AIMS Geosciences
AIMS Geosciences, 5 (1): 1–24.
DOI: 10.3934/geosci.2019.1.1
Received: 29 October 2018
Accepted: 09 January 2019
Published: 18 January 2019
http://www.aimspress.com/journal/geosciences

Research article

Soil carbon sequestration across a chronosequence of tallgrass prairie restorations in the Ozark Highlands region of northwest Arkansas

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Abstract: Prairie restoration studies and research conducted in native prairie systems have been mostly centered in the Great Plains region of the United States and little research has been pursued in Arkansas to further understand the soil carbon (C) sequestration potential over time of remnant prairie sites and prairie restorations. The objective of this study was to evaluate the effects of restoration age and soil moisture regime on near-surface soil C and other soil property changes over time in a chronosequence of humid-temperate tallgrass prairie restorations (i.e., 15, 16, 17, and 38 yr) in the Ozark Highlands region of northwest Arkansas. A nearby undisturbed, native prairie was also studied for comparison as a baseline. Soil samples were collected from the top 10 cm in 2005 and 2017 and the change over time was assessed for soil bulk density, pH, electrical conductivity, soil organic matter (SOM), total C (TC), total nitrogen (TN), and the fraction of TC and TN in SOM. Soil property magnitudes from the 2017 sampling only were also compared among sites to evaluate the current state of the restorations. Soil properties within the restorations generally behaved as expected, with beneficial decreases in soil BD and increases in SOM, TC, TN, and TC and TN fractions of SOM occurring over time as restoration age increased and tended towards that in the native prairie. The direct measurement of change in total C content over time differed (P = 0.03) between soil moisture regimes among ecosystems, where the greatest soil C sequestration rate of 0.6 Mg C ha^{-1} yr^{-1} was recorded in the native prairie in the aquic soil moisture regime, while soil C sequestration rates ranged from −0.21 to 0.12 Mg C ha^{-1} yr^{-1} across the four prairie restorations. Results indicate that the prairie restorations evaluated in this study are still evolving and have not yet reached the rate of C sequestration observed in the native, undisturbed prairie ecosystem and that direct measurement of soil C storage changes over time should be used whenever possible.

Keywords: prairie restoration; native prairie; silt-loam soils; soil carbon

1. Introduction

Tallgrass prairies, which once occupied over 162 million ha of North America, are known to accumulate and sequester large amounts of carbon (C) from the atmosphere [1]. If left undisturbed, the dominant grasses in native prairies grow extensive root systems and symbiotic networks with the diverse soil microbial community, promoting soil aggregation, to create highly developed ecosystems with a positive imbalance that leads to increased storage of stabilized C compounds. However, following European settlement and agricultural advancement, almost all native tallgrass prairies have been lost and only 1% of their original extent remains in the continental US, making the native tallgrass prairie one of the rarest and most endangered ecosystems in North America [2]. Arkansas in particular has had a large majority of its native prairie land anthropologically converted, primarily for agricultural purposes, with only 0.05% of the original prairie area that once spanned across the state still present today [3]. Thus, finding suitable native prairie and prairie restoration study sites is challenging and, consequently, could require pseudoreplication to facilitate research purposes, where pseudoreplication involves using replicate observations from a single site being assumed to be independent of one another as if they represented single observations from multiple sites.

Since prairie ecosystems are habitats for thousands of plant and animal species and are also major contributors in the global C cycle, restoration projects are rising in interest because of aesthetic, environmental, ecological, and biological conservation purposes [4]. The growing movement of prairie restoration efforts has focused primarily on restoring marginally productive or fallow lands back to more natural and historic land use [5]. However, in the US, prairie restoration studies and research conducted in native prairie systems have been mostly centered in the Great Plains region and little research has been conducted in Arkansas to further understand the soil C storage potential over time of remnant prairie sites and prairie restorations.

