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# Landuse and Physiographic Region Effects on Soil Carbon and Nitrogen Sequestration in Arkansas

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## Abstract

Increasing understanding of soil carbon (C) sequestration dynamics and general functioning in disappearing native grassland ecosystems, has the potential to enhance soil rehabilitation and ecosystem restoration. The objective of this study was to evaluate the effects of landuse (native tallgrass prairie and managed agriculture) and physiographic region (northwest Arkansas and east-central Arkansas) on the change in soil C and nitrogen (N) storage and other soil properties over a 15-year period. Despite the native prairie losing soil C at a rate of  $4.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$  over the 15-year duration of this study, soil C storage in 2016 was more than 2.5 times greater in the native prairie than in the cultivated agroecosystems in the Grand Prairie. Averaged across landuse, TC concentration ( $P < 0.01$ ) and content ( $P < 0.01$ ) changed more over time in the Ozark Highlands region of northwest Arkansas ( $0.02\% \text{ year}^{-1}$  and  $0.28 \text{ Mg ha}^{-1} \text{ year}^{-1}$ , respectively), than in the Grand Prairie region of east-central Arkansas. This study demonstrates the value of direct measurements over time for assessing temporal changes in soil properties and results can potentially direct future restoration activities to be as successful as possible.

**Keywords:** carbon sequestration, silt-loam soils, managed grassland, cultivated cropland, and native prairie

## 1. Introduction

Greenhouse gas (GHG) concentrations in the atmosphere have been on the rise since the Industrial Revolution began in the eighteenth century and have led to an enhancement of the greenhouse effect and dramatic increases in global air temperatures. The combined average land and surface air temperatures from 1880 to 2012, calculated from a linear trend with 90% certainty, showed mean warming of  $0.85^\circ\text{C}$ , which ranged from  $0.65$  to  $1.06^\circ\text{C}$ , across the globe [1]. This striking increase in air temperature over such a short period of time has evolved into the climatic variations witnessed today that scientists have termed global climate change. The scientific consensus is that the rising air temperatures are the result of an unprecedented rise in GHG emissions over the last 150 years, due primarily to

human activity in the form of burning fossil fuels, agricultural land conversion and management, and deforestation [1].

Carbon dioxide (CO<sub>2</sub>) is the most abundant GHG in the atmosphere and has risen from 280 mg L<sup>-1</sup> before the Industrial Revolution in 1730 to over 400 mg L<sup>-1</sup> in 2015 and is predicted to continue increasing by 2 mg L<sup>-1</sup> per year [1]. In 2010, the CO<sub>2</sub> derived from burning fossil fuels and industrial processes contributed around 65% of total global GHG emissions, while forestry, land clearing for agriculture, and soil degradation collectively accounted for 11% of the global emissions [1]. In 2015, agricultural production alone accounted for 9% of total US GHG emissions [2]. Fossil fuels are burned during agricultural production, from heavy machinery and equipment, and these emissions account for nearly 25% of the total global GHG emissions originating from fossil fuels [1]. However, other sources of CO<sub>2</sub> emissions associated with agricultural production result from the initial conversion and continued tillage of soils that contain substantial amounts of soil organic carbon (SOC).

Carbon flows through the global C cycle between five primary pools: the oceanic pool, geologic pool (fossil fuels), pedologic (soil) pool, atmospheric pool, and biotic pool. Most of the C held within the terrestrial ecosystem is stored within the soil (~2500 Pg), with only a fraction of the total terrestrial C stored within plant biomass (~560 Pg) [3]. The global C cycle and SOC creation are fueled by the photosynthetic activity of plants and other autotrophic organisms, which convert CO<sub>2</sub> into glucose (C<sub>6</sub>H<sub>12</sub>O<sub>6</sub>) or energy that is used to develop biomass. Following the decomposition of autotrophic organisms and the heterotrophic organisms that consume them, a portion of the C captured during photosynthesis remains stored in the soil in a process known as soil C sequestration.

Soil C sequestration potential within an ecosystem is dependent on the same factors that lead to pedogenesis: parent material, climate, biota, topography, and time. Climate and biota tend to play a more significant role in the C cycle and therefore are often more important to the soil C sequestration process. Colder climates are more likely to accumulate SOC because soil microbial decomposition of soil organic matter (SOM) is slowed and sometimes paused when temperatures reach below freezing (0°C) [4]. In addition to temperature, the other main climatic factor that affects soil C sequestration is moisture, where a fine line exists between optimal soil moisture and too much or too little soil moisture. Optimal soil moisture contributes to increase in above- and belowground autotrophic productivity, which leads to greater available plant biomass. Too much soil moisture decreases soil microbial decomposition rates of SOC when soil moisture levels reach a point where periodic reducing conditions occur. However, increased moisture levels that do not reach reducing conditions have the potential to increase soil microbial decomposition rates, as microbes gain more access to the soil pores through the movement of water. In contrast, too little soil moisture limits plant productivity, hence the potential production and input of SOM for soil microbes to consume and convert to SOC.

The C compounds returned to the soil during microbial decomposition, in the form of SOM, consist of three separate pools: active, intermediate or slow, and passive. These pools are classified by the amount of time the SOM remains stable before further decomposing and returning to the atmosphere, mostly as CO<sub>2</sub>, via microbial respiration. Soil organic matter within the active pool consists of labile or easily decomposable particulate organic matter [5]. The active pool of SOM contributes most of the beneficial effects of soil structural stability, which enhances a soil's infiltration capacity and resistance to erosion and can be readily increased by adding fresh plant and animal residues. However, due to the potential instability of the organic material, the active C pool can be easily lost due to reductions in organic additions or increased tillage.

Agricultural production is one of the leading disturbances of the SOC pools because of the management practice of conventional tillage [6]. Over the years, due to reduced C inputs and continual disturbance through conventional tillage, between 40 and 60% of SOC has been lost following the conversion of lands from tallgrass prairie to cultivated agriculture [7]. The decrease can be explained by the initial land conversion to non-native vegetation, followed by the rapid oxidation of SOM from conventional tillage and minimal vegetative cover and biomass inputs back to the soil. Rapid declines in SOC are due partly to the mechanical disintegration of soil aggregates during repeated annual tillage, which exposes organo-mineral surfaces that had otherwise been unavailable for decomposition by microbes when previously undisturbed and the physical loss of SOC due to erosion [8]. However, some level of SOM turnover is necessary to incorporate and protect fresh C inputs from rapid decay and mineralization, whereas SOM turnover that occurs too quickly or too often can lead to decreases in microaggregate stability and formation, therefore decreasing soil C sequestration potential [9].

Soil formation and resulting soil properties are inextricably linked with climatic factors and parent material. Arkansas resides in a unique climatic transition zone in the mid-southern United States, with arid to semi-arid grassland to the west and northwest and humid-temperate deciduous forest to the south and southeast. The climate gradient that spans through Arkansas also controls the botanical composition and interacts with distinct topographic and geologic gradients. Consequently, Arkansas is separated into at least two distinct climates and parent material sources. The northwest region of Arkansas, known as the Ozark Highlands [Major Land Resource Area (MLRA) 116A] [10], is relatively warm and wet and dominated by deciduous forest vegetation both presently and as the climax vegetation community. Cherty limestone residuum is the soil parent material for much of the Ozark Highlands. Soils in the Ozark Highlands are typically moderately deep and medium- to fine-textured Udupts and Udalfs. The Ozark Highlands also contains remnants of the Osage Prairie, which once extended through south-central and southwestern Missouri, as well as northwest Arkansas [11]. Presently, less than 0.5% of the original Osage prairie exists, due to the conversion to pasture and hay meadows now populated with naturalized (i.e., introduced) species [11]. East-central Arkansas contains the remnants of the tallgrass prairie regionally referred to as the Grand Prairie, within MLRA 134—Southern Mississippi Valley Silty Uplands [10], which is an area that is also relatively warm and wet, with fertile alluvial parent material.

Comparing native prairies across these two physiographic regions in Arkansas, Brye et al. [12] reported that SOM concentrations in the top 10 cm in native prairie ecosystems generally increased south and eastward across Arkansas, due to increasing precipitation in the Grand Prairie region compared to the Ozark Highlands, therefore leading to increase above- and belowground productivity. In contrast, a study conducted by Brye and Gbur [13] reported that, averaged across landuse, soils in the Grand Prairie region had the lowest average SOC sequestration rate ( $-0.04 \text{ kg SOC m}^{-2} \text{ year}^{-1}$ ) in the top 10 cm compared to that observed in the Ozark Highlands ( $0.05 \text{ kg SOC m}^{-2} \text{ year}^{-1}$ ). Brye and Gbur [13] also reported that, averaged across physiographic region, soils under agricultural management had a lower average SOC sequestration rate ( $-0.03 \text{ kg SOC m}^{-2} \text{ year}^{-1}$ ) in the top 10 cm compared to that observed for native prairies ( $0.04 \text{ kg SOC m}^{-2} \text{ year}^{-1}$ ).

