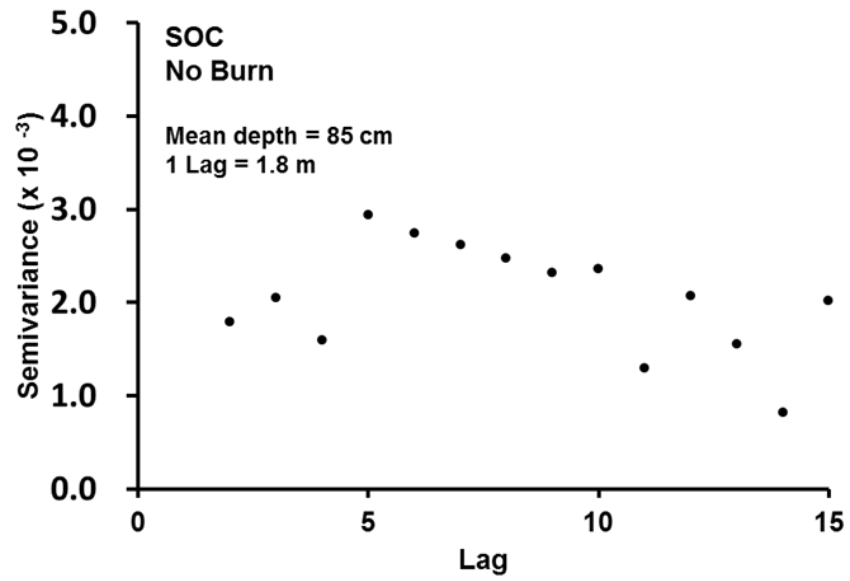
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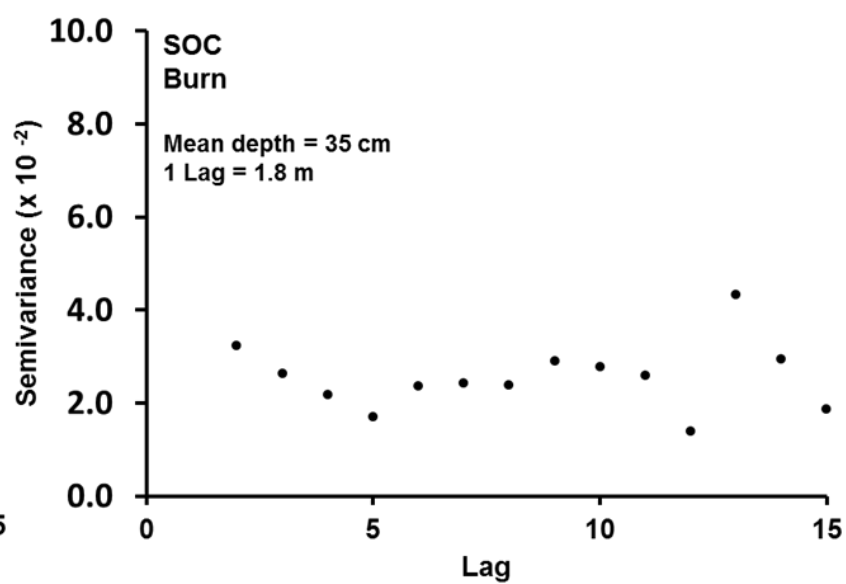
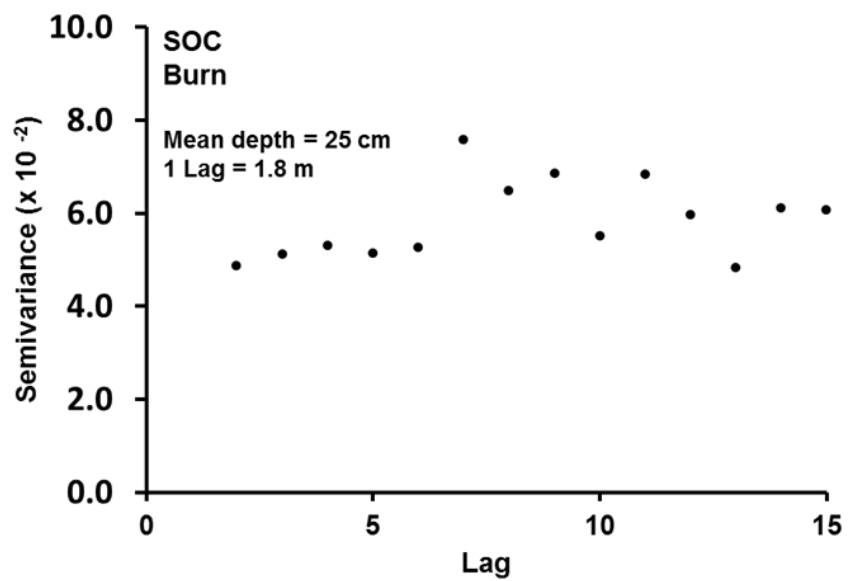
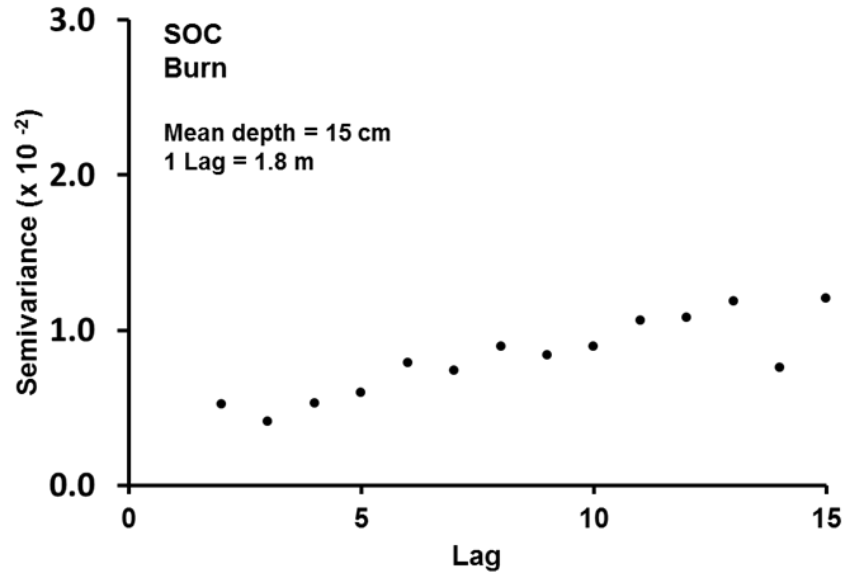
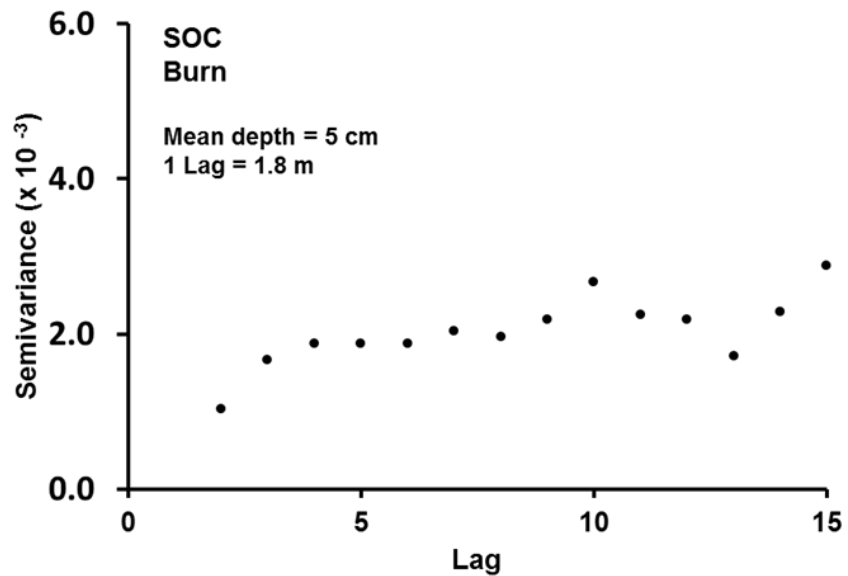