Arkansas has at least two distinct climates and multiple soil parent material sources. The northwest region of Arkansas, known as the Ozark Highlands [Major Land Resource Area (MLRA) 116A] [6], is relatively warm and wet and dominated by deciduous forest vegetation both presently and as the historic climax vegetation community. However, despite being predominantly populated by deciduous forests, the Ozark Highlands contains the remnants of the Osage Prairie, which once extended through south-central and southwestern Missouri, as well as northwest Arkansas [7]. According to Brye and West [5], compared to the upper Midwest and the Great Plains, the customarily warmer and wetter soil conditions of the warm-temperate humid zone of the mid-southern United States, more specifically the Ozark Highlands, will presumably lead to varied restoration responses. Colder climates are more likely to accumulate soil organic C (SOC) because microbial decomposition of soil organic matter (SOM) is slowed and sometimes paused when temperatures reach below freezing [8]. Warmer and wetter climates tend to stimulate the growth of above- and belowground biomass, but also increase decomposition of SOC due to the stimulation of the soil microbial community that carries out decomposition and respiration, which, in turn, cycles carbon dioxide (CO_2) back into the atmosphere.

However, decomposition of SOC creates condensates that are recalcitrant to further microbial decomposition that can bind with soil minerals, actively enhancing soil structure and aggregation, while simultaneously protecting a fraction of SOC from further microbial attack [9]. These organo-mineral complexes are then considered a part of the long-term (passive) C pool, where they can remain for anywhere from 1500 to 3500 years or longer [10,11]. However, grassland restoration studies in both climate regions have shown that, past a certain threshold of accumulation, SOC sequestration rates slow or cease once a new equilibrium of SOC addition and decomposition within the system has been reached [12–15].

Many factors are involved with the success of a prairie restoration project, including previous land use, topography, soil moisture regime, climate, initial soil conditions, time, parent material and the types and degree of management. Therefore, the outcomes of prairie restoration projects are not guaranteed, unless site-specific conditions have been taken into consideration [15]. A meta-analysis study conducted by Post and Kwon [16] concluded the average global C sequestration rate on land converted from agriculture to grassland was 33.2 g C m^{-2} yr^{-1}. Other studies specific to Conservation Reserve Program (CRP) grassland restorations in the United States have proposed a range of average soil C sequestration rates to vary from 11 to 304 g C m^{-2} yr^{-1} [9,17,18]. However, variations among these studies can be attributed to different detection limits and soil depths, differences in measurement and statistical techniques, site characteristics, ecosystem age, climate, as well as planted species. The objective of this study was to evaluate the effects of restoration age and soil moisture regime (i.e., aquic and udic) on near-surface soil C and other soil property changes over time in a chronosequence of humid-temperate tallgrass prairie restorations (i.e., 15-, 16-, 17-, and 38-years old) in the Ozark Highlands region of northwest Arkansas. Soils in an aquic soil moisture regime (SMR) are classified as being saturated long enough for microbial and root respiration to deplete dissolved oxygen to the point of being virtually absent, leading to reducing conditions and greatly slowing microbial decomposition of SOM [19]. In contrast, soils in a udic SMR are required to have, except for short periods, a three-phase system (soil-liquid-gas) in all or part of the soil moisture control system when the soil temperature is above 5 °C [19]. Consequently, it was hypothesized that various soil physical properties [i.e., soil bulk density, pH, electrical conductivity (EC), SOM, total C (TC), and total nitrogen (TN) concentrations and contents, and the fraction of TC and TN in SOM] would differ among prairie restorations of varying ages and an undisturbed native prairie. More specifically, the greatest changes over time were hypothesized to occur in the younger prairie restorations in the aquic SMR.

2. Materials and methods

2.1. Site description

Research has been conducted periodically since 2005 at Pea Ridge National Military Park near Garfield, AR, which has a series of four tallgrass prairie restorations that were initiated in 1979, 2000, 2001, and 2002 [20]. Consequently, in 2017, these four restorations were 15, 16, 17, and 38 years old. A range of management practices, including burning and baling, have been implemented to promote the restoration process of the historic tallgrass prairie ecosystem that existed throughout the area. The

National Parks Service initiated the restoration projects to return various park property areas to their documented state during the battle of Pea Ridge/Elkhorn Tavern during the Civil War. Previous land use of the three more modern restorations was managed grassland dominated by tall fescue (*Lolium arundinaceum* [Schreb.] Darbys) and Bermudagrass (*Cynodon dactylon* [L.] Pers.) and supported rotational grazing of 5 and 20 head of cattle per hectare, with periodic liming and fertilization with N, P, and K as necessary [3]. Approximately 16 km southwest of the park is the Searles Prairie, which is a 4-ha, native tallgrass prairie in Rogers, AR. The Searles Prairie is managed by the Arkansas Natural Heritage Commission, contains numerous prominent prairie mounds, and is periodically burned [21].