A study conducted within the Ozark Highlands region evaluating the effects of grassland management on soil physical and chemical properties, including SOC, in the top 10 cm over a 6-year period in silt-loam soil reported that certain management schemes, including grazing and haying, had minimal effect on near-surface soil properties, indicating that contemporary managed forage lands in the Ozark Highlands are not being degraded by agricultural management, but are in fact



remaining similar to the remnant prairies from which they were converted [14]. In contrast, a study conducted, within the Grand Prairie region, on a chronosequence of four Typic Albaqualfs in adjacent fields in Prairie County, Arkansas, varying only in time under cultivation with the control as a native, undisturbed tallgrass prairie, reported an exponential decrease in SOC in the top 10 cm as years of cultivation increased [15]. Brye and Pirani [16] showed a significant difference in soil C concentration and content in the top 10 cm between native prairie (2.3–3.2% C; 2.5–3.4 kg C m<sup>-2</sup>) and adjacent tilled agricultural systems (1.0–1.7% C, 1.3–2.0 kg C m<sup>-2</sup>) in the Grand Prairie region of east-central Arkansas. Specifically, the difference in soil C tended to be greater when the agricultural fields had been tilled for 30 or more years than when the agricultural fields had been tilled for less than 30 years [16]. Following the conversion from native prairie to intensely tilled agriculture, a 17–52% decrease in soil-quality-related parameters was observed, including soil OM, total N, and total C [16].

Many of these examples of losses in SOC, and other resulting soil-quality parameters, can be interpreted positively as the potential to enhance and regain soil C storage in soils affected by long-term agricultural activity. With a combination of site-specific best management practices, like conservation tillage, no-tillage, cover crops, and elimination of fallow periods, which increase C input into the system, agricultural fields have the potential to become C sinks instead of their historic role as C sources. The objective of this study was to evaluate the effects of landuse (i.e., native tallgrass prairie and managed agriculture) and physiographic region on the change in soil C storage and other soil properties over a 15-year period. It was hypothesized that soil C and N storage in the top 10 cm would remain constant or slightly increased within the prairie remnants, while soil under agricultural management (i.e., managed pastureland, and cultivated agriculture) would likely decrease over a 15-year period between 2001 and 2016. Cultivated row-crop agriculture on alluvial soils was hypothesized to have lower C and N storage than managed pastureland on residual soils due to the long history of intensive tillage, despite alluvial soils typically being considered more fertile than residual soils.

## 2. Materials and methods

### 2.1 Site description

The Stump and Chesney Prairies in Benton County in the Ozark Highlands region of northwest Arkansas have various degrees of disturbed, agricultural landuse adjacent to the prairies in the same soil map unit as exists in the prairies (**Table 1**). Specifically, adjacent to the Stump Prairie resides a managed grassland, dominantly tall fescue (*Lolium arundinaceum* [Schreb.] Darbys.), that has been infrequently cultivated in the last 20 years for cutting and removing the aboveground vegetation (i.e., haying) multiple times a year. In addition, a managed pastureland that has never been cultivated, but has been consistently grazed multiple times per year for the past 20 years with varying head of cattle, also resides adjacent to the Stump Prairie. Adjacent to the Chesney Prairie resides an area that has been periodically cultivated and planted with a row crop [i.e., corn (*Zea mays* L.) or soybean (*Glycine max* L.)] in the last 20 years; however, the area has been left fallow for the past 15 years without a row crop being planted.

The Seidenstricker Prairie, in Prairie County, Arkansas, resides in an area known as the Grand Prairie and has three adjacent agricultural fields, with similar soil mapping units as exists in the prairie, that were once part of the prairie itself

| Region/parent material       | Site           | Landuse                             | Years managed | Soil series | Soil taxonomic description | Slope (%) |
|------------------------------|----------------|-------------------------------------|---------------|-------------|----------------------------|-----------|
| Ozark Highlands/<br>residuum | Stump          | Periodically cultivated hayfield    | >20           | Jay         | Oxyaquic Fragiudalf        | 0         |
|                              | Stump          | Never cultivated managed pasture    | >20           | Jay         | Oxyaquic Fragiudalf        | 0         |
|                              | Stump          | Native prairie                      | 0             | Jay         | Oxyaquic Fragiudalf        | 1         |
|                              | Chesney        | Periodically cultivated agriculture | >20           | Jay         | Oxyaquic Fragiudalf        | 2         |
|                              | Chesney        | Native prairie                      | 0             | Jay         | Oxyaquic Fragiudalf        | 2         |
| Grand Prairie/<br>alluvium   | Seidenstricker | Cultivated agriculture              | 31*           | Dewitt      | Typic Albaqualf            | 0         |
|                              | Seidenstricker | Cultivated agriculture              | 42*           | Dewitt      | Typic Albaqualf            | 0         |
|                              | Seidenstricker | Cultivated agriculture              | 60*           | Dewitt      | Typic Albaqualf            | 0         |
|                              | Seidenstricker | Native prairie                      | 0             | Dewitt      | Typic Albaqualf            | 0         |

\*Indicates years before 2016, therefore native prairie was converted to cultivated agriculture in 1986, 1975, and 1957, respectively.

**Table 1.**  
Summary of site characteristics by geographic region.

that have now been consistently annually intensively cultivated and cropped under a rice (*Oryza sativa* L.)-soybean-wheat (*Triticum aestivum* L.) rotation in most years since 1957, 1975, and 1986 (**Table 1**). Consequently, as of 2016, the native prairie and three adjacent agricultural fields represented a chronosequence with varying years under cultivated agriculture (i.e., 0, 31, 42, and 60 years, respectively).

2.2 Regional characteristics

The Ozark Highlands (36–38°N lat., 91–95°W long.), MLRA 116A [10], occupies portions of southwest and south-central Missouri, eastern Oklahoma, and north-west and north-central Arkansas. The area is a low-elevation, disjointed mountainous region, covering roughly 2.1 million ha [13]. Soils in the Ozark Highlands are typically Udults and Udalfs with deep, medium- to fine-textured cherty residuum weathered from limestone [17]. Oak (*Quercus* spp.) forests dominate the vegetation in the Ozark Highlands, but a large extent of tallgrass prairie was also historically present. The Chesney and Stump Prairies are located within the Springfield Plateau, a region that extends over 640,000 ha, which consisted of low, undulating plains (240–430 m in elevation) covered in prairie, savannah, hardwood forest, and acidic glade ecosystems [10]. Historic prairie ecosystems covered >30,000 ha within the Springfield Plateau. The Chesney and Stump prairies are the only remnants of a

much grander historical prairie that spanned over 4000 ha in northwest Arkansas known as the Lindsley Prairie [18].

The Grand Prairie (34°0′–35°30′ N lat., 91°15′–92°10′ W long.), part of MLRA 134, is in east-central Arkansas and covers roughly 0.5 million ha [10]. Soils in the Grand Prairie are typically deep to very deep Udalfs, with medium texture and mixed mineralogy [17], that are developing in fertile alluvial parent material sourced from the historic flooding of the Mississippi River, with or without a thin loess cover. The historic land cover in the Grand Prairie region was grasslands, which historically covered ~130,000 ha as tallgrass prairie, of which <1% remains today due primarily to the introduction and expansion of mechanized agriculture [19]. Consequently, presently, the predominant landuse within the Grand Prairie region is cultivated, row-crop agriculture, where rice, soybean, and wheat are the dominant crops.

The regions also vary by climate. The climate of the Grand Prairie region is, on average, warmer than the Ozark Highlands, with mean annual temperatures of 16.6 and 14.5°C, respectively [20]. Average annual precipitation in the northwest Arkansas portion of the Ozark Highlands is approximately 116 cm, while that in the Grand Prairie region is 126 cm [20].