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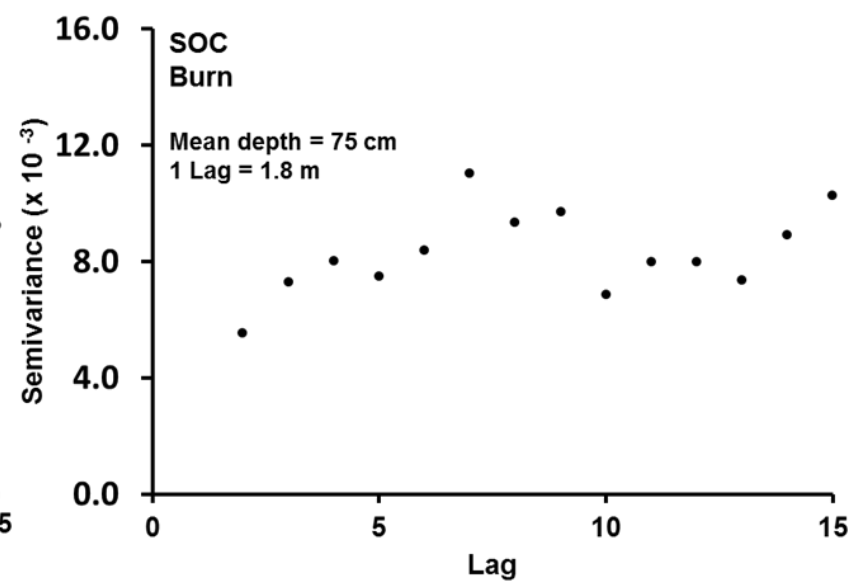
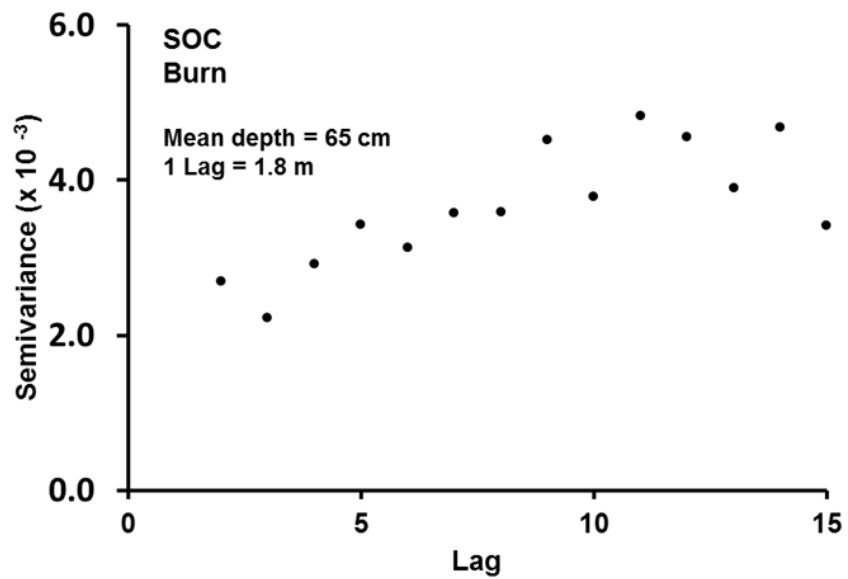
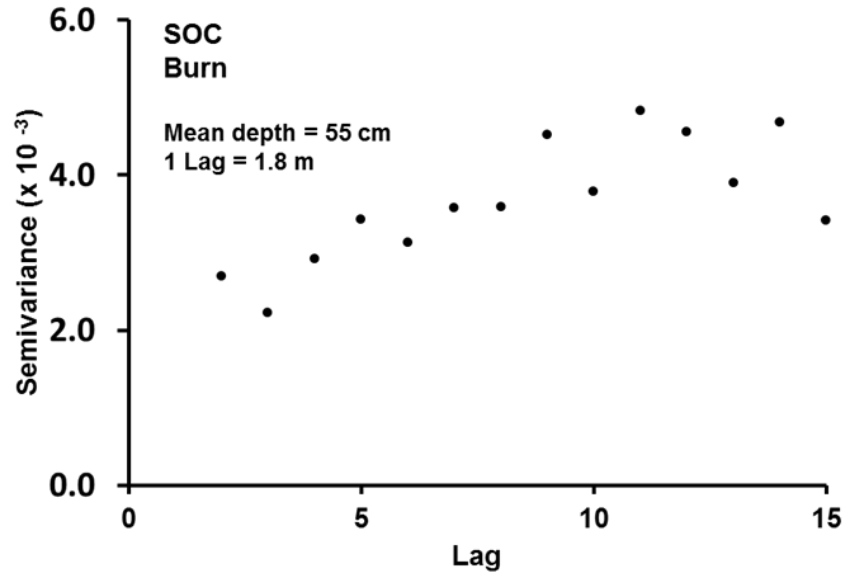
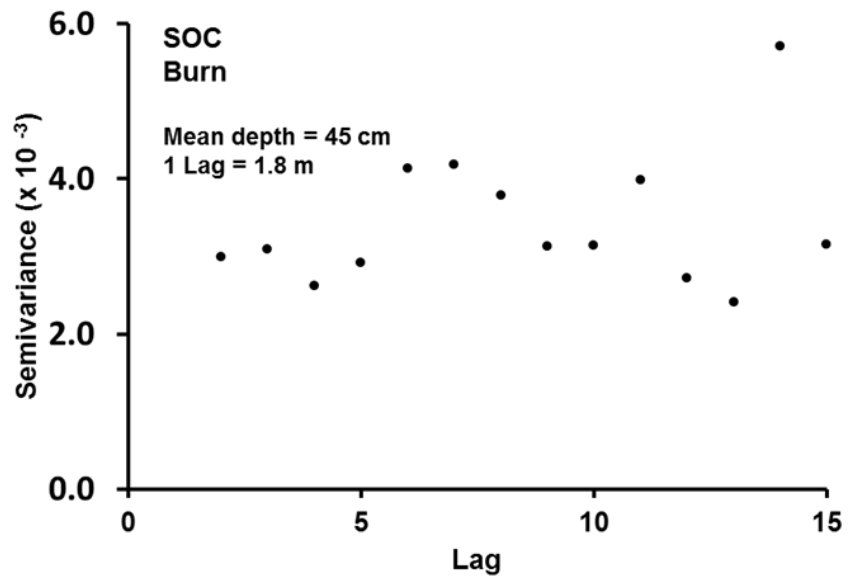
Appendix A: SOC variograms