Both the Searles Prairie and the prairie restorations at Pea Ridge National Military Park reside in the Ozark Highlands (36 to 38°N lat., 91 to 95°W long.), which is in MLRA 116A [6]. The Ozark Highlands MLRA covers approximately 2.1 million ha in parts of southwest and south-central Missouri, eastern Oklahoma, and northwest and north-central Arkansas [5]. The Ozark Highlands is a low-elevation, disjointed mountainous region primarily underlain by limestone and sandstone residuum that is dominated by oak (*Quercus* spp.) forests, but a large extent of co-mingled tallgrass prairie was also historically present in a savannah-type setting [21]. The 30-yr (1980–2010) mean annual precipitation in the northwest Arkansas portion of the Ozark Highlands is 115 cm and the 30-yr mean annual air temperature in the region is 13.7 ℃, with an average January minimum of −3.3 ℃ and an average July maximum of 30.7 ℃ [22].

With the exception of the 1979-initiated prairie restoration, all four other prairie areas have soils present that are characterized as being in either an aquic or a udic soil moisture regime. However, the 1979-inititated prairie restoration has only udic soils present. The five prairie ecosystems in this study are hereafter referred to as either prairie restoration (PR) or native prairie (NP) with either aquic or udic soil moisture regime (SMR), where the restorations are also separately referred to, based on their age since restoration began (i.e., PR15, PR16, PR17, and PR38). Consequently, nine prairie ecosystem-SMR combinations were evaluated in this study.

2.2. *Soil sampling scheme*

In November 2005, soil samples were initially collected in the four prairie restorations at Pea Ridge Military Park and in the Searles Prairie [3,15]. On January 10 and 11, 2017, another set of soil samples was collected at both sites. Similar to previous studies [3,5,14,15,23–25], in each soil map unit represented at the Searles Prairie and in each prairie restoration (Table 1), soil samples were collected manually at five sampling points 15-m apart (i.e., at the 0-, 15-, 30-, 45-, and 60-m marks) from the top 10 cm along a 60-m transect using a slide hammer and a 4.8-cm-diameter, stainless steel core chamber. Soil samples were oven-dried at 70 ℃ for 48 hours, weighed for bulk density determinations, and subsequently crushed and sieved to pass through a 2-mm mesh screen for soil chemical property determinations. Soil pH and EC were potentiometrically determined 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 hr at 360 ℃. Total C (TC) and N (TN) 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 soil organic C (SOC). Using measured TC, TN, and SOM concentrations, the soil C:N ratio and fraction of TC and TN in SOM were calculated for each soil sample. Measured TC, TN, and SOM concentrations (g kg^{-1}) were also used, with measured bulk densities and the 10-cm sample depth interval, to calculate TC, TN, and SOM contents (kg ha^{-1}). In order to calculate C and N sequestration rates, the 2005 soil property data were subtracted from 2017 data, and the differences were divided by the fractional number of years between samplings. Table 1 also summarizes the mean soil particle-size distribution in the top 10 cm among transects sampled in each of the five ecosystems.

2.3. Statistical analyses

The soil samples collected along each transect were assumed independent of one another and were therefore used as pseudoreplication of treatment combinations. However, due to the scarcity of native prairie and prairie restoration sites in the Ozark Highlands, the assumption was made that the results reported were reasonably representative of true spatially replicated results that would have been achieved had multiple sites with similar land-use histories and soil characteristics been available and utilized in this study. This assumption was based on Brye and Riley [3] demonstrating that the within-ecosystem variability was either similar or greater than the between-ecosystem variability for numerous measured, near-surface soil properties, including soil bulk density, pH, EC, SOM, TC and TN concentrations and contents, and C:N ratio.