### 2.3 Soil sampling scheme

Between early August 2001 and mid-April 2002, initial soil samples were collected at Stump and Chesney Prairies in the Ozark Highlands region of northwest Arkansas and at the Seidenstricker Prairie in the Grand Prairie region of east-central Arkansas. Soil property data in the top 10 cm from the initial soil samples collected in 2001/2002 were determined and reported in Brye and West [11] and Brye et al. [21] for the Stump and Chesney prairies and in Brye and Slaton [22] and Brye et al. [12] for the Seidenstricker Prairie. At the same time, between early August 2001 and mid-April 2002, the above-described, adjacent agricultural areas were sampled at all three prairie sites. Between late October and early November 2016, a subsequent set of soil samples were collected in all three prairie sites and in their adjacent agricultural areas. In each soil map unit represented within each prairie and in the same or similar soil map unit in the adjacent agricultural areas, soil samples were collected from the top 10 cm along a 60-m transect at five sampling points spaced 15 m apart (i.e., at the 0-, 15-, 30-, 45-, and 60-m marks). A slide hammer, with a 4.8-cm-diameter, stainless steel core chamber, was used to manually collect the soil samples, which were subsequently oven-dried at 70°C for 48 h, weighed for bulk density determinations, and crushed and sieved to pass through a 2-mm mesh screen for soil chemical property determinations.

Percentages of sand, silt, and clay in the top 10 cm from the initial soil samples collected in 2001/2002 were determined and reported in Brye and West [11] and Brye et al. [21] for the Stump and Chesney prairies and in Brye and Slaton [22] and Brye et al. [12] for the Seidenstricker Prairie. Soil pH was potentiometrically measured using an electrode in a 1:2 (wt/vol) soil-to-water paste. Soil organic matter was determined by weight-loss-on-ignition after 2 h at 360°C. Total C and N were determined by high-temperature combustion (Elementar Variomax CN Analyzer, Elementar Americas, Inc., Mt. Laurel, NJ). No soil among sampled transects effervesced upon treatment with dilute hydrochloric acid, thus all measured soil C was assumed to be SOC. The C:N ratio and fractionation of C and N in the SOM were calculated for each sample using measured concentrations. In addition, for each soil sample, TC, TN, and SOM contents (kg ha<sup>-1</sup>) were calculated from

measured concentrations ( $\text{g kg}^{-1}$ ), measured bulk densities, and the 10-cm depth interval. To calculate C and N sequestration rates, the 2001/2002 contents were then subtracted from 2016 contents and the differences were divided by the number of years between sampling (~15 years).

## 2.4 Statistical analyses

A two-factor analysis of variance (ANOVA) was conducted using SAS 9.4 (SAS Institute, Inc., Cary, NC), based on a completely random design, to evaluate the effects of physiographic region (i.e., Ozark Highlands and Grand Prairie), landuse (i.e., native prairie and managed agriculture), and their interaction on changes in soil bulk density, pH, EC, SOM, C, and N storage, C:N ratio, and C and N fractions of SOM in the top 10 cm over time. A second two-factor ANOVA was conducted using SAS to evaluate the effects of physiographic region, landuse, and their interaction on soil bulk density, pH, EC, SOM, C, and N storage, C:N ratio, and C and N fractions of SOM in the top 10 cm from the 2016 sampling only to assess the current state of soil property differences among treatments. In addition, a linear regression analysis was conducted in Minitab (version 13, Minitab, Inc., State College, PA) using the 2016-measured data only for the Grand Prairie sites to assess soil C storage trends over time under cultivation. For all statistical analyses, significance was judged at  $P < 0.05$ ; thus, when appropriate, means were separated by least significant difference (LSD) at the 0.05 level.

## 3. Results and discussion

### 3.1 Soil property differences after 15 years

In 2016, after 15 years of consistent management or natural time progression, all measured soil properties, with the exception of bulk density, C:N ratio, and the C and N fractions of SOM, differed ( $P < 0.05$ ) between regions within landuses (**Table 2**). Soil bulk density and the C and N fractions of SOM differed ( $P < 0.03$ ) between physiographic regions and differed ( $P < 0.04$ ) between landuses, while the soil C:N ratio was unaffected ( $P > 0.05$ ) by region or landuse (**Table 2**), thus was similar and averaged 13.5 across all region-landuse combinations (**Table 3**). **Table 3** also summarizes the means and standard errors among ecosystem-landuse combinations for soil properties from the original 2001/2002 soil sampling.

Soil pH and EC were greatest ( $P < 0.01$ ; **Table 2**) in the Grand Prairie region within the agricultural landuse (6.7 and  $0.168 \text{ dS m}^{-1}$  respectively), and lowest in the native prairie landuse in the same region (4.7 and  $0.072 \text{ dS m}^{-1}$  respectively), but only pH and EC in the agricultural landuse in the Grand Prairie differed from the other region-landuse combinations (**Table 3** and **Figure 1**). Soil pH and EC were likely more regulated in the more conventional agricultural landuses in the Grand Prairie from annual fertilizer additions and irrigation, respectively. Brye and Pirani [16] similarly concluded that soil pH and EC were generally greater under tilled agricultural than under native prairie landuse.

In 2016, after 15 years of consistent management, SOM concentration and content were both more than two-fold greater in the Ozark Highlands under both landuses and in the Grand Prairie under prairie landuse, which did not differ, than in the Grand Prairie under cultivated agricultural landuse (**Figure 2**). Similarly, TN concentration and content were lowest, by more than 50%, in the Grand Prairie under cultivated agricultural landuse, while TN concentration was greatest under



| Soil property              | Region | Landuse | Region × landuse |
|----------------------------|--------|---------|------------------|
| <i>P</i>                   |        |         |                  |
| BD (g cm <sup>-3</sup> )   | 0.03   | <0.01   | 0.83             |
| pH                         | <0.01  | <0.01   | <0.01            |
| EC (dS m <sup>-1</sup> )   | 0.16   | <0.01   | <0.01            |
| SOM (%)                    | <0.01  | <0.01   | <0.01            |
| SOM (Mg ha <sup>-1</sup> ) | <0.01  | <0.01   | <0.01            |
| TN (%)                     | <0.01  | 0.02    | 0.04             |
| TN (Mg ha <sup>-1</sup> )  | <0.01  | 0.10    | <0.01            |
| TC (%)                     | <0.01  | < 0.01  | 0.03             |
| TC (Mg ha <sup>-1</sup> )  | <0.01  | < 0.01  | <0.01            |
| C:N ratio                  | 0.26   | 0.45    | 0.32             |
| TN fraction of SOM (%)     | <0.01  | 0.04    | 0.92             |
| TC fraction of SOM (%)     | <0.01  | 0.03    | 0.60             |

**Table 2.**  
*Analysis of variance summary of the effects of physiographic region (Ozark Highlands and Grand Prairie), landuse (managed agriculture and native prairie), and their interaction on the change in soil bulk density (BD), pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), and total carbon (TC) concentration and content, C:N ratio, and the C and N fractions of SOM in the top 10 cm over a 15-year period in silt-loam soils in Arkansas.*

prairie landuse in both regions, which did not differ, and TN content was greatest under prairie landuse in the Grand Prairie (**Table 4** and **Figure 1**). Total N concentration and content were also greater under prairie than managed agricultural landuse in the Ozark Highlands (**Table 4** and **Figure 2**). Similar to TN, TC concentration and content were more than twofold greater under prairie landuse in both regions, which did not differ, than under cultivated agriculture in the Grand Prairie (**Table 4** and **Figure 2**). Total C concentration and content were also greater under prairie than agricultural landuse in the Ozark Highlands (**Figure 2**). Differences in TC and TN content among region-landuse combinations were likely the result of combined differences in TC and TN concentrations and bulk density, where, averaged across landuse, bulk density was 1.1 times greater in the Grand Prairie than in the Ozark Highlands and, averaged across region, was also 1.1 times greater under managed agricultural than native prairie landuse (**Table 3**). However, the differences in TC and TN concentrations alone (**Table 4** and **Figure 2**) clearly demonstrate that there are substantial differences in the net balance between above- and/or belowground C and N inputs and losses.

