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Spatial and temporal variability of soil organic carbon on a corn–soybean watershed with 23 years of agroforestry

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Abstract

Unsustainable agricultural practices deplete soil organic carbon (SOC), affecting ecosystem services, land productivity, soil health, and water quality. This study evaluated the long-term effects of row crop (RC), agroforestry buffers (AB), grass buffers (GB), and grassed waterways (GWW) on SOC. Agroforestry buffers (grass and tree) and grass buffer treatments were established in 1997 on a corn (*Zea Mays* L.)–soybean (*Glycine Max* [L]. Merr.) rotation. Grid soil samples from 86 locations were collected in 10 transects to determine SOC at 0–10 and 10–20 cm depths. The general linear model and the generalized linear mixed model were conducted to evaluate treatment, landscape, soil depth, and series effects on SOC. Kriging interpolation was used to visualize the temporal and spatial change of SOC in the watersheds, comparing samples collected in 2000 and 1994 with samples collected in 2020. The mean SOC percentage (SOC%) in the top 10 cm depth for the RC, AB, GB, and GWW areas was 1.94, 2.19 2.41, and 2.51%, respectively ($\rho < .001$). The soil depth was significant ($\rho < .001$) between samples from 0–10 cm and 10–20 cm. The mean SOC% among soil series showed no significant differences at the studied depths. The mean SOC% of 0–10 cm for RC, AB, and GWW were 1.85, 1.88, and 2.30% in 2000 and 1.94, 2.19, and 2.51% in 2020. The foot-slope position had the highest (2.41%) and the summit position had the lowest SOC (2.02%) percentages. The SOC% in the RC treatment from 0–10 cm at the summit, backslope, and foot slope positions were ranked 1.83 < 2.22 < 2.31%, respectively. Perennial vegetation and undisturbed land management practices increased SOC compared with the RC areas.

1 | INTRODUCTION

The average decadal growth rate of carbon dioxide (CO_2), which was 2.0 ppm per year in the 2000s, surged to 2.4 ppm per year during the 2010–2019 period at the Mauna Loa station of the National Oceanic and Atmospheric Administration. Land use practices including agriculture and forestry are the second leading economic sector that contributes to the emissions of greenhouse gasses the most (IPCC, 2014). Conversion of forests to agriculture has caused significant soil organic carbon (SOC) losses and increased CO_2 emissions (Cardinael et al., 2017; Hou et al., 2019; Milne et al., 2007; Sanford et al., 2012; Udawatta & Jose, 2012). According to Chambers et al. (2016), agricultural practices have caused 66

Abbreviations: AB, agroforestry buffer; CT, conventional till; GB, grass buffer; GWW, grassed waterway; NT, no-till; RC, row crop; SOC, soil organic carbon; SOC%, soil organic carbon percentage.

± 12 Pg of SOC loss globally. Lal (2004) reported that land use transformation from natural to agricultural settings lost 60% SOC in temperate environments and 75% or more in the tropics. Additionally, intensive cropping, tillage, and insufficient C inputs have contributed to SOC depletion (Xu et al., 2020). For example, simulations by Yu et al. (2020) showed that from 1998 to 2008, tillage in the US caused a 52% release of SOC in agricultural fields.

Reductions in SOC adversely affect soil health by deteriorating its physical, biological, and chemical properties (Alagele, Anderson, & Udawatta, 2019; Sainju et al., 2003). Karami et al. (2012) applied 4.54, 13.61, and 22.70 Mg of organic matter ha^{-1} to soils and found that the highest mean weight diameter, geometric mean diameter, water stable aggregates, and soil moisture content were associated with the 22.70 Mg ha^{-1} rate. Besides, Karami et al. (2012) reported that at the higher SOC application rates, soil test K, P, Fe, and Mn increased, while bulk density decreased. Soil organic carbon plays a significant role in nutrient cycling in soils according to Murphy (2015), where 83 kg of N and 20 kg of P are stored in each thousand kg of SOC. Since a higher content of organic matter increases water stable aggregates, soils become less susceptible to water erosion (Veum et al., 2012; Weerasekara et al., 2016).

Soil organic matter (SOM) enhances microbial activity and humus production, which favors N fixation, decomposition processes, mineralization, nutrient cycling, soil water holding, and buffering capacity (Brady & Weil, 2002). Conversely, the activity of microorganisms can significantly affect carbon (C) cycling in soils. It is estimated that 1.4% of the global SOC is in microbial biomass C form (Babur & Dindaroglu, 2020). The close relationship between SOC and soil microbes is vital for the balance of C between the terrestrial and atmospheric pools. For instance, around 8% of the total atmospheric C interchanges between the terrestrial and atmospheric pools with microbial respiration as an essential process that releases C to the atmosphere (Gougoulias et al., 2014). Soil organic matter changes are influenced by soil, climate, and land management factors (Bellamy et al., 2005). Practices that enhance SOC based on soil–landscape relationships should be studied and characterized to develop better land management guidelines to improve SOC.

Agroforestry practices have shown to be effective in increasing SOC by generating biomass, favoring its accumulation, increasing the longevity of C, and preventing losses of C from agricultural fields. Agroforestry practices in agricultural watersheds favor significant C sequestration compared with sole forest and grasslands systems because of the combined advantages of these two systems (Kort & Turnock, 1998; Sharrow & Ismail, 2004; Udawatta et al., 2014). The patterns of SOC accumulation depends on the type of plants present on the landscape. Grassland rapidly accumulates SOC on shallow soil horizons, whereas trees can favor its accumulation at deeper horizons because of their root systems (Hou et al., 2019; Sharrow & Ismail, 2004; Udawatta et al., 2014). The addition of litter and biomass from trees to the soil surface increases C stocks in the soil surface, and it serves as a significant source of SOC (Paustian et al., 1997). Grasslands can also store up to 90% of their C as SOC because of their rapid decay compared with trees that store most of their C in woody biomass (Sharrow & Ismail, 2004).

Core Ideas

- Sequestration of carbon in soils under grass and agroforestry buffers was evaluated after 23 yr of implementation.
- Agroforestry and grass buffers increased the soil organic carbon among watersheds and treatments.
- This study indicates the importance of agroforestry buffers on carbon sequestration, leading to healthier soils and mitigate climate change.
- Soil depth and landscape positions are important factors affecting C distribution in soils.