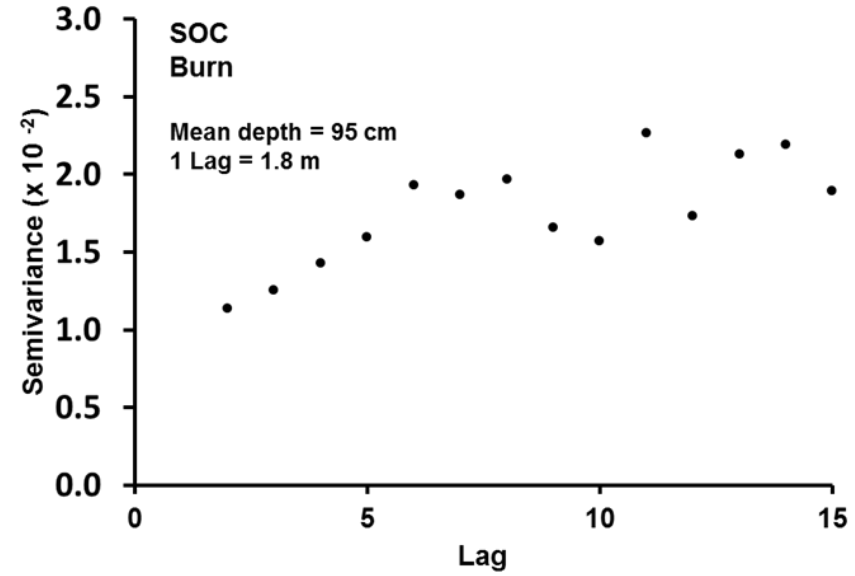
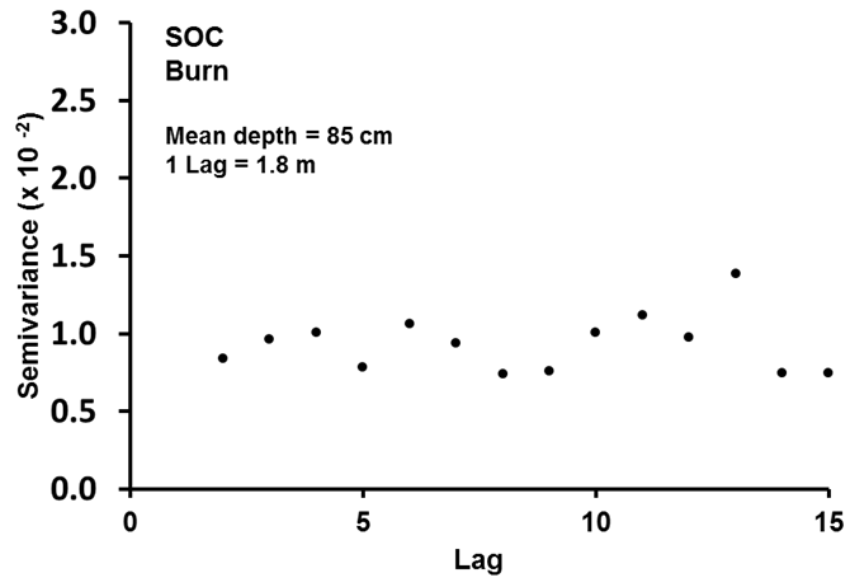




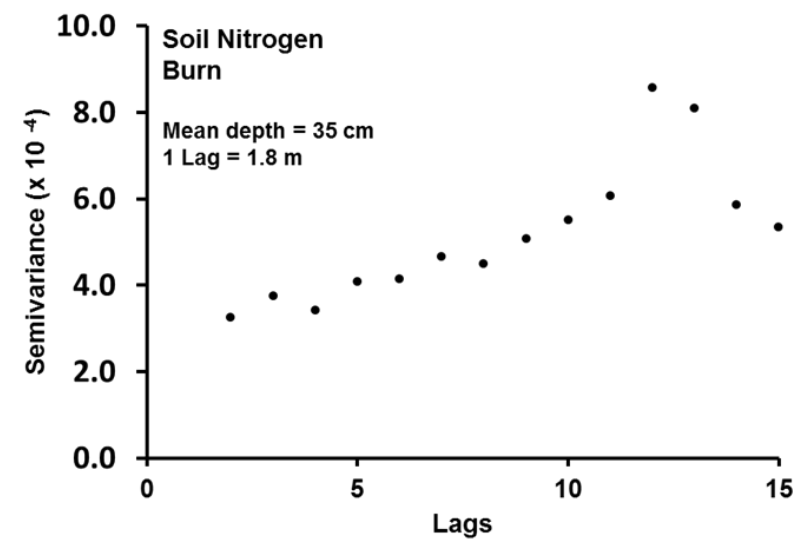
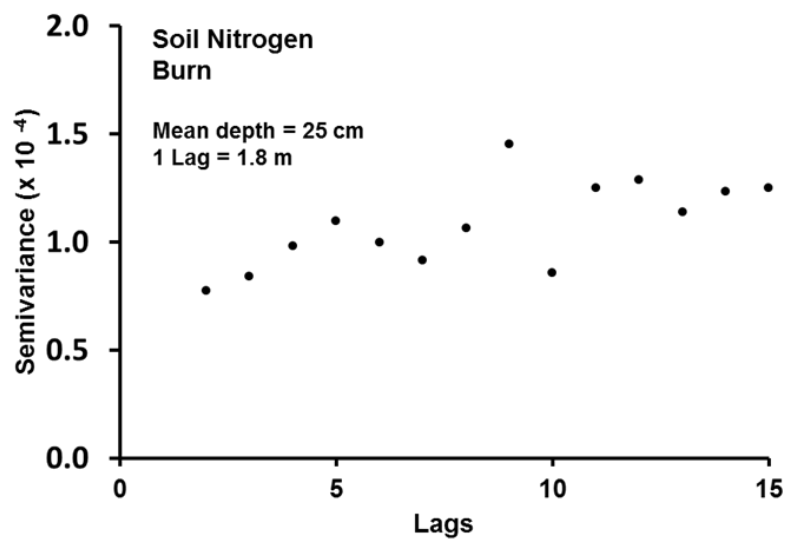
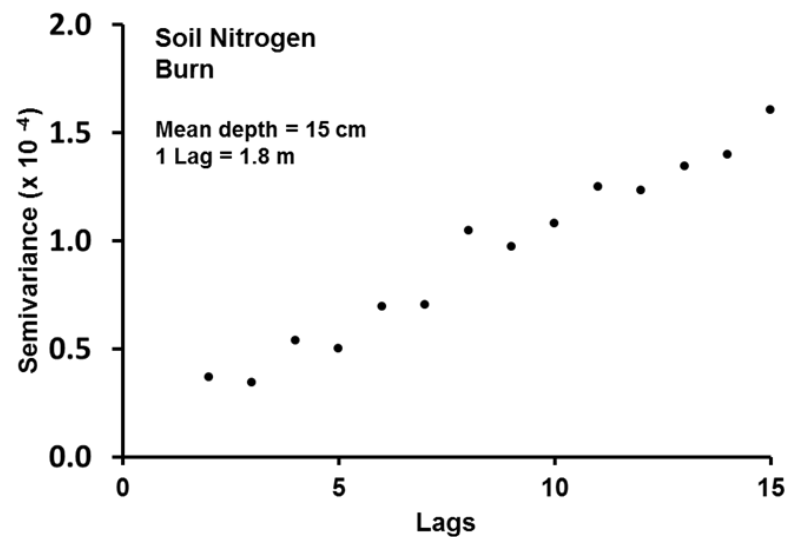
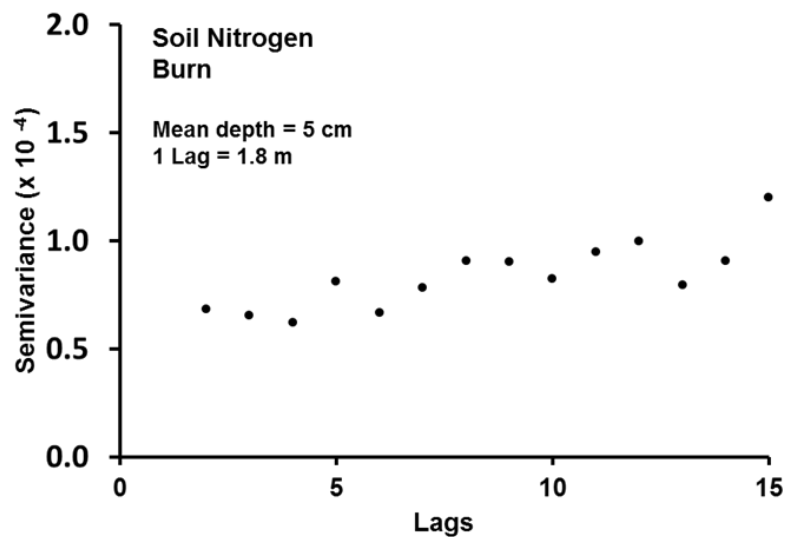


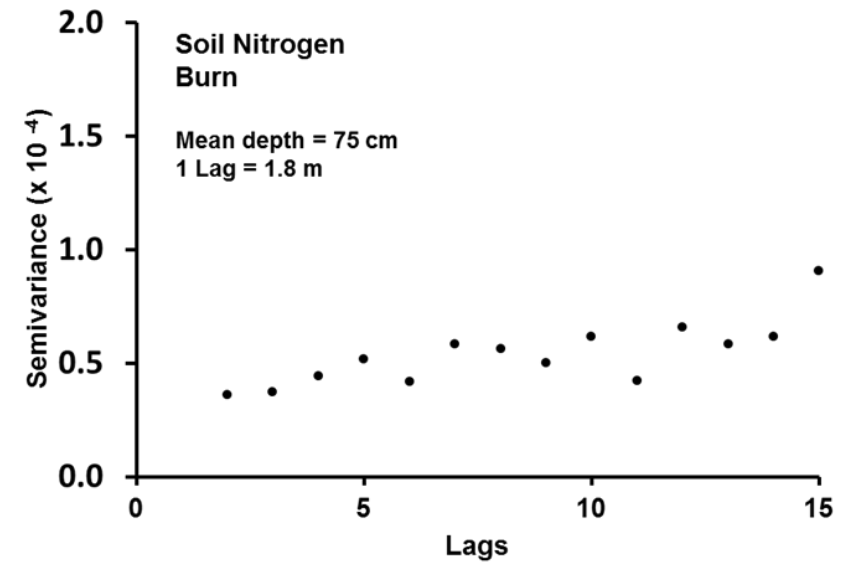