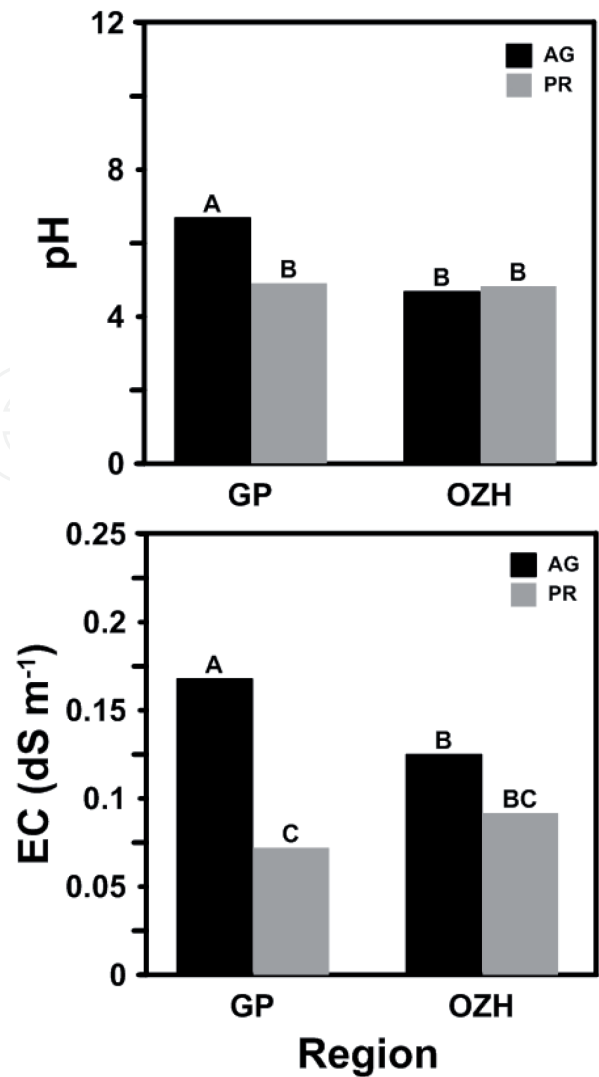
Averaged across landuse, TN and TC fractions of SOM were both 1.3 times greater in the Ozark Highlands than in the Grand Prairie (**Table 3**). Averaged across region, TN and TC fractions of SOM were both 1.1 times greater under managed agricultural than native prairie landuse (**Table 3**). The differences in TC and TN fractions of SOM between regions and between landuses indicate that, in the Ozark Highlands and in the managed agricultural landuse use in general, the SOM pool is less diverse with other soil nutrients than in the Grand Prairie and native prairie landuse.

In contrast to the results of this study, Brye and Gbur [13] reported greater SOM, TN, and TC contents under the native prairie in the Grand Prairie, citing warmer and wetter annual climatic conditions that would promote greater belowground root biomass and OM, N, and C inputs compared with the Ozark Highlands.

| Treatment  | Soil properties <sup>†</sup> |               |                             |                                  |                                 |                                 |                |               |              |
|--|------------------------------|---------------|-----------------------------|----------------------------------|---------------------------------|---------------------------------|----------------|---------------|--------------|
|  | BD<br>(gcm <sup>-3</sup> )   | pH            | EC<br>(dS m <sup>-1</sup> ) | SOM<br>(Mg<br>ha <sup>-1</sup> ) | TN<br>(Mg<br>ha <sup>-1</sup> ) | TC<br>(Mg<br>ha <sup>-1</sup> ) | C:N            | N/SOM<br>(%)  | C/SOM<br>(%) |
| <i>Region</i>  |                              |               |                             |                                  |                                 |                                 |                |               |              |
| Grand<br>Prairie (GP)  | 1.21                         | 5.7           | 0.120                       | 39.5                             | 1.24                            | 17.0                            | 13.7           | 3.22          | 44.0         |
| Ozark<br>Highlands<br>(OZH)  | 1.14                         | 4.9           | 0.108                       | 54.3                             | 2.33                            | 30.7                            | 13.3           | 4.29          | 56.8         |
| <i>Landuse</i>   |                              |               |                             |                                  |                                 |                                 |                |               |              |
| Agriculture<br>(AG)  | 1.23a                        | 5.8           | 0.146                       | 40.0                             | 1.67                            | 21.8                            | 13.4           | 3.97a         | 52.6a        |
| Prairie (PR)   | 1.11b                        | 4.8           | 0.082                       | 53.8                             | 1.91                            | 25.9                            | 13.6           | 3.54b         | 48.2b        |
| <i>Ecosystem × landuse</i>   |                              |               |                             |                                  |                                 |                                 |                |               |              |
| GP-AG  | 1.27                         | 6.7a          | 0.168a                      | 26.5b                            | 0.89d                           | 12.2c                           | 13.7           | 3.38          | 46.4         |
| GP-PR  | 1.15                         | 4.7b          | 0.072b                      | 52.5a                            | 1.59c                           | 21.7b                           | 13.7           | 3.05          | 41.7         |
| OZH-AG   | 1.20                         | 4.9b          | 0.125b                      | 53.6a                            | 2.44a                           | 31.3a                           | 13.1           | 4.55          | 58.9         |
| OZH-PR   | 1.07                         | 4.8b          | 0.092b                      | 55.0a                            | 2.23b                           | 30.1a                           | 13.6           | 4.03          | 54.7         |
| <i>Ecosystem × landuse combination means (± standard error) from the 2001/2002 sampling<sup>††</sup></i>                                 |                              |               |                             |                                  |                                 |                                 |                |               |              |
| GP-AG  | 1.15<br>(0.02)               | 5.9<br>(0.1)  | 0.098 (0.01)                | 32.3 (1.3)                       | 1.37<br>(0.03)                  | 15.1<br>(0.3)                   | 11.0<br>(<0.1) | 4.34<br>(0.2) | 47.9 (2.3)   |
| GP-PR  | 1.13<br>(0.01)               | 4.7<br>(<0.1) | 0.072<br>(<0.01)            | 58.1 (1.8)                       | 2.33<br>(0.07)                  | 28.9<br>(0.8)                   | 12.4<br>(0.2)  | 4.02<br>(0.1) | 49.9 (1.2)   |
| OZH-AG   | 0.13<br>(0.04)               | 5.1 (0.1)     | 0.104 (0.01)                | 54.0 (2.7)                       | 2.68<br>(0.17)                  | 26.6<br>(1.6)                   | 10.0<br>(0.3)  | 4.94<br>(0.1) | 49.0 (1.0)   |
| OZH-PR   | 0.06<br>(0.02)               | 4.8<br>(<0.1) | 0.072<br>(<0.01)            | 49.2 (2.1)                       | 2.18<br>(0.11)                  | 24.1<br>(1.4)                   | 11.0<br>(0.2)  | 4.43<br>(0.1) | 48.7 (1.0)   |
| <sup>†</sup> Different lower case letters for a soil property within a treatment category indicates a significant difference (P < 0.05). |                              |               |                             |                                  |                                 |                                 |                |               |              |
| <sup>††</sup> Data reproduced from Brye and West [11], Brye et al. [21], Brye and Slaton [22], and Brye et al. [12].                     |                              |               |                             |                                  |                                 |                                 |                |               |              |

**Table 3.**  
Summary of mean soil property changes by treatment (i.e., physiographic region, landuse and their interaction) over a 15-year sampling period for soil bulk density (BD), pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), total carbon (TC), C:N ratio, and the N (N/SOM) and C (C/SOM) fractions of SOM in the top 10 cm in silt-loam soils in Arkansas.

Similarly, comparing soil properties among only native prairies, Brye et al. [12] concluded that SOM and SOC concentrations and C:N ratio were at least numerically greater in the Grand Prairie than in the Ozark Highlands. However, Brye et al. [12] also reported that, based on a significant linear relationship, both TN and TC increased with increasing SOM concentration faster in the Ozark Highlands than in the Grand Prairie. Brye and West [11] reported that neither TN nor TC concentration differed in the top 10 cm between landuses in 2001/2002 when comparing the same sites used for this study in the Ozark Highlands. However, TN and TC concentration data were obtained through high-temperature combustion, whereas SOM concentration, which is obtained by weight-loss on ignition at a lower temperature, was significantly greater in the grazed than in the ungrazed pasture or native prairie soils [11]. These results indicate that the proportion of SOC within SOM likely differs between management systems, in which the quality of substrate entering



**Figure 1.** Landuse effects by physiographic region on the change in soil pH and electrical conductivity (EC) in the top 10 cm over the 15-year sampling period under either agricultural management (AG) or undisturbed prairie (PR) landuse in the Grand Prairie (GP) region of east-central Arkansas or the Ozark Highlands (OZH) region of northwest Arkansas. Different letters associated with mean values on a panel are different at  $P < 0.05$ . An asterisk (\*) indicates mean value is greater than 0 ( $P < 0.05$ ).

the SOC pool through humification is likely more recalcitrant or physiochemically protected in the native prairie, indicating more C storage is occurring within the passive SOC pool.