Agroforestry assists in retaining SOC by enhancing soil biodiversity, reducing runoff, and preventing losses of sediment-bound SOC (Hou et al., 2019; Udawatta et al., 2011, 2019). Shi et al. (2018) indicated that agroforestry practices stored more SOC (99 Mg ha^{-1}) than croplands (40 Mg ha^{-1}) but less than grasslands (110 Mg ha^{-1}). Other important factors that determine agroforestry's SOC sequestration potential are system age, stand density, and species composition. According to Hou et al. (2019), deciduous hardwood species favored continuous SOC accumulation over the whole experiment, while evergreen hardwood and evergreen softwood enhanced SOC, primarily after 30 yr. It implies that the integration of site-suitable trees and other perennial vegetation can help further enhance SOC in agricultural watersheds (Udawatta et al., 2005; Udawatta & Jose, 2012).

Landscape positions affect the dynamics of organic matter deposition and decomposition. Clay et al. (2005) indicated that poor land management practices on corn–soybean rotations might cause variable SOC depletion depending on the landscape position. Conforti et al. (2016) reported seven times higher SOC in foot slope and summit positions than in backslope positions. However, Udawatta et al. (2014) reported 2.22% C in the foot slope, 1.98% in the shoulder, and 1.74% in the backslope positions of agricultural watersheds. The differences in SOC across landscape positions can be explained by detachment, movement, and deposition of particles among landscape positions due to drainage water flow velocity. For example, poorly-drained soil promotes dry matter production and decreases organic matter decomposition rates (Brady & Weil, 2002).

Previous soil and water studies have revealed differences in SOC and other related parameters among management practices of current watershed studies (Alagele, Anderson, Udawatta, et al., 2019; Udawatta et al., 2008, 2014; Veum et al., 2012). However, these studies did not evaluate management and landscape effects on SOC in a grid sampling design with geospatial data analysis. Grid sampled SOC could account for spatial variability among treatments, landscape positions, and soil depths. These findings can help understand SOC dynamics of agricultural watersheds with agroforestry buffers. The primary objective of this study was to determine the effects of management and landscape positions on SOC storage 23 yr after the establishment of agroforestry buffers. The specific objectives were to (a) evaluate the spatial distribution of SOC in watersheds with corn (*Zea Mays* L.)–soybean [*Glycine Max* (L). Merr] rotation, agroforestry buffers (AB), grass buffers (GB), and grassed waterways (GWW), (b) determine effect of soil depth on SOC of RC, AB, GB, and GWW management practices, (c) determine SOC at the three soil series in the watersheds, (d) determine the temporal changes in SOC between current and previously reported data, and (e) determine the SOC contents at summit, backslope, and foot slope landscape positions.

2 | MATERIALS AND METHODS

2.1 | Site description

The study watersheds are located at the Greenley Memorial Research Center of the University of Missouri-Columbia, Knox County, Missouri, USA (40˚01′ N, 92˚11′ W) (Figure 1). The study site consists of three adjacent north-facing watersheds instrumented with water sampling devices in 1991. The east watershed (control) is the smallest of the group with an area of 1.65 ha. In the center is located the agroforestry watershed (4.44 ha). On the west is the grass buffer watershed (3.16 ha). The three watersheds were maintained under a corn–soybean rotation with no-till management since 1990. Agroforestry and grass buffer treatments were established in 1997 on the center and west watersheds. Grass buffers on agroforestry and grass buffer watersheds consist of 4.5-m wide grass–legume strips with redtop (*Agrostis gigantean* Roth), brome grass (*Bromus inermys* Leyss.), and birdsfoot trefoil (*Lotus corniculatus* L.) spaced at 36.5 m. The agroforestry watershed has pin oak (*Quercus palustris* Muenchh.), swamp white oak (*Q. bicolor* Willd.), and bur oak (*Q. macrocarpa* Michx.) located in the center of the grass–legume strips planted at 3 m apart. In 2012, crop areas of the agroforestry buffer and grass buffer watersheds were planted with a 9 kg ha^{-1} mix of Roundtree big blue stem (*Andropogon gerardii* Vitman; 38.3%), Rumsey Indiangrass (*Sorghastrum nutans* L. Nash ; 28.3%), Kanlow switchgrass (*Panicum virgatum* L.; 16.4%), Illinois bundleflower (*Desmanthus illinoensis* Michx.) (7.8%), and partridge pea [*Chamaecrista fasciculata* (Michx.)] (9.2%) and harvested for biomass a year after their establishment until 2019. Corn was planted in the control watershed in the spring of 2019, and soybean was planted in all the watersheds in 2020.

Soils in the watersheds were mapped as Kilwinning silt loam (fine, smectitic, mesic Vertic Epiaqualfs), Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), and Armstrong loam (fine, smectitic, mesic Aquertic Hapludalfs) (Soil Survey Staff, 2019). The southern part of the three watersheds (1 to 3% slopes) have Putnam silt loam soil, the Kilwinning silt loam occupies the central portion of the three watersheds (2 to 5% slopes), and the northern part of the watersheds (5 to 9% slopes) has Armstrong loam soil (SoilWeb, 2019).

The soil profiles have Bt horizons between 20 to 36 cm in depth, with low saturated hydraulic conductivity. The shallow argillic horizons with low hydraulic conductivity enhance runoff during rain events. According to Soil Survey Staff (2019), the pH for Putnam and Kilwinning silt loam soils ranges from 5.7 to 7.1 and for the Armstrong series ranges from 6 to 7. Udawatta et al. (2014) reported 1.93 and 1.99% SOC percentage (SOC%) on the surface of the control and agroforestry watersheds, respectively, for samples collected in 2000. The annual long-term precipitation (1956–2018) in the region is 957 mm (https://mrcc.isws.illinois.edu; http://agebb.missouri.edu). Approximately 69% of the precipitation falls in April through September. The mean air temperature in July is 24.4 ˚C, and the mean temperature in January was −1.79 ˚C.