Following the above-described assumptions, 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 ecosystem (i.e., PR15, PR16, PR17, PR38, and NP), SMR (i.e., udic and aquic), and their interaction on changes in soil bulk density, pH, EC, and SOM, TC, and TN concentrations and contents, C:N ratio, and TC and TN fractions of SOM over time in the top 10 cm. A separate two-factor ANOVA was also conducted to evaluate the effects of ecosystem, SMR, and their interaction on just the 2017 measured soil properties. In addition, a linear regression analysis was conducted using only the 2017-measured data to assess soil property trends over time, where, similar to the method used for a prairie restoration study conducted on a collection of fine-textured soils in southern Wisconsin [12], the native prairie was assigned an age of 3000 years old. 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.

Table 1. Summary of land use, soil properties from the top 10 cm, and topographic characteristics associated with the four prairie restorations at the Pea Ridge National Military Park and a nearby native tallgrass prairie evaluated in this study in the Ozark Highlands region of northwest AR.

Land use	Years of restoration*	Soil series[†]	Soil taxonomic description	Sand** (kg kg^{-1})	Silt** (kg kg^{-1})	Clay** (kg kg^{-1})	Soil textural class	Slope (%)
Prairie Restoration	38	Captina	Typic Fragiudult	0.44	0.44	0.12	Loam	1–3
		Peridge[††]	Typic Paleudalf	0.54	0.36	0.10	Sandy loam	1–3
	17	Taloka	Mollic Albaqualf	0.45	0.38	0.17	Loam	0–1
		Captina	Typic Fragiudult	0.32	0.59	0.09	Silt loam	1–3
	16	Jay	Oxiaquic Fragiudalf	0.39	0.46	0.15	Loam	1–3
		Captina	Typic Fragiudult	0.46	0.45	0.09	Loam	1–3
		Taloka	Mollic Albaqualf	0.43	0.42	0.15	Loam	0–1
		Peridge	Typic Paleudalf	0.49	0.43	0.08	Loam	1–3
	15	Jay	Oxyaquic Fraguidualf	0.48	0.42	0.10	Loam	1–3
		Taloka	Mollic Albaqualf	0.41	0.44	0.15	Loam	0–1
		Peridge	Typic Paleudalf	0.55	0.40	0.05	Sandy loam	1–3
Native Prairie	0	Cherokee	Typic Albaqualf	0.40	0.48	0.12	Loam	0
		Jay	Oxiaquic Fragiudalf	0.34	0.58	0.09	Silt loam	1–3

* Indicates number of years passed since initial restoration to the data of last soil sampling (i.e., 2017).

** Sand, silt, and clay distributions were obtained from Brye et al. [15].

[†] Soil series were obtained from the Web Soil Survey [26].

[††] Indicates that soil series has been recorrelated after 2005 and was changed from Cane to Peridge [15,26].

3. Results and discussion

3.1. Soil property changes over time

Changes in soil BD, pH, EC, TC, and TC fraction of SOM in the top 10 cm over the 12-year period of sampling (2005 to 2017) differed ($P < 0.05$) among ecosystems, between SMRs, or among treatments combinations (Table 2). Soil BD changes over time differed ($P < 0.01$; Table 2) among ecosystems within SMRs. The 17-yr-old prairie restoration in the udic SMR experienced the numerically largest soil BD increase over time (0.01 g cm^{-3} yr^{-1}), but the increase did not differ from that in either SMR in the 15-yr-old prairie restoration or in the aquic SMR in the native prairie. However, the increase in the 17-year-old restoration in the udic SMR was significantly different from zero, while the others were not (Table 3; Figure 1). In contrast, the 17-yr-old prairie restoration in the aquic SMR experienced the numerically largest soil BD decrease over time (−0.01 g cm^{-3} yr^{-1}), but the decrease did not differ from that in either SMR in the 16-yr-old prairie restoration. However, the soil bulk density decrease in the 17-yr-old prairie restoration in the aquic SMR was also different from a change of zero, while the bulk density decreases over time in either SMR in the 16-yr-old prairie restoration did not differ from a change of zero (Table 3; Figure 1). Soil BD changes over time did not differ between SMRs in the 15- and 16-yr-old prairie restorations or in the native prairie. A study conducted on a native tallgrass prairie remnant on a silt-loam soil in east-central Arkansas that had been subject to periodic burning and vegetation removal by haying showed decreased soil bulk density over a 12-year period, supporting the hypothesis that proper management techniques can improve soil health [23]. However, although managed with periodic burning and vegetative removal, the prairie restoration sites at Pea Ridge Military Park are not managed on a consistent schedule. Therefore, direct correlation between different management practices and increased soil health in the current study is unattainable.