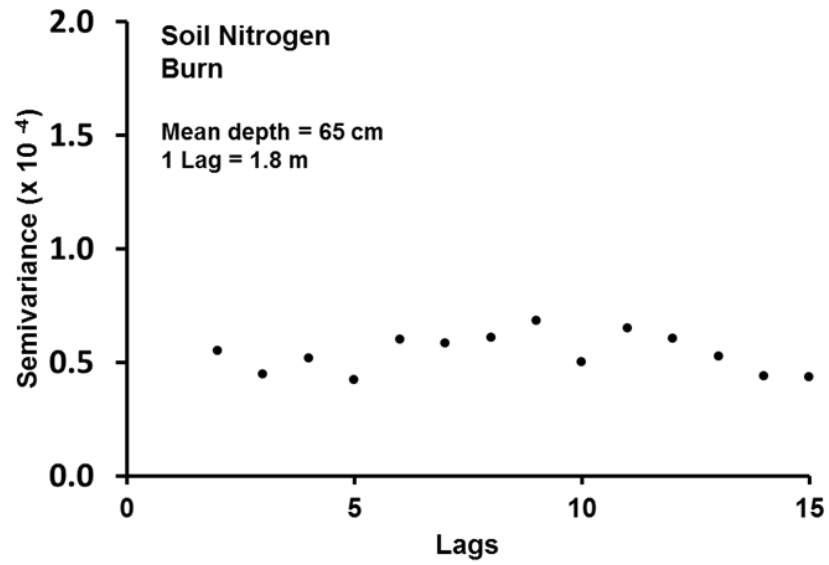
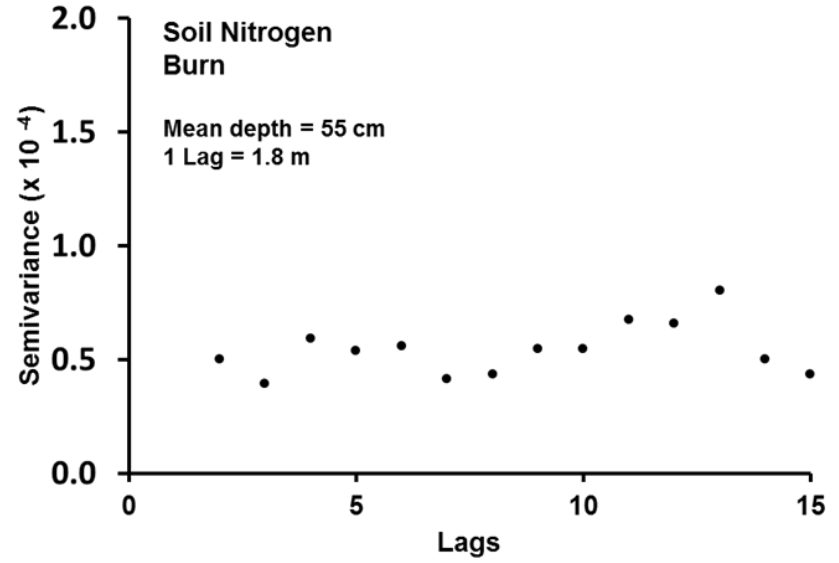
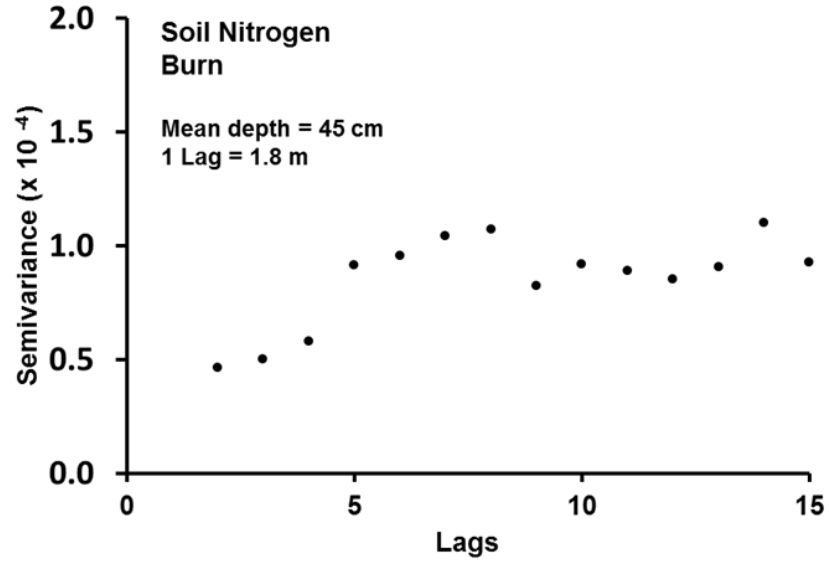


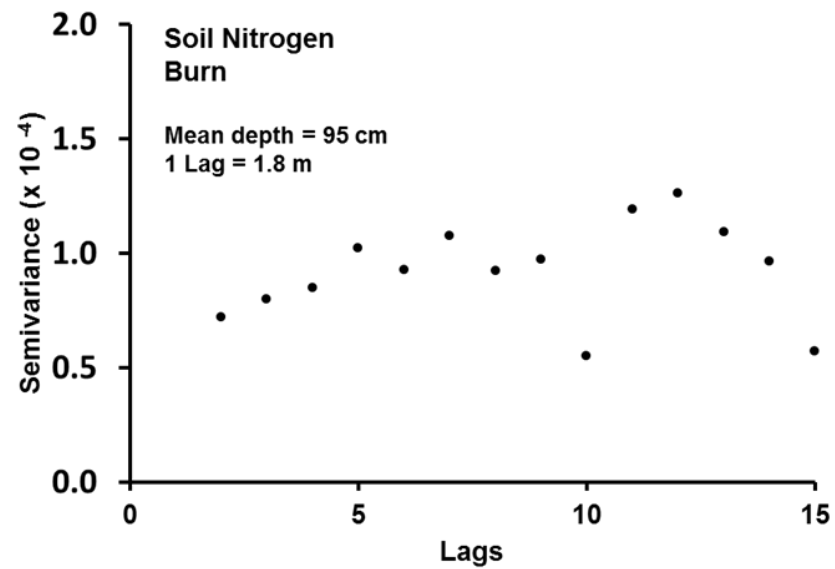
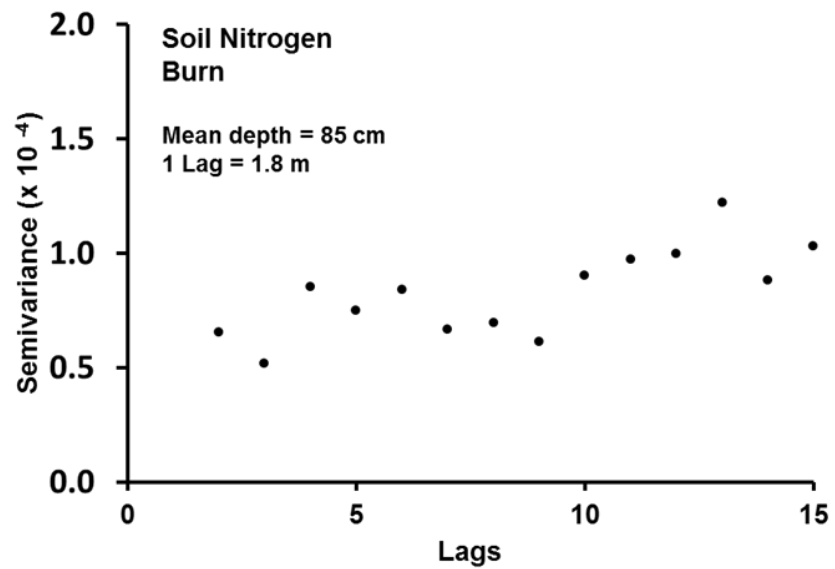


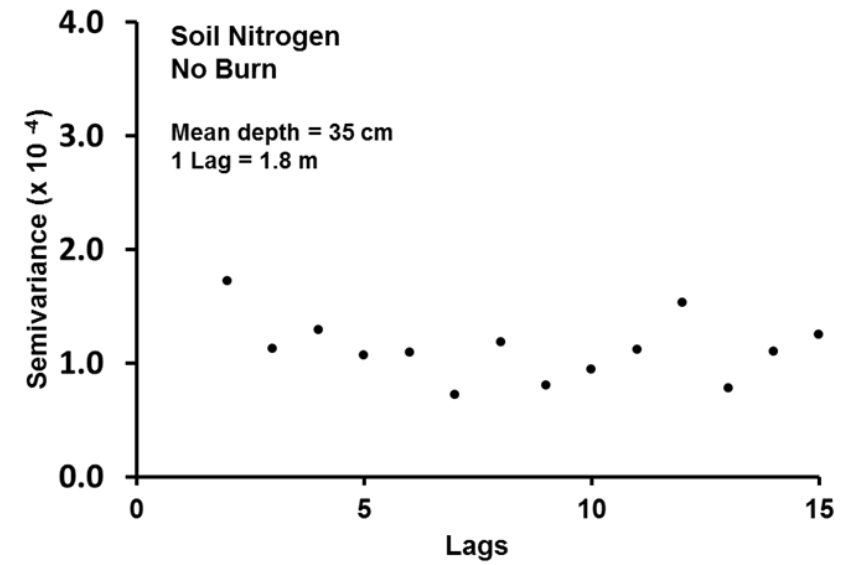