2.2 | Soil sampling and laboratory analysis

Soil samples were collected in 10 transects to account for variations among treatments and landscape positions (Figure 1). Eighty-six locations were sampled to generate SOC raster images through kriging interpolation among watersheds, management types, and depths. Soil samples were collected on 22 Jul. 2020 for 0–10 cm and 10–20 cm soil depths, using a push probe (1.5 cm diameter). Soil samples were placed in labeled plastic bags and transported to the laboratory for analysis. This and previous studies at these paired watersheds followed a design-based approach as described by (Brus & Gruijter, 1997, 2012). A stratified simple random sampling was performed to obtain global SOC% means by management practice, landscape position, soil series, and depth. Because data from 2000 and 2020 were collected following a design-based approach and reported for the same depths, no normalization process was needed (Karunaratne et al., 2014).

All soil samples were stored at 4 ˚C until analysis. Soil C was determined by the Serving Testing and Research Laboratory of the Ohio State University, by loss on ignition

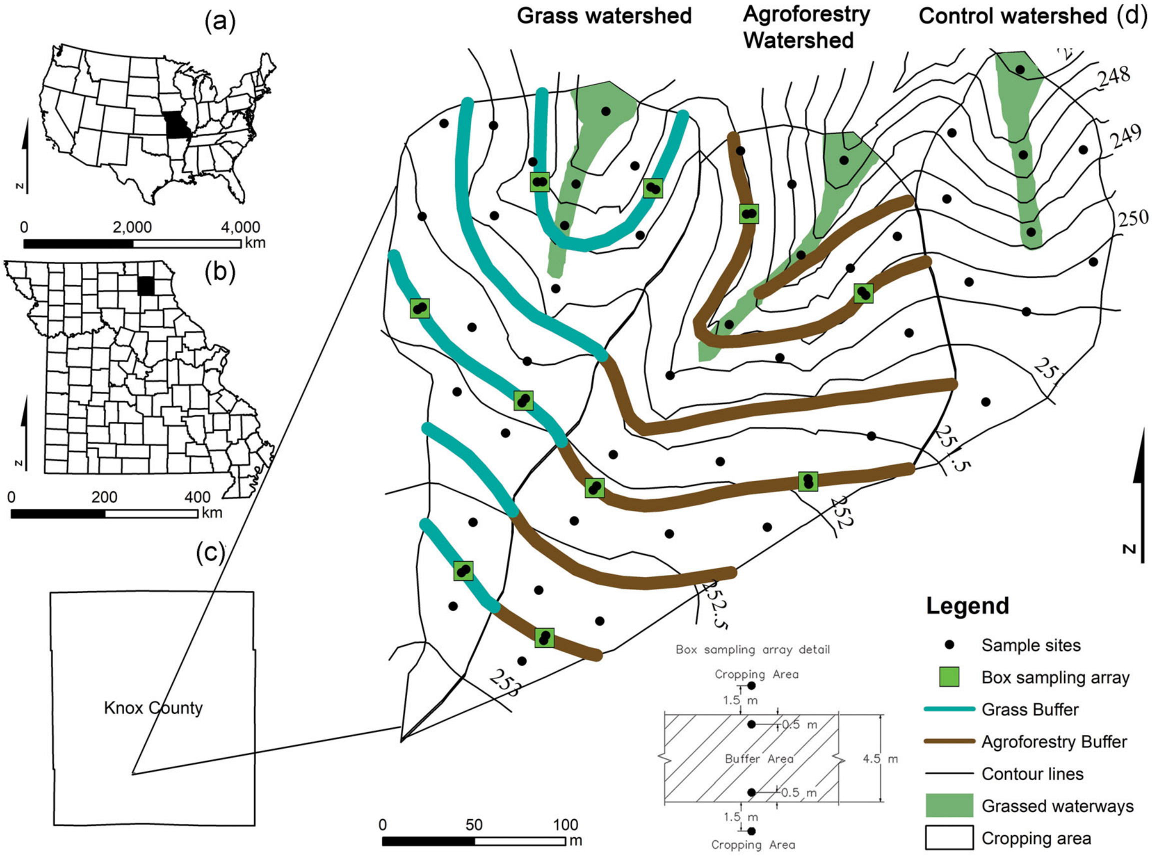

FIGURE 1 (a–c) Location of Missouri within the United States, Knox County, and the Greenley Memorial Research Center. (d) The grass buffer watershed (west), agroforestry watershed (center), and control watershed (east). Black points represent 46 sampling locations, 10 green boxes (4 sampling locations per box) represent additional 40 sampling locations, narrow lines represent 0.5-m interval contour lines, dark green areas represent grassed waterways, brown lines represent agroforestry buffers, and cyan lines represent grass buffers. The green squares represent the box sampling arrays. Each box consisted of two samples within the respective buffer and two samples in the row crop area adjacent to the buffer

and the use of the Van Bemmelen factor. Soil carbon percentages were converted to stock (kg ha^{-1}) by using bulk density values reported by Seobi et al. (2005) for 2000 and Alagele, Anderson, & Udawatta (2019) for 2020 samples.

2.3 | Statistical analysis

The data was tested for normality using Shapiro–Wilk and equal variance by Levene's test. Regular fixed models assume that the only source of variation is the randomness of the sampling, which can be challenging to satisfy in SOC studies within watersheds because of the number of variables affecting soil parameters in a watershed scale. The assumption of independence in the data can be inappropriate when several data points are collected from the same experimental unit. Therefore, a simple ANOVA is not adequate to analyze treatment effects in those cases (Slaets et al., 2021). In order to properly represent the variability of the SOC within the watersheds and the spatial correlation of the data, we used tri and bi-variate generalized linear mixed model procedures (mixed-model) in SAS 9.4 (SAS Institute). The mixed model allowed us to use management, depths, and landscape positions as fixed effects and introduce the location as a random effect.