### 3.2 Soil property changes over time

Most of the soil property differences measured in this study in the top cm over a period of 15 years from 2001/2002 to 2016 were affected by physiographic region, landuse, or both (**Table 5**). Changes in soil pH ( $P < 0.01$ ) and EC ( $P = 0.01$ ) over the 15-year period differed among regions within landuses (**Table 5**). In contrast, changes in SOM content, TC and TN content and concentration, C:N ratio, TC and TN fractions of SOM over time differed ( $P < 0.05$ ; **Table 5**) between regions, while changes in TC content, C:N ratio, and TC fraction of SOM over time also differed ( $P < 0.05$ ; **Table 5**) between landuses. Neither changes in soil bulk density nor SOM concentration over time were affected by region or landuse ( $P > 0.05$ ; **Table 5**).

Soil pH and EC in the top 10 cm increased the most over time under cultivated, row-crop agricultural management in the Grand Prairie, which was a greater change over time than for the other three region-landuse combinations, which did

| Treatment               | Soil properties <sup>†</sup> |        |        |
|-------------------------|------------------------------|--------|--------|
|                         | SOM (%)                      | TN (%) | TC (%) |
| <i>Region</i>           |                              |        |        |
| Grand Prairie (GP)      | 3.33                         | 0.12   | 1.44   |
| Ozark Highlands (OZH)   | 4.88                         | 0.21   | 2.75   |
| <i>Landuse</i>          |                              |        |        |
| Agriculture (AG)        | 3.31                         | 0.14   | 1.81   |
| Prairie (PR)            | 4.90                         | 0.21   | 2.39   |
| <i>Region × landuse</i> |                              |        |        |
| GP-AG                   | 2.09b                        | 0.07c  | 0.97c  |
| GP-PR                   | 4.58a                        | 0.14b  | 1.92b  |
| OZH-AG                  | 4.53a                        | 0.21a  | 2.64a  |
| OZH-PR                  | 5.23a                        | 0.21a  | 2.86a  |

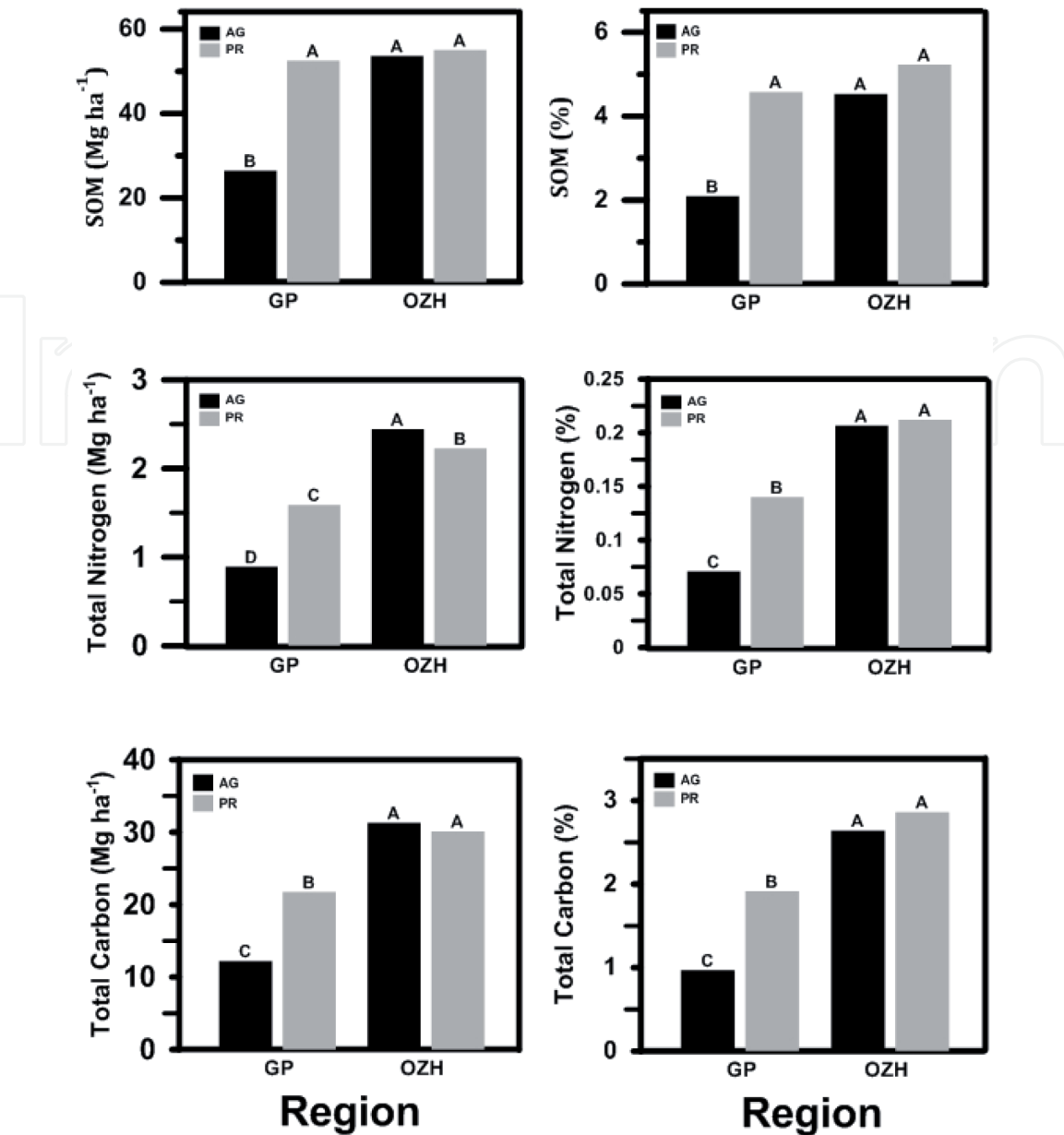
<sup>†</sup>Different lower case letters for a soil property within a treatment category indicates a significant difference ( $P < 0.05$ ).

**Table 4.**  
Summary of mean soil property changes by treatment (i.e., physiographic region, landuse, and their interaction) over a 15-year sampling period for soil organic matter (SOM), total nitrogen (TN), total carbon (TC) concentrations in the top 10 cm in silt-loams soils in Arkansas.

not differ (**Table 6** and **Figure 3**). However, soil pH and EC also decreased the most over time under non-cultivated agricultural landuse in the Ozark Highlands (**Table 6** and **Figure 3**). The differences in soil pH and EC change over time under agricultural landuse likely were due to periodic lime applications and exposure to bicarbonate-rich irrigation water for row-crop production in the Grand Prairie. In contrast, soil pH and EC did not change over time under native prairie landuse in either region, which may have occurred due to already having achieved some level of equilibrium that maintained the soil in a well-buffered state. Similar to the results of this study, based on samples collected in 1987 to a depth of 10 cm, also at the Seidenstricker site in the Grand Prairie, Brye et al. [15] concluded that soil pH levels were greater in the oldest cultivated, agriculturally managed soils, 12- and 30-year-old at the time, than in the native prairie and the youngest (1-year-old) cultivated, agriculturally managed soil. Following a resampling of the same sites in 2001, Brye et al. [15] reported that soil pH was still greater in the cultivated agroecosystems than in the prairie, but that soil pH did not differ among the three cultivated agroecosystems by 14 years later. Brye and Gbur [14], who compared soil property differences in the top 10 cm between native, undisturbed, and managed grasslands in the Ozark Highlands between 2001 and 2008, concluded that, although numerically greater in the agroecosystems, soil pH did not differ in the top 10 cm between native prairie and managed forage landuse, but soil pH levels had decreased by 8% in the 7 years between samplings. The soil pH decrease was attributed to a lack of liming in the managed forage lands and the presence of natural mineralization of the SOM and nitrification processes that had been slowly acidifying the soil [14].