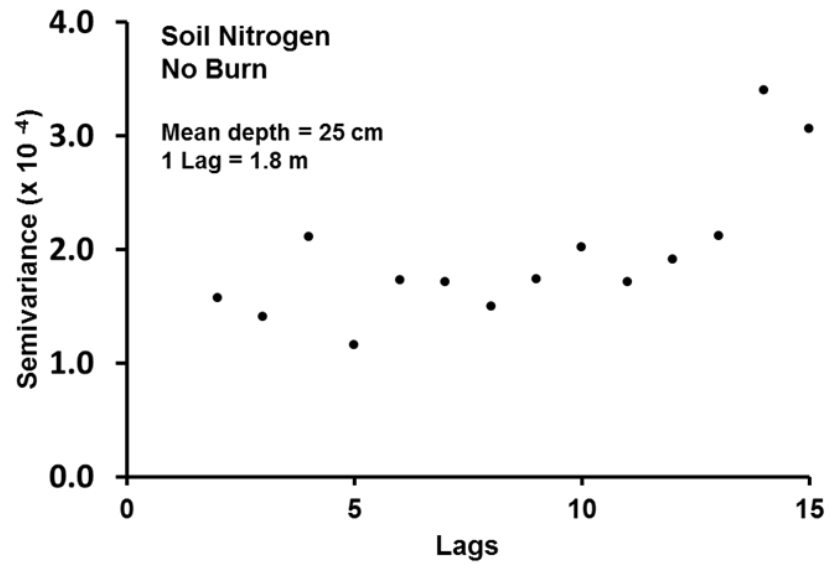
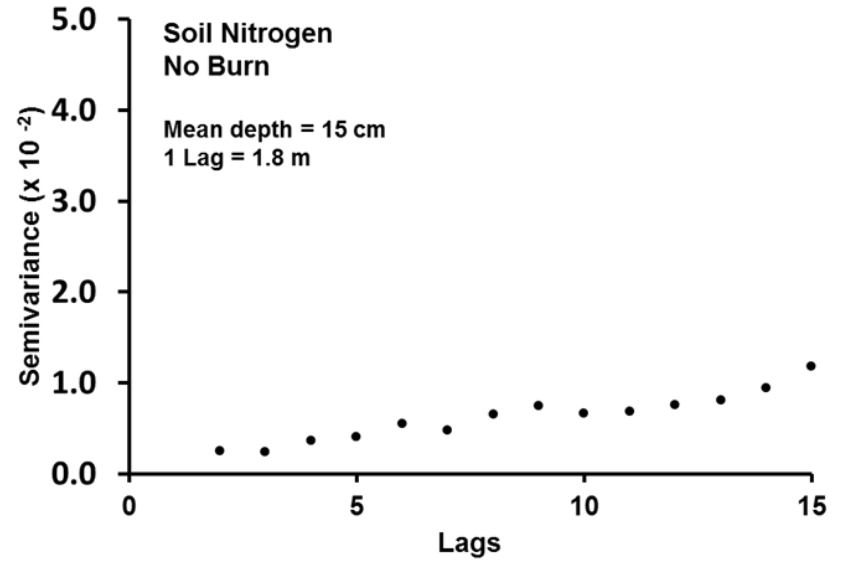
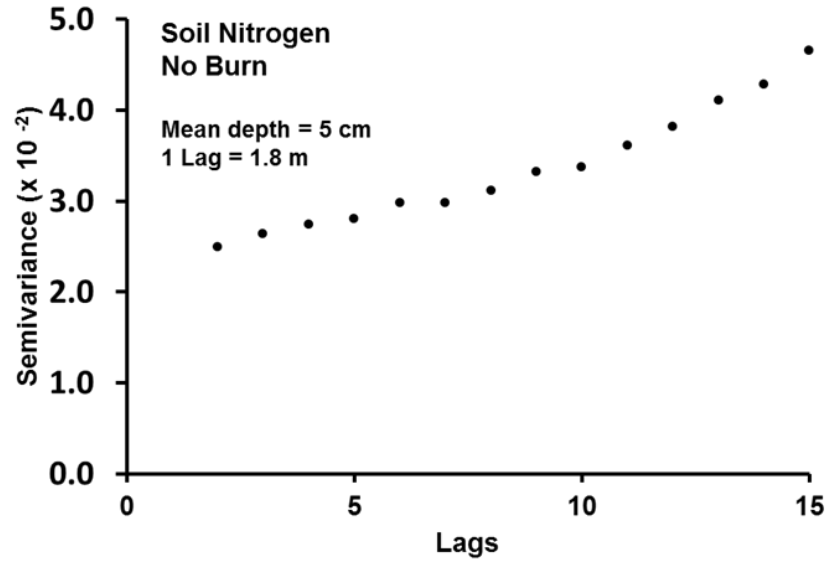


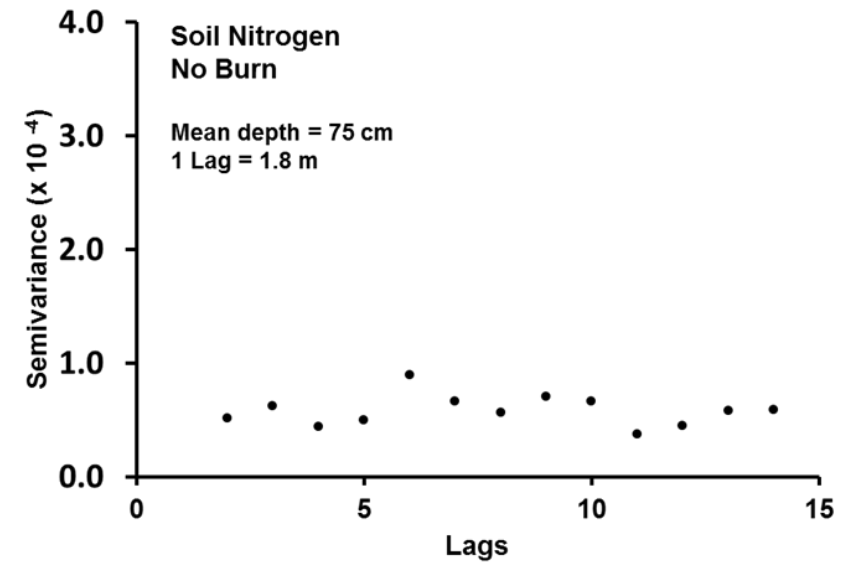
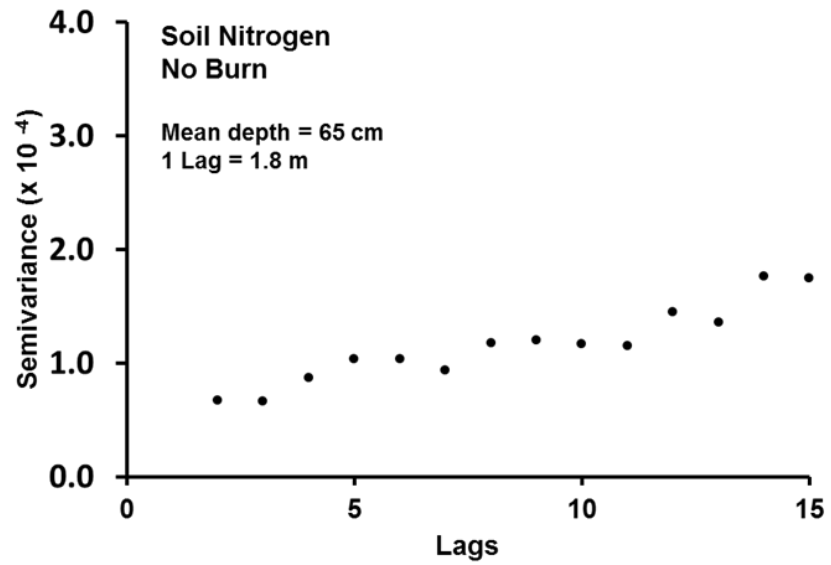
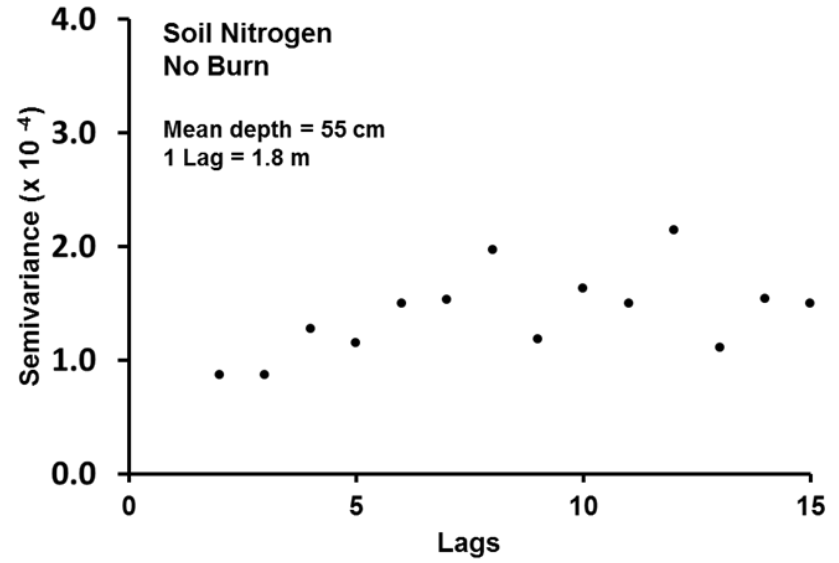