An appropriate representation of the variability can be made by introducing the random effect of the location to help adequately determine the effect of the studied treatments (Brus & Gruijter, 2012; Gili & Noellemeyer, 2013). Also, Gili and Noellemeyer (2013) mentioned that it is difficult to detect differences in C and P in soils when using fixed models unless the contrast in soil parameters is large. Maps showing the spatial and temporal changes in SOC% were developed by using point kriging interpolation within the Spatial Analyst Tool of ArcMap. The kriging method used was ordinary, and the model for the semi-variogram was spherical. Soil organic carbon maps were created independently using existing punctual data for 1994 and 2000 and newly collected samples for the 2020 map. Modeled semi-variograms for each SOC map were utilized to predict the SOC% among the watersheds and generate the SOC% surfaces for the three years presented (i.e., 1994, 2000, and 2020) and the three depths studied (i.e, 0–10, 10–20, and 0–20 cm). Even though SOC% data between

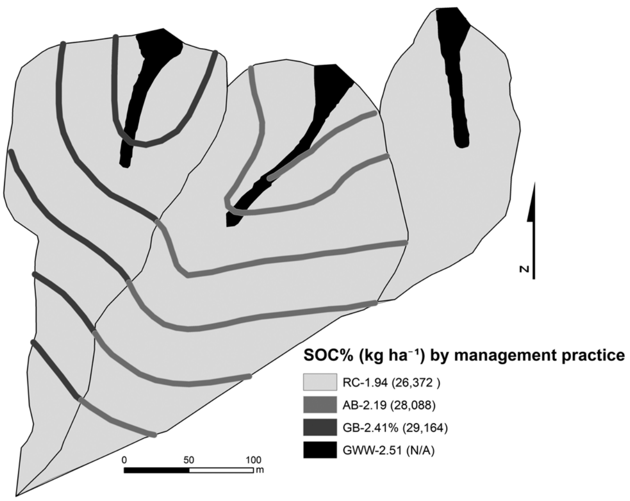

FIGURE 2 Spatial variation of soil organic carbon percentage (SOC%) and stock in the 0–10 cm depth among row crop (RC), agroforestry buffers (AB), grass buffers (GB), and grassed waterways (GWW) at the Greenley Research Center, Novelty, Missouri. Values within parenthesis indicate carbon stock (kg ha^{-1})

years can have some correlation, because the objective of the SOC maps was to provide a visual perspective of the spatial-temporal variation of the SOC% in watersheds at each specific year, the kriging interpolation was performed by watershed by year. Therefore, there are no covariance terms between years due to the independence of the maps.

3 | RESULTS AND DISCUSSION

3.1 | Management effects on SOC

Soil samples were collected from 0–10 cm and 10–20 cm depths by management practices to quantify management effects on SOC. The mean SOC% and stock for each management practice was calculated by averaging all the samples collected at their respective land cover of watersheds (Figure 2). The mean SOC% of the RC management was calculated by averaging the SOC of the samples collected in the control watershed, which has been managed as a no-till crop area since the beginning of the experiment in 1990. The SOC% among management practices were significant ($\rho < .001$) for the 0–10 cm depth, not significant for 10–20 cm, and significant ($\rho < .05$) for the 0–20 cm depth (Figure 3). The SOC% in the 0–10 cm depth ranged from 1.94% (26,372 kg ha^{-1}) in the RC treatment to 2.51% (N/A) in the GWW treatment. In the top 10 cm, soil of AB, GB, and GWW treatments had 13, 24, and 29% greater SOC concentrations than the RC. Soil organic carbon percentages ranged from 1.65% (24,116 kg ha^{-1}) in the RC treatment to 1.79% (25,544 kg ha^{-1}) in the GB treatment for the 10–20 cm depth (Figure 3). Agroforestry buffers, GB, and GWW areas contained 3, 8, and 7% greater SOC% than the RC at the 10–20 cm depth. For the 0–20 cm sampling depth, SOC% varied between 1.80% (25,316 kg ha^{-1}) in the RC treatment to 2.13% in the GWW (N/A) treatment. The SOC% from 0–20 cm in the AB, GB, and GWW areas was 8, 17, and 18% greater, respectively, than in the RC.

Previous studies at these three watersheds also found the highest SOC% at the GWW treatment and the lowest at the RC area. Udawatta et al. (2008) found SOC% among management practices following the pattern RC < GB < AB < GWW. Alagele et al. (2019) also reported the highest SOC% in the GWW treatment and the lowest SOC% in the RC area 21 yr after the buffers were established. Weerasekara et al. (2016) reported SOC% among the managements following the pattern RC < GB < GWW < AB 17 yr after establishment.

Denser grass, including reed canary grass (*Phalaris arundinacea* L.), in the GWW located in the lowest landscape positions of the watersheds retained more SOC% than the other land covers. These areas receive nutrients and soils transported by runoff water, which favors the buildup of SOC (Alagele, Anderson, Udawatta, et al., 2019; Udawatta et al., 2008, 2014; Weerasekara et al., 2016). Furthermore, GWW were never tilled since the experiment was established in 1990. In another study in Wisconsin, Sanford et al. (2012) compared six different management systems after 20 yr of the implementation of best management practices. Their study reported C storage of 4,570 kg ha^{-1} yr^{-1} from a mixed pasture (Timothy [*Phleum pretense* .], bromegrass [*Bromus inermis* L.], orchardgrass [*Dactlyis glomerata* L.], and red clover [*Trifolium pretense* L.]) plot, whereas a corn–soybean rotation plot stored 1,040 kg ha^{-1} yr^{-1} for the soybean period and 2,300 kg ha^{-1} yr^{-1} for the corn period. Similar observations of greater SOC in the grassed waterways than the crop areas can be found in the literature (Ledo et al., 2020; Sanford et al., 2012; Yang et al., 2019).

A comparison between the two buffer types indicated that perennial vegetation management influenced SOC accumulation and it changed as the system matured. The mean SOC% of the current study for the 0–10 cm depth of the AB and GB was 2.19 (28,088 kg ha^{-1}) and 2.41% (29,164 kg ha^{-1}), respectively (Figure 3). The GB indicated 10% greater SOC% than the AB treatment. At the 10–20 cm depth, the average SOC% for the same treatments were 1.70 (23,348 kg ha^{-1}) and 1.79% (25,544 kg ha^{-1}). Even though no significant differences were found at this depth range, the GB indicated a 5% greater SOC% than the AB treatment. For 0–20 cm, the average SOC% for the same treatments were 1.95 (25,731 kg ha^{-1}) and 2.10% (27,697 kg ha^{-1}). The GB indicated 8% greater SOC% than the AB treatment.