In contrast to soil pH and EC, averaged across landuse, SOM content in the top 10 cm decreased over time in the Grand Prairie ( $-0.37 \text{ Mg ha}^{-1} \text{ year}^{-1}$ ), but did not change over time in the Ozark Highlands (**Table 3**). Soil bulk density did not differ over time (**Table 5**), but, despite the change in SOM concentration over time being unaffected ( $P > 0.05$ ) by region (**Table 5**), SOM concentration decreased





**Figure 2.** Landuse effects by physiographic region on soil pH and electrical conductivity (EC) in the top 10 cm from the 2016 sampling only under either agricultural management (AG) or undisturbed prairie (PR) landuse in the Grand Prairie (GP) region of east-central Arkansas and the Ozark Highlands (OZH) region of northwest Arkansas. Different letters associated with mean values on a panel are different at  $P < 0.05$ .

more in the Grand Prairie than in the Ozark Highlands (**Table 6**), which was likely responsible for the decrease in SOM content in the Grand Prairie over time. Furthermore, the Grand Prairie region, on average, is slightly warmer and wetter than in the Ozark Highlands. Consequently, microbial decomposition of SOM was likely somewhat greater over time in the Grand Prairie than in the Ozark Highlands. Brye and Gbur [14] also concluded that SOM content did not change over time in either the native prairies or the managed grasslands in the Ozark Highlands region. In a study comparing landuse effects between the Ozark Highlands and the Grand Prairie regions among silt-loam-textured soils to a depth of 10 cm, between 2001 and 2007, Brye and Gbur [13] also demonstrated that, averaged across landuse, SOM content decreased in the Grand Prairie, but did not change over time in the Ozark Highlands and attributed the results to the regional climate differences. The Grand Prairie region also typically experiences longer durations of warmer temperatures, which stimulate microbial activity and lead to greater microbially mediated SOM decomposition rates.

| Soil property                               | Region | Landuse | Region × landuse |
|---|--------|---------|------------------|
| <i>P</i>                                    |        |         |                  |
| BD (g cm <sup>-3</sup> yr <sup>-1</sup> )   | 0.55   | 0.08    | 0.87             |
| pH (yr <sup>-1</sup> )                      | <0.01  | 0.01    | <0.01            |
| EC (dS m <sup>-1</sup> yr <sup>-1</sup> )   | 0.17   | <0.01   | 0.01             |
| SOM (% yr <sup>-1</sup> )                   | 0.08   | 0.22    | 0.44             |
| SOM (Mg ha <sup>-1</sup> yr <sup>-1</sup> ) | <0.01  | 0.59    | 0.68             |
| TN (% yr <sup>-1</sup> )                    | 0.05   | 0.76    | 0.15             |
| TN (Mg ha <sup>-1</sup> yr <sup>-1</sup> )  | <0.01  | 0.57    | 0.16             |
| TC (% yr <sup>-1</sup> )                    | <0.01  | 0.67    | 0.19             |
| TC (Mg ha <sup>-1</sup> yr <sup>-1</sup> )  | <0.01  | 0.04    | 0.22             |
| C:N ratio (yr <sup>-1</sup> )               | 0.04   | <0.01   | 0.37             |
| TN fraction of SOM (% yr <sup>-1</sup> )    | 0.02   | 0.99    | 0.96             |
| TC fraction of SOM (% yr <sup>-1</sup> )    | <0.01  | 0.06    | 0.76             |

**Table 5.**  
*Analysis of variance summary of the effects of physiographic region, landuse, and their interaction on soil bulk density (BD), pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), and total carbon (TC) concentration and content, C:N ratio, and the TN and TC fractions of SOM in the top 10 cm from the 2016 sampling in silt-loam soils in Arkansas.*

Similar to SOM content, averaged across landuse, TN concentration ( $-0.004\%$  year<sup>-1</sup>; **Table 4**) and content ( $-0.04$  Mg ha<sup>-1</sup> year<sup>-1</sup>; **Table 6**) decreased by more than a factor of two over time in the Grand Prairie respectively; table than in the Ozark Highlands, which also decreased over time ( $-0.002\%$  year<sup>-1</sup> and  $-0.01$  Mg ha<sup>-1</sup> year<sup>-1</sup>, respectively; **Tables 6** and **7**). Despite the annual input of fertilizer N for optimal row-crop production in the Grand Prairie, which only meant to meet the crop N requirement, no other mechanisms of N input are enough to overcome the net loss of N over time from the top 10 cm by likely leaching and/or volatilization. In contrast to the results of this study, Brye and Gbur [13] reported that, averaged across landuses, TN content increased over time at a rate of  $0.04$  Mg ha<sup>-1</sup> year<sup>-1</sup> in the Ozark Highlands, but decreased at the same rate ( $-0.04$  Mg ha<sup>-1</sup> year<sup>-1</sup>) in the Grand Prairie in the top 10 cm between 2001 and 2007. However, in a chronosequence of tallgrass prairie restorations in the Ozark Highlands, TN content in the top 10 cm decreased over time with restoration age and trended toward that in a nearby native prairie, which contained the lowest TN content [23]. The variation in results among studies highlights the multifaceted and highly limiting nature of N in both natural and cultivated ecosystems.

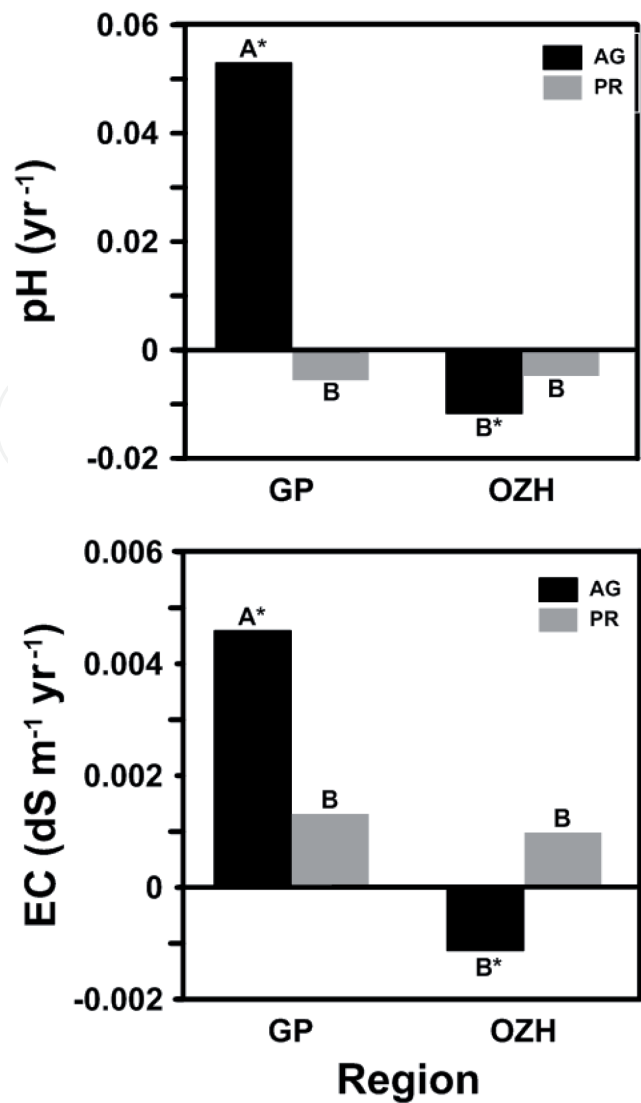
Similar to TN, averaged across landuse, TC concentration ( $-0.03\%$  year<sup>-1</sup>; **Table 7**) and content ( $-0.33$  Mg ha<sup>-1</sup> year<sup>-1</sup>; **Table 6**) decreased over time in the Grand Prairie. However, in contrast, TC concentration ( $0.02\%$  year<sup>-1</sup>, **Table 7**) and content ( $0.28$  Mg ha<sup>-1</sup> year<sup>-1</sup>, **Table 6**) both increased over time in the Ozark Highlands. There are many complex processes that have been linked to fluctuations and accumulations of C within soils, such as plant physiological responses to atmospheric CO<sub>2</sub>; light; and environmental stressors, like temperature, nutrients, and water, as well as microbial responses to soil moisture and temperature variations. In the case of this study, all of these factors are potentially at work, with likely a stronger influence stemming from microbial responses to differences in soil moisture and temperature between physiographic regions, where greater microbial decomposition is occurring in the slightly warmer and wetter climate of the Grand Prairie than in the Ozark Highlands. Erosion from wind and water can also play a major role in SOC