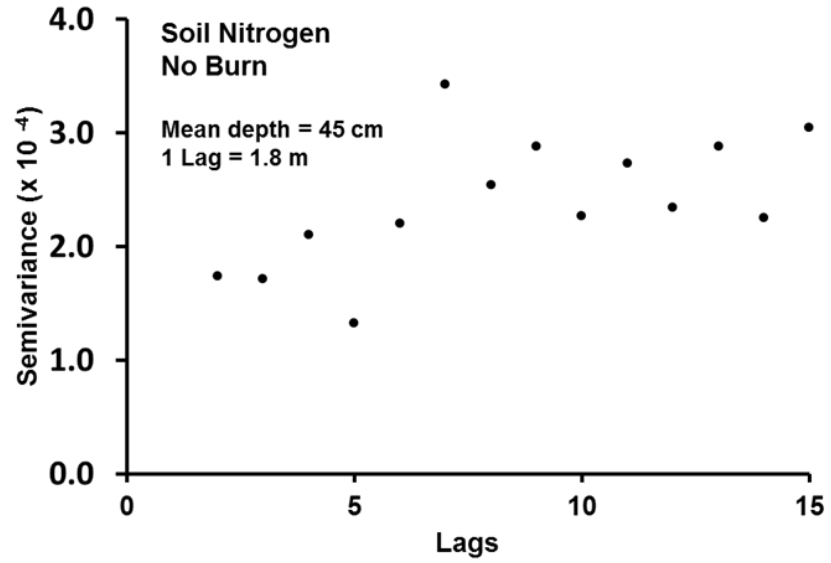
Appendix B: Soil Nitrogen Variograms

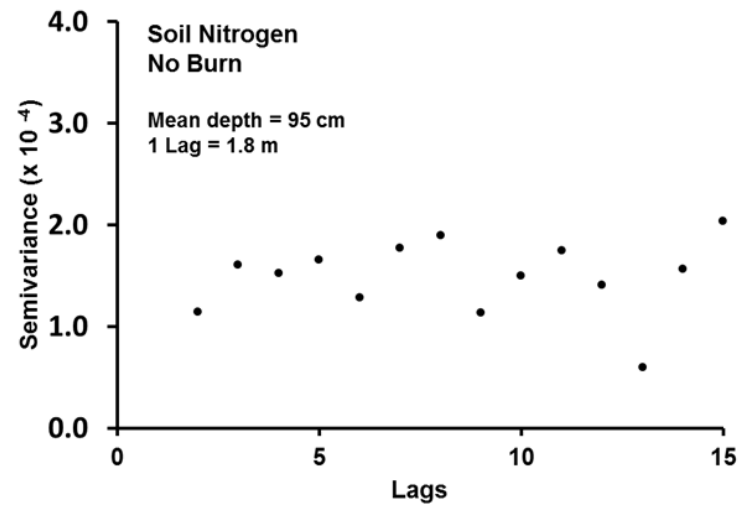
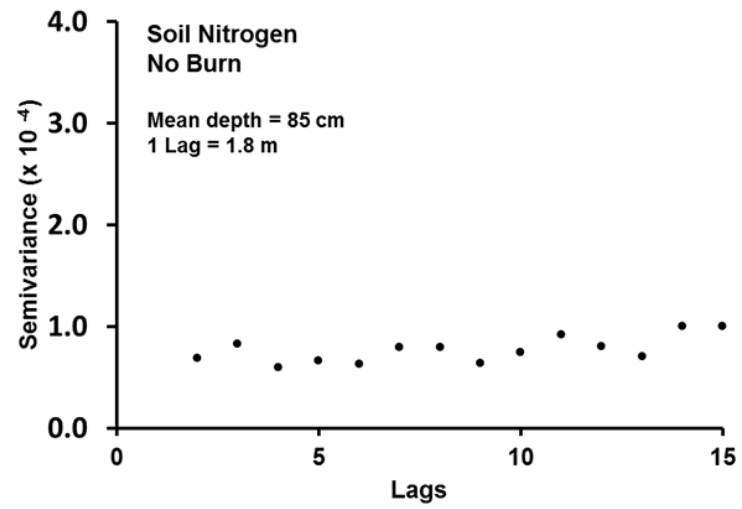












Vita

April Newman earned a B.S. in Environmental Studies from the University of Nevada, Las Vegas in 2002 and an M.S. in Forestry from the School of Renewable Natural Resources at LSU in 2010. Her research interests focus primarily on the hydrology of soils in wetlands and forests, and she sees the main concepts of these fields as complimentary to furthering understanding about carbon cycling at multiple scales. Ms. Newman has long held the view that wetland loss is among the most critical environmental problems of our time and looks forward to applying her knowledge and skills to help reverse it.