In a metadata analysis, De Stefano and Jacobson (2018) reported SOC stock increased 26, 40, and 34% at 0–15 cm, 0–30 cm, and 0–100 cm, respectively, due to the shift from traditional agriculture to agroforestry. In the current study, AB, which consists of trees and grasses, retained more carbon than

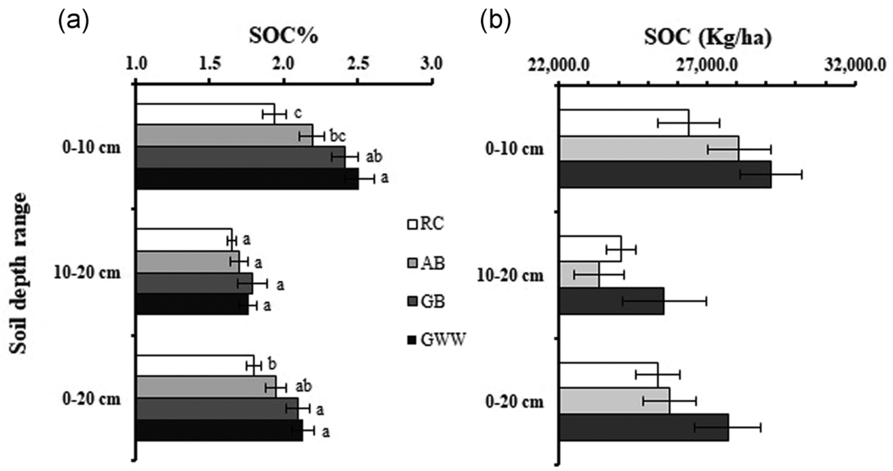

FIGURE 3 Mean soil organic carbon percentage (SOC%) for row crop (RC), agroforestry buffer (AB), grass buffer (GB), and grassed waterways (GWW) treatments for 0–10 cm ($\rho < .001$), 10–20 cm ($\rho > .05$), and 0–20 cm ($\rho < .05$) depths (a) in 2020 and (b) its respective stock version. GWW were not included in B because of the absence of bulk density data for this treatment (N/A). Bars denote standard errors. Letters indicate significant differences within a depth range

the RC area; however, their effect was lower than the effect of GB. The lower capacity of the AB compared with the GB can be explained by the higher mortality of the grass under the shade of trees and the lower root density of trees than grasses especially on surface horizons. The cool-season grasses in this study have some degree of intolerance to reduced sunlight conditions. For example, Pang et al. (2019) found that redtop (*Agrostis gigantean* Roth) and birdsfoot trefoil (*Lotus corniculatus* L.) decreased their yield (g pot^{-1}) by 12 and 50%, respectively, when changed from full sunlight to dense shade (20% sunlight). Kumar et al. (2010) analyzed root length and surface area in agroforestry buffers with cottonwoods (*Populus deltoids* Bortr. ex Marsh.) and grass buffers with tall fescue (*Festuca arundinacea* Schreb 'Kentucky 31'), red clover (*Trifolium pretense* L.), and Korean clover (*Kummerowia stipulacea* Maxim.). They found that the GB and the AB had mean root lengths of 161 and 138 cm 100 cm^{-3}, respectively. At the current study site, trees are on average eight meters tall and canopy closure between trees has occurred. Therefore, grass species under the trees do not receive sufficient sunlight for optimum growth, and reduced growth was observed due to shading, interference, and competition for resources. Tree effects including shade and competition for resources may have reduced surface root density in the surface 0–20 cm under AB buffers compared with grass only buffers.

The three paired watersheds have been under no-till (NT) management since the beginning of the experiment in 1990. Literature about the effects of NT vs. conventional till (CT) management can be controversial. However, authors found that NT practices tend to increase SOC at shallow depths (0–15 cm), and CT increased SOC at depths below the plow layer because of the translocation of residue from the surface to the subsurface (Haddaway et al., 2017; Ogle et al., 2019; Omara et al., 2019). Other variables also play important roles in SOC storage when NT is implemented, such as climate and soil properties. For example, Ogle et al. (2019) reported that tropical or warm and moist climates can increase SOC storage under NT compared with CT. The authors mentioned that the results for SOC retention, comparing NT and CT, are inconclusive under cool and warm temperate dry climates. Therefore, NT may have increased SOC in the RC of the studied watersheds at the studied depths (0–10, 10–20, and 0–20 cm) compared with the CT scenario.

3.2 | Depth effect on SOC

The SOC of the samples were calculated for each management practice and depth (0–10 cm, 10–20 cm, and 0–20 cm) (Figure 3). The SOC% for 2020 in the top 10 cm of soil of RC, AB, GB, and GWW areas was 18, 29, 35, and 43% greater than in the subsequent 10 cm. Standard error values of SOC% ranged between 0.03 to 0.10 among all the studied depths. The depth effect among management practices was highly significant ($\rho < .001$). The greatest reduction of SOC% due to depth was in the GWW and followed by the GB, which indicates that grass species in these watersheds had the greatest C accumulation in the surface soil. The denser roots of GB and GWW increased the SOC% in the top 10 cm depth (Figure 3), while the SOC was lower at the RC and AB due to lower root density. For the subsequent 10 cm, the GB had more SOC% than GWW, AB, and RC, which can be explained by deeper and better-established roots compared with the other managements.