| Treatment             | Soil properties <sup>†</sup> |                      |                     |                     |                     |                     |                    |       |                     |
|-----------------------|------------------------------|----------------------|---------------------|---------------------|---------------------|---------------------|--------------------|-------|---------------------|
|                       | BD                           | pH                   | EC                  | SOM                 | TN                  | TC                  | C:N                | N/SOM | C/SOM               |
| Region                |                              |                      |                     |                     |                     |                     |                    |       |                     |
| Grand Prairie (GP)    | 0.005                        | 0.027                | 0.002               | −0.37b <sup>*</sup> | −0.04b <sup>*</sup> | −0.33b <sup>*</sup> | 0.13b <sup>*</sup> | 0.25  | −0.32b <sup>*</sup> |
| Ozark Highlands (OZH) | 0.003                        | −0.006               | 0.001               | 0.04a               | −0.01a <sup>*</sup> | 0.28a <sup>*</sup>  | 0.18a <sup>*</sup> | −0.04 | 0.52a <sup>*</sup>  |
| Landuse               |                              |                      |                     |                     |                     |                     |                    |       |                     |
| Agriculture (AG)      | 0.006                        | 0.019                | 0.003               | −0.21               | −0.02               | 0.06a               | 0.19a <sup>*</sup> | 0.44  | 0.29                |
| Prairie (PR)          | 0.001                        | 0.001                | 0.000               | −0.13               | −0.03               | −0.12b              | 0.12b <sup>*</sup> | 0.05  | −0.09               |
| Region × landuse      |                              |                      |                     |                     |                     |                     |                    |       |                     |
| GP-AG                 | 0.008                        | 0.053a <sup>††</sup> | 0.005a <sup>*</sup> | −0.38               | −0.03               | −0.19               | 0.18               | −0.09 | −0.10               |
| GP-PR                 | 0.001                        | 0.000b               | −0.000b             | −0.36               | −0.05               | −0.47               | 0.08               | 0.42  | −0.54               |
| OZH-AG                | 0.005                        | −0.015b <sup>*</sup> | 0.001b <sup>*</sup> | −0.03               | −0.02               | 0.32                | 0.21               | 0.03  | 0.68                |
| OZH-PR                | 0.000                        | 0.003b               | 0.000b              | 0.11                | −0.01               | 0.24                | 0.16               | −0.06 | 0.35                |

<sup>\*</sup>An asterisk indicates mean value is greater than 0 ( $P < 0.05$ ).  
<sup>†</sup>Units for the soil properties are as follows: BD,  $\text{g cm}^{-3} \text{ yr}^{-1}$ ; pH,  $\text{yr}^{-1}$ ; EC,  $\text{dS m}^{-1} \text{ yr}^{-1}$ ; SOM, TN, and TC,  $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ; C:N,  $\text{yr}^{-1}$ ; and N/SOM and C/SOM,  $\% \text{ yr}^{-1}$ .  
<sup>††</sup>Different lower case letters for a soil property within a treatment category indicate a significant difference ( $P < 0.05$ ).

**Table 6.** Summary of mean soil properties in the top 10 cm by treatment (i.e., physiographic region, landuse and their interaction) for soil bulk density (BD), pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), total carbon (TC), C:N ratio, and the N and C fractions of SOM from the 2016 sampling in silt-loam soils in Arkansas.

loss in soils, as well as the oxidation of SOC associated with cultivation, which could also be contributing to the overall loss of soil C in the Grand Prairie. Conventional tillage is carried out on an annual basis in the agricultural sites from the Grand Prairie used in this study, thereby increasing the potential loss of topsoil and C from erosion and the loss of SOC from oxidation and decomposition. Similar to the results of this study, Brye et al. [15] reported a net loss of SOC from the top 10 cm in the Grand Prairie during a 14-year period from the same Seidenstricker sites used in this study, where, averaged by landuse, SOC decreased at a rate of  $0.1 \text{ Mg SOC ha}^{-1} \text{ year}^{-1}$ . Over a 6-year period between 2001 and 2007, Brye and Gbur [13] also reported, averaged across landuse, soil C sequestration rates in the top 10 cm were 0.5 and  $-0.4 \text{ Mg SOC ha}^{-1} \text{ year}^{-1}$  in the Ozark Highlands and the Grand Prairie, respectively. Similarly, Brye and Gbur [14] reported that, on average, SOC increased by  $0.13 \text{ Mg SOC ha}^{-1} \text{ year}^{-1}$  in the top 10 cm in the Ozark Highlands. In contrast to the results of this study, a field experiment conducted on a silt-loam soil under soybean production in the Mississippi River Delta region of eastern Arkansas, approximately 80 km east of the sites in the Grand Prairie used for this study, showed that TC in the top 10 cm increased at an average of  $0.6 \text{ Mg SOC ha}^{-1} \text{ year}^{-1}$  over a 6-year study period across numerous tillage-burn-residue-level treatment combinations [24]. A study conducted across Texas (e.g., Bushland, Temple, and Corpus Christi) determined the linear relationship between SOC sequestration and average annual temperature was stronger ( $r^2 = 0.99$ ) than with rainfall ( $r^2 = 0.40$ ), where SOC decreased by  $0.17 \text{ Mg ha}^{-1} \text{ year}^{-1}$  for every degree increase in the annual



**Figure 3.** Landuse effects by physiographic region on soil organic matter (SOM), total nitrogen, and total carbon content and concentration in the top 10 cm from the 2016 sampling only under either agricultural management (AG) or undisturbed prairie (PR) landuse in the Grand Prairie (GP) region of east-central Arkansas and the Ozark Highlands (OZH) region of northwest Arkansas. Different letters associated with mean values on a panel are different at  $P < 0.05$ .

temperature, and SOC only decreased by  $0.0023 \text{ Mg ha}^{-1} \text{ year}^{-1}$  as rainfall increased [25]. Results of the current study support the well-documented pattern that SOC sequestration is greater in cooler (i.e., the Ozark Highlands) compared to warmer climates (i.e., the Grand Prairie); however, the relationship between soil moisture levels and SOC sequestration is more difficult to predict and does not follow a linear relationship.

As a result of decreased TN and increased TC, averaged across landuse, the soil C:N ratio increased in both regions, but increased more over time in the Ozark Highlands ( $0.18 \text{ year}^{-1}$ ) than in the Grand Prairie region ( $0.13 \text{ year}^{-1}$ , **Table 6**). Similar to the results of this study, Brye and Gbur [13] concluded that the soil C:N ratio increased between 2001 and 2007, but only under the agricultural landuse in the Grand Prairie and that the soil C:N ratio did not change over time under native prairie in the Grand Prairie and the Ozark Highlands, as well as under agricultural landuse in the Ozark Highlands. In contrast, Brye and Gbur [14] showed that the soil C:N ratio increased by 3.6% between 2002 and 2008 in grasslands in the Ozark Highlands.

Averaged across landuse, the TN fraction of SOM changed more over time in the Grand Prairie ( $0.25\% \text{ year}^{-1}$ ) than in Ozark Highlands ( $-0.04\% \text{ year}^{-1}$ ), but both did not differ from a change of zero (**Table 6**). In contrast, the TC fraction of



| Treatment               | Soil properties           |                          |                          |
|-------------------------|---------------------------|--------------------------|--------------------------|
|                         | SOM (% yr <sup>-1</sup> ) | TN (% yr <sup>-1</sup> ) | TC (% yr <sup>-1</sup> ) |
| <i>Region</i>           |                           |                          |                          |
| Grand Prairie (GP)      | -0.04b <sup>*</sup>       | -0.004b <sup>*</sup>     | -0.03b <sup>*</sup>      |
| Ozark Highlands (OZH)   | -0.01a                    | -0.002a <sup>*</sup>     | 0.02a <sup>*</sup>       |
| <i>Landuse</i>          |                           |                          |                          |
| Agriculture (AG)        | -0.04                     | -0.003                   | -0.00                    |
| Prairie (PR)            | -0.01                     | -0.003                   | -0.01                    |
| <i>Region × landuse</i> |                           |                          |                          |
| GP-AG                   | -0.05                     | -0.003                   | -0.02                    |
| GP-PR                   | -0.04                     | -0.004                   | -0.04                    |
| OZH-AG                  | -0.03                     | -0.003                   | 0.01                     |
| OZH-PR                  | -0.01                     | -0.001                   | 0.02                     |

<sup>\*</sup>An asterisk indicates mean value is greater than 0 ( $P < 0.05$ ).

**Table 7.** Summary of mean soil properties by treatment (i.e., physiographic region, landuse, and their interaction) for soil organic matter (SOM), total nitrogen (TN), total carbon (TC) concentrations in the top 10 cm from the 2016 sampling in silt-loam soils in Arkansas.