In 2000, the mean SOC% at 0–10 cm was 1.85, 1.88, and 2.3% for the RC, AB, and GWW, respectively, and for 10–20 cm SOC% was 1.36, 1.34, and 1.67%. The greatest decrease in SOC% from the surface 10 cm to the next 10 cm of

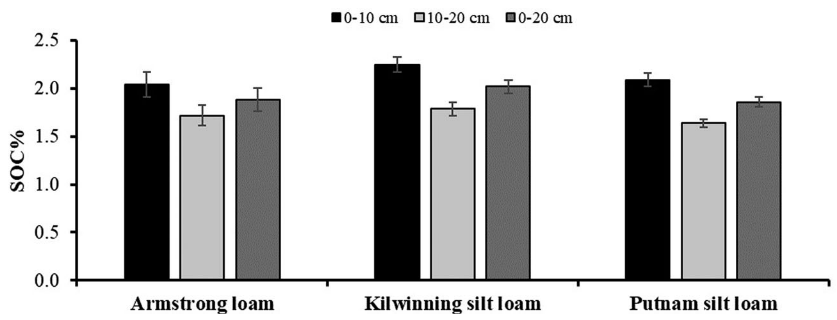

FIGURE 4 Mean soil organic carbon percentage (SOC%) for Armstrong loam, Kilwinning silt loam, and Putnam silt loam for soil samples at 0–10 cm, 10–20 cm, and 0–20 cm depth at the paired watersheds at the Greenley Research Center, Missouri, USA. Bars denote standard errors. No significant differences were found among soil series

the samples collected in 2000 was found in the AB treatment, which was 29% less than in the top 10 cm of soil. Overall, Udawatta et al. (2014) reported that the SOC% in the control watershed was 1.93% in the 0–10 cm depth and 1.40% for 10–20 cm below the soil surface. They also reported SOC% of 1.99 and 1.44% in the agroforestry watershed at 0–10 cm and 10–20 cm depths, respectively. The greatest reductions of SOC between the top 10 cm and the next 10 cm depth changed from AB in 2000 to GWW in 2020, which indicates that the AB was better established compared with 2000 when they were only three growing seasons at the watershed. It also reinforces the concept that the GWW accumulates SOC in shallower soil horizons. The death of surface grass roots, due to the increased shade under trees on AB, may also have contributed to reduced differences between 0–10 and 10–20 cm depths in the AB.

In a study conducted in agricultural fields in Iowa, Taylor et al. (2002) reported 85% reduction of soil organic matter from 0–30 cm soil depth to 100–130 cm. Similarly, Kramer and Gleixner (2008) reported a 38% reduction in SOC% when comparing the first 20 cm of soil with the subsequent 20 cm depth. Lorenz and Lal (2005) reported that SOC storage decreased by 57, 23, and 44% in the 1–3 m depth compared with the top 1-m depth for grasslands, shrublands, and forests, respectively. Their study also indicated that 95% of root biomass for the mentioned land uses were found in the 0.60, 1.35 and 1.00 m depths, respectively. Wilhelm et al. (2004) indicated that roots have a greater influence on soil organic matter and C retention than above-ground residue because their C content is an important fraction of soil C compared with the above-ground residue that is easily lost as CO_2.

3.3 | Soil series and SOC

The effect of the soil series on the distribution of SOC% was evaluated in the crop areas among the three paired watersheds, which included three soil series. The SOC% in the top 10 cm of soils for the Armstrong loam, Putnam silt loam, and Kilwinning silt loam was 2.04, 2.09, and 2.25%, respectively (Figure 4). For the 10–20 cm and same soil series, SOC% was 1.72, 1.64, and 1.79%, respectively. The SOC% was not significantly different among soil series. According to Soil Web (2021), for the first 20 cm depth, the Armstrong loam soil in the watersheds contain 71% silt + clay percentage of particles, while the Kilwinning and Putnam silt loam contain 95.4 and 97.4% silt + clay fractions, respectively. In another study, Zhou et al. (2019) reported that samples containing 98.38% of silt–clay fraction had four times more organic carbon than samples with 49.27 and 67.14% silt + clay fractions. Soil texture data from samples collected in 2000 was analyzed to make a detailed correlation with the SOC at that time, but the small range of variation of their silt + clay fractions did not allow us to make an adequate comparison (data not presented).

The amount of carbon that a given soil can store is highly related to its texture. Past studies have shown that finer soils can generally retain more carbon than coarser soils, and they also indicate that the clay and silt portions of soils can form aggregates that provide protection to carbon against microbial uptake (Hassink, 1997; Ingram & Fernandes, 2001).

3.4 | Temporal variation of SOC

Since the implementation of GWW, AB and GB, several studies have been conducted throughout the years at the study site. The overall trend of the SOC% in the studied soils has increased, resulting in higher SOC% in the undisturbed perennial management practices than in the RC area. In this study, SOC% for the RC, AB, and GWW were 1.94 ± 0.08, 2.19 ± 0.08, and 2.51 ± 0.10% (Table 1), compared with 1.85 ± 0.05, 1.88 ± 0.09, and 2.30 ± 0.17% in 2000, respectively. Since 2000, the average SOC% for 0 to 10 cm in the AB and GWW has increased 16.5 and 9%, respectively (Table 1). These changes represent 4,244 and 1,991 additional kg ha^{-1} C on AB and RC areas between 2000 and 2020. The average SOC% in the top 10 cm of the GB has increased by 14% since 2006. Buffers occupied approximately 10% of the land area and stored two times more C in the surface 10 cm of soil than the NT crop areas. Agroforestry-induced soil C storage has been identified as a partial solution for climate change by the IPCC, and can help offset C losses from soils. For example, by using 6,000 sites, Bellamy et al. (2005) showed

TABLE 1 Reported average soil organic carbon (SOC) percentage by management practice for 0-to-10-cm depth. The buffers were established in 1997 and the grassed waterways in 1990. The grass buffers were not sampled in 2000. Bulk density data for GWW and for samples collected in 2006, 2008, and 2018 were not available

	Sampling month and year				
Treatment area	**March 2000**	**June 2006**	**June 2008**	**May 2018**	**May 2020**
	%				
Crop	1.85 ± 0.05 (24,381 ± 693)	1.75 ± 0.10	1.84	1.22 ± 0.02*	1.94 ± 0.08 (26,372 ± 1,044)
Grass buffer		2.11 ± 0.15	2.27	1.45 ± 0.02*	2.41 ± 0.09 (29,164 ± 1,045)
Agroforestry buffer					
Distance from a tree: 150 cm	1.88 ± 0.09 (23,844 ± 1,164)	2.28 ± 0.15	2.82	1.54 ± 0.02*	2.19 ± 0.08 (28,088 ± 1,075)
Grassed waterway	2.30 ± 0.17	2.39 ± 0.15	2.62	2.40 ± 0.02*	2.51 ± 0.10
Reference	Udawatta et al. (2014)	Udawatta et al. (2008)	Weerasekera et al. (2016)	Alagele et al. (2019)	Current study

*Reported values correspond to 0-to-30-cm depth. Values in parenthesis are C stock (kg ha^{-1}).

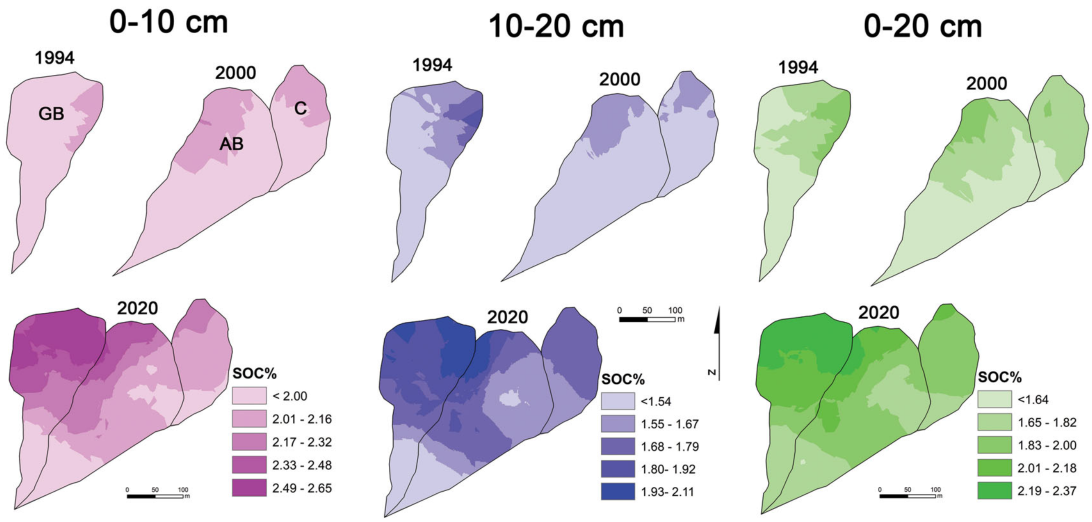

FIGURE 5 Spatial distribution of soil organic carbon percentage (SOC%) for 0–10 cm, 10–20 cm, and 0–20 cm depth in the grass buffer watershed (GB) in 1994, agroforestry (AB) and control (C) watersheds in 2000, and in the three paired watersheds in 2020 at the Greenley Memorial Center, Knox County, MO, USA

that England and Wales lost 0.6% C annually from 0–15 cm soil depth from all land use types between 1978 and 2003. Adoption of agroforestry buffers on land can help recover some of the lost carbon and store more carbon even in deeper soils.

The spatial-temporal increase of SOC in the three paired watersheds for 0–10 cm, 10–20 cm, and 0–20 cm soil showed that the northern parts of the watersheds retained the greatest amount of SOC (Figure 5). These areas were at the lowest elevation of each watershed, and they received all the water and eroded material from the upper parts of the watersheds. They also maintained higher moisture conditions compared with the southern areas of the watershed, which favored SOC retention. The control watershed had the lowest SOC because it did not contain vegetative buffer strips and has been managed under continuous row crop production since the experiment started. The SOC ranges in the color scales decreased with increasing depth (Figure 5); however, the spatial distribution pattern of the SOC at the analyzed depth ranges was similar. The time effect was evident when comparing the SOC of the watersheds in 1994 and 2000 with 2020. The expansion of the darker colors indicated a buildup of SOC over time, and it progressed from north to south. According to the results of the semi-variograms, the maps from 2020 contained SOC% data that was spatially correlated in a wider range than the maps for 1994 and 2000 (Table 2). Soil samples from 1994 and 2000 were collected by watershed, and the sampling points were concentrated in smaller areas compared with the samples collected in 2020. The data from 2020 had 3–18 times greater range than 1994 and 2000 data. Therefore, data from

TABLE 2 Parameters of the theoretical semi-variograms fitted to the spatial soil organic carbon percentage (SOC%) data to create the maps shown in Figure 5

Map	Depth	Nugget	Sill	Range	RMSSE
	cm			m	
2020	0–10	0.07	0.15	270	1.05
	10–20	0.04	0.08	194	0.95
	0–20	0.04	0.1	252	1.02
2000	0–10	0.03	0.19	38	0.99
	10–20	0	0.14	15	0.85
	0–20	0	0.13	13	0.91
1994	0–10	0.24	0.33	57	0.96
	10–20	0.17	0.19	48	0.93
	0–20	0.18	0.23	47	0.94

Note. RMSSE, root mean squared standardized error.

2020 showed a more favorable spatial correlation because of its larger ranges than 1994 and 2000 data. Also, 1994 and 2000 data present larger semi-variance than 2020 data.

As seen in previous studies, semi-variogram characteristics depend on the model used, the sampling scale, and the parameter studied, considering the reported units (Bishop & Lark, 2007; Karunaratne et al., 2014). For example, Karunaratne et al. (2014) used lag distances in the order of thousands of meters because of the scale of the watershed they studied. On the other hand, Bishop and Lark (2007) utilized smaller lag distances for the smaller area in their study, which represents the sampling scale effect. In this study, we used smaller lag distances than Karunaratne et al. (2014) because of the smaller watershed areas. Bishop and Lark (2007) found semi-variances in the order of thousands ($[\text{mg kg}^{-1}]^2$) for available potassium models, representing the parameter effect. In contrast, Karunaratne et al. (2014) and the current study found semi-variances in the order of fractions of ($[\%]^2$) for SOC% models. The units of the modeled parameter will affect the semi-variogram by influencing the semi-variance.

Udawatta et al. (2008) reported no significant differences in SOC between the AB and GB treatments; however, they found that the mean SOC% for 0–10 cm depth for the GB and AB was 2.27 and 2.82%, respectively. These values were 30 and 60% greater than the value found in the RC. Udawatta et al. (2014) reported that the average SOC% for 0–10 cm depth of the agroforestry and control watersheds was 1.99 and 1.93%, respectively, whereas for the 10–20 cm depth, the average SOC% was 1.44 and 1.40%, respectively. Weerasekara et al. (2016) found average SOC% percentages of 1.84, 2.27, 2.82, and 2.62%, for the RC, GB, AB, and GWW, respectively. Soil samples collected from the watersheds in 2018 had 1.22, 1.45, 1.54, and 2.40% SOC for the RC, GB, AB, and GWW, respectively (Alagele et al., 2019). The lower values in 2018 samples compared with all the other samples were due to 0–30 cm sampling depth for 2018, whereas SOC% in the other years was reported for 0–10 cm depth. As discussed earlier, decrease of soil C with increasing soil depth caused lower values in 2018 samples than other years.