SOM, averaged across landuse, increased over time in the Ozark Highlands (0.52% year<sup>-1</sup>), where the TC fraction of SOM decreased over time in the Grand Prairie (-0.32% year<sup>-1</sup>) (**Table 6**). Increased TN within the available above- and below-ground biomass and the resulting SOM, especially in N-limited ecosystems such as native prairies or agricultural fields, can lead to increased microbial decomposition and therefore loss of C and N within the soil until periods of anaerobic conditions or cooler temperatures slow down decomposition process, therefore resulting in an accumulation of SOC. Brye and Gbur [14] reported that TC and TN fractions of SOM did not change over time in the Ozark Highlands, whereas the difference in results could be the result of the shorter sampling period of only 7 years used by Brye and Gbur [14] compared to the longer 15-year sampling period used in this study.

In contrast to the other measured soil properties, changes in TC content, C:N ratio, and TC fraction of SOM in the top 10 cm differed ( $P < 0.05$ ) over time between landuses (**Table 5**). Averaged across physiographic region, the change in TC content and the TC fraction of SOM over time were greater in the agricultural compared to the native prairie landuse, but neither soil property change over time differed from a change of zero (**Table 6**). In contrast to TC content and the TC fraction of SOM, averaged across physiographic region, the C:N ratio increased more over time in the agricultural (0.19 year<sup>-1</sup>) than in the native prairie landuse (0.12 year<sup>-1</sup>; **Table 6**).

These results are somewhat contradictory to the stated hypothesis, where greater SOC sequestration was expected to occur in the native prairie landuse over time. However, the disagreement between the results and the stated hypothesis was likely driven by the fact that the largest numeric increase in TC content occurred within the agricultural landuse (0.32 Mg ha<sup>-1</sup> year<sup>-1</sup>) in the Ozark Highlands and the greatest numeric decrease occurred in the native prairie in the Grand Prairie (-0.47 Mg ha<sup>-1</sup> year<sup>-1</sup>). Since the agriculturally managed soils in the Ozark Highlands were not tilled on any regular basis and were used as grazed pastureland and mowed hayland, it is within reason that SOC would be increasing within these

ecosystems, as there are likely fertilizers added annually or semi-annually to these agroecosystems in the form of both inorganic fertilizers and/or manure, which would stimulate plant growth and increase above- and belowground biomass to add to the SOM and SOC pools.

Managed grazing practices (i.e., rotational grazing) have also been known to increase SOC storage in soils. A grazing study conducted in a northern mixed-grass prairie in Wyoming under both light and heavy stocking rates reported increased SOC in the top 30 cm ( $0.30 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ ) compared to the non-grazed surrounding exclosures [26]. However, a meta-analysis conducted on C sequestration in native rangelands of the North American Great Plains revealed that, although there was no statistical relationship between the change in SOC content and the longevity of a grazing management practice, the general trend suggested a decrease in SOC sequestration as the age of the grazing management system increased, where the range of years under management were between about 20 and 80 years [27]. The duration under consistent grassland management for the sites in this study within the Ozark Highlands was roughly greater than 20 years, thus was at the younger end of the age range evaluated by Derner and Schuman [27].

The decrease in TC in the native prairie within the Grand Prairie was unexpected, where the most likely explanation was the combination of severe fragmentation and periodic vehicle traffic and compaction from agricultural machinery in order to reach the cultivated fields surrounding the prairie. Contrary to the results of this study, Brye et al. [15] reported that, in the same native prairie at the Seidenstricker site in this study, a significant increase in SOC concentration occurred from 1987 to 2001. Brye and Gbur [13] also reported that landuse differences in SOC content change over time, averaged across physiographic region, equated to SOC sequestration rates of  $0.4$  and  $-0.3 \text{ Mg ha}^{-1} \text{ year}^{-1}$  in the top 10 cm of the native prairie and agricultural landuse, respectively. The loss of SOC by the conversion of natural vegetation to cultivated landuse, as well as the continued loss of SOC as duration under cultivation increases, is well known, despite varying results due to factors such as soil texture, cropping system, residue management, and climate [6, 8, 28–30]. Tillage can have one of the greatest influences on SOC loss over time due the disturbance of the macroaggregates that form around and protect particles of undecomposed SOM, leading to the mineralization of that SOM, and consequently a loss of SOC. A study conducted on a silty-clay-loam soil in south-central Texas reported an average 50% increase in SOC storage in the top 5 cm over a 20-year sampling period under a no-tillage management plan compared to a conventional tillage practice [30].

Jones and Donnelly [31] conducted a meta-analysis study among landuses ranging from native undisturbed grasslands to poorly managed rangelands and concluded global soil C sequestration rates in the top 15 and/or 30 cm ranged from 0 to approximately  $8 \text{ Mg SOC ha}^{-1} \text{ year}^{-1}$ . In the current study, the largest mean soil C sequestration rate was measured in the agriculturally managed soils within the Ozark Highlands ( $0.32 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ ). However, greater SOC sequestration rates were expected to occur in the native prairies compared to the agricultural landuse and greater accumulation of SOM, TC, and TN was expected in the Grand Prairie region compared to the Ozark Highlands based on results of previous studies conducted at these sites [11–15]. Differences between studies conducted previously at these sites could stem from variations in sampling and analytical methods over time; however, differences are more likely the result of actual changes over time, identified by direct measurements, over a longer period (i.e., 15 years) in this study instead of using regression analyses or linear relationships and shorter study periods (i.e.,  $\leq 8$  years) that were used in several of the previous studies [11–15].

Considering only the Grand Prairie sites consisting of a native tallgrass prairie and three agroecosystems that varied in duration under cultivation that originated as part of the native prairie tract, regression analysis revealed no significant relationship between soil C sequestration rate in the top 10 cm over the 15-year period from 2001 to 2016 ( $P > 0.05$ ) or TC storage from 2016 alone ( $P > 0.05$ ) and duration of years of annual cultivation. Severe fragmentation and mismanagement of the native tallgrass prairie could be the cause of this lack of a significant linear relationship. Brye et al. [15] somewhat similarly concluded that the relationship between SOC and years of cultivation did not change significantly over a 14-year period between 1987 and 2001 in the same study sites within the Seidenstricker site.

#### 4. Conclusions

Changes in near-surface soil C and N and related properties, assessed by direct measurement, over a 15-year period in silt-loam soils in Arkansas differed between physiographic regions and landuse and among their treatment combinations. Similar to that hypothesized, averaged across region, SOM, TC, and TN in the native prairie landuse did not change over time, indicating some degree of equilibrium exists in the less-disturbed, more natural ecosystems. However, in contrast to that hypothesized, SOM, TC, and TN also did not change over time in the managed agricultural landuse when averaged across region. Though not significant, cultivated row-crop agriculture on alluvial soils was shown to have at least numerically lower C and N storage and C and N decreased more over time than that in managed pastureland on residual soils, likely due to the long history of intensive tillage, despite alluvial soils typically being generally considered more fertile than residual soils.

Results of this study demonstrate how the combination of climate and soil parent material, which constituted the major differences between physiographic regions that were investigated in this study, can have a large influence on SOM, C and N storage, and change over time. Despite differing types of managed agricultural landuse between the two regions, physiographic region clearly had a greater influence than landuse, as evidenced by more soil property changes over time evaluated in this study differing between regions when averaged across landuse than differed between landuses when averaged across regions.

Results also showed that more numerous differences between regions and landuses were identified when only a single measurement set in time was considered compared to much fewer differences between regions and landuses recognized when assessing change over time based on direct measurements. In the absence of direct measurements, any inferences drawn about temporal trends in soil properties, particularly those like SOM, C, and N, that are key to improving understanding about the effects of rising mean annual air temperatures, rising atmospheric greenhouse gas concentrations, and global climate change in general must be tempered with numerous caveats because those inferences could be misleading.

Many types of ecosystems are resilient and conditioned to resist change. Though inconvenient for numerous reasons, direct measurement over time in long-term studies, as were conducted in this study, perhaps offers the most appropriate methodology to assess temporal variation in soil properties and ecosystem characteristics toward understanding global climate change. Therefore, long-term, direct-measurement studies should be maintained and expanded to increase the accuracy of cataloging important ecosystem processes, such as soil C sequestration and other beneficial soil properties, particularly in disappearing native prairie ecosystems in Arkansas and elsewhere. The results of long-term studies will provide more useful and effective guidance for rehabilitating and/or restoring areas of

degraded land and/or minimally productive agricultural land. Ecosystem restoration projects will not only likely increase soil health and sustainability, but applying similar restoration principles to agricultural lands may increase productivity and collectively contribute to slowing, or potentially reversing, the global threat of rising greenhouse gases in the atmosphere and climate change.

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## Conflict of interest

There are no conflicts of interest to declare.

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