Watershed studies usually present a lag time from the implementation of treatments and measurable responses of the watershed. Therefore, long-term monitoring is vital to characterize ecosystem services including C buildup, water quality benefits, and improved biodiversity of upland agroforestry buffers in agricultural fields (Udawatta & Jose, 2012; Udawatta et al., 2019). During the 23-yr study period, SOC accumulation on these watersheds showed significant differences among vegetation types, management practices, and soil depths. Similar to our findings, a study in France showed 78% increase of SOC on a field growing sunflower (*Helianthus annuus* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) after black walnut (*Juglans nigra* L.) tree rows were established 41 years ago (Cardinael et al., 2017).

3.5 | Landscape position and SOC

The landscape positions were divided by elevation ranges. The foot slope position was from 247 to 251 m, the backslope position from 251 to 252.5 m, and the summit position from 252.5 to 253 m of elevation. The SOC% among landscape positions was statistically significant ($\rho < .05$) for the RC at studied soil depths and not significant for the AB and GB treatments. The SOC% among the landscape positions was ranked foot slope > backslope > summit for all the managements systems (Figure 6). The average SOC% in the summit position in the top 10 cm for the crop, agroforestry buffer, and grass buffer areas were 1.83 ± 0.06, 2.02 ± 0.10, and 2.21 ± 0.1%, respectively. At the backslope position, the SOC% was 2.22 ± 0.06, 2.10 ± 0.12, and 2.36 ± 0.15% and at the foot slope position were 2.31 ± 0.12, 2.37 ± 0.13, and 2.56 ± 0.13.

Udawatta et al. (2008) found a similar SOC distribution pattern among landscape positions of summit (1.21%), backslope (1.66%), and foot slope (2.00%) positions, respectively, in the RC area. Soil organic carbon distribution at landscape positions for the GB treatment were 2.03, 2.30, and 2.32%, respectively. Similarly, the SOC% in the AB treatment was 2.12, 2.24, and 2.81% for the respective landscape positions. Alagele et al. (2019) also reported a similar SOC% trend among landscape positions in the three paired watersheds with 1.46, 1.57, and 1.59% for the summit, backslope, and foot slope, respectively. In a cropland management study, conducted in the middle part of the Upper Blue Nile basin, Abebe et al. (2020) reported similar trends on SOC among landscape positions. In their study, SOC increased from summit < backslope < foot slope. In another study, Wang et al.

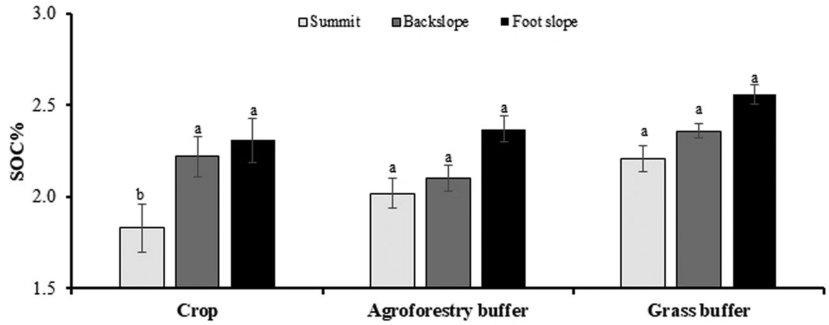

FIGURE 6 Mean soil organic carbon percentage (SOC%) in the top 10-cm depth in the row crop, agroforestry and grass buffer areas at the summit, backslope and foot-slope positions at the Greenley Research Center, Missouri, USA. Bars denote standard errors. Letters indicate significant differences among landscape positions within management practices ($\rho < .05$)

(2008) reported SOC% of 1.53 ± 0.04, 1.41 ± 0.4, and 1.75 ± 0.03% for the summit, side-slope and toe-slope, respectively. Similarly, Safadoust et al. (2016) found in Iran the same trend as Wang et al.(2008) for wheat cultivation and pastures. The results Wang et al. (2008) found can be explained by the greater variability on SOC of samples in the side-slope position, reflected as a greater standard error compared with the other landscape positions. Also, they did not find statistical differences between the summit and side-slope positions. Overall, studies indicated that greater SOC was found in the bottom part of a watershed, and SOC retention in the summit and backslope can be more sensitive to land management and soil characteristics.

4 | SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate the effects of agroforestry, grass buffers, grassed waterways, and crop area on SOC after 23 years of implementation of the vegetative buffers. Land management practices influenced SOC accumulation, and strategically-designed land use practices can enhance carbon sequestration on agricultural fields. The SOC% among management systems were ranked RC < AB < GB < GWW. The SOC% at AB, GB, and GWW was 1.13, 1.24, and 1.3 times greater than the RC. The average SOC% among management practices in the top 10 cm was 18-43% greater than in the subsequent 10 cm, and the greatest difference was observed in the GWW. The time after the implementation of the agroforestry buffers is a major determinant affecting carbon sequestration in agricultural fields because the SOC% in the top 10 cm of soil for the AB and GWW in 2020 was 16.5 to 9% greater, respectively, than in 2000. The grass buffers showed a 14% increase in soil C between 2006 and 2020. Perennial vegetative buffers have increased SOC compared with row crop with time. Establishing upland agroforestry strips on agricultural fields can effectively contribute to C sequestration and mitigate climate change. Future studies on the long-term performance of agroforestry and grass buffers on SOC retention will help to develop better implementation guidelines for these buffers to further enhance C sequestration and mitigate climate change.

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AUTHOR CONTRIBUTIONS

Miguel Salceda: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing-original draft; Writing-review & editing. Ranjith P. Udawatta: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Supervision; Visualization; Writing-review & editing. Kelly A. Nelson: Writing-review & editing. Sidath S. Mendis: Writing-review & editing. Sougata Bardhan: Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

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