Similar to soil BD, soil C content changes over time also differed ($P = 0.03$; Table 2) among ecosystems within SMRs. The numerically largest soil C content increase over time, or soil C sequestration rate, occurred in the aquic SMR in the native prairie (0.60 Mg ha^{-1} yr^{-1}; Table 3; Figure 1). These results are likely the result of the periodic water logging and anaerobic conditions that characterize an aquic SMR, which would tend to increase the amount of stored C within the soil as decomposition of SOM is slowed when anaerobic conditions persist. Though some would expect a native, undisturbed prairie to be in equilibrium with respect to soil C content, this notion would more generally apply to soils in a udic SMR that experience relatively large soil moisture fluctuations; hence the results demonstrated for the native prairie in the udic SMR, where soil TC did not change over time. However, in the aquic SMR, relatively lower soil moisture fluctuations would be expected compared to the udic condition, thus allowing SOM and C to continue to build up over time.

Although the increase in soil C content over time in the native prairie within the aquic SMR differed from zero, the increase did not differ from the soil C sequestration rate in the udic SMR in the 17-yr-old prairie restoration. With the exception of the aquic SMR in the native prairie, the soil C content change over time did not differ among any of the other treatment combinations and the soil C sequestration rate averaged −0.12 Mg ha^{-1} yr^{-1} (Table 3; Figure 1). The small change in soil C content is likely indicative of the gradual, yet multi-faceted, process of soil C sequestration in natural ecosystems. Similarly, in a study conducted by Brye et al. [27] on the progression of a tallgrass prairie on a fine-textured, predominantly silt-loam soil in southern Wisconsin, total soil C content in the top 60 cm did not differ over time and was stable from year to year between 1995 and 1999. Brye et al. [27] concluded that either the 5-yr assessment period between 19 and 24 years into prairie restoration was not long enough to observe significant annual shifts, the rate of change in various soil properties could be slower than predicted, or the restoration goals were achieved and after 19 years under restoration the ecosystem has stabilized and reached equilibrium. However, Brye et al. [27] also concluded that total soil C in the top 60 cm of the prairie restoration was increasing relative to the soil C content changes measured in the adjacent cultivated agricultural field and approached that measured in the two contiguous remnant tallgrass prairies. Results of Brye et al. [27] highlight the difficulty in interpreting quantitative measurements of soil properties and a need to monitor vegetation characteristics as well to draw concrete conclusions about the progress of a prairie restoration project. Despite the significant differences in soil C content changes over time among ecosystem-soil-moisture-regime combinations, the change in soil C concentration over time was unaffected (P > 0.05) by any treatment and no changes differed from zero (Tables 2 and 3). This result indicates that the change in soil C content over time (i.e., soil C sequestration rate) was primarily driven by the change in bulk density rather than a large change in the soil C concentration over time.

Table 2. Analysis of variance summary of the effects of ecosystem, soil moisture regime (SMR), and their interaction on the change in soil bulk density, pH, electrical conductivity, organic matter, total nitrogen, and total carbon concentration and content, C:N ratio, and the nitrogen and carbon fractions of soil organic matter over a 12-year period in a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Soil Property	Ecosystem	SMR	Ecosystem x SMR
		P	
Bulk density (g cm^{-3} yr^{-1})	0.06	0.04	< 0.01
pH (yr^{-1})	0.02	0.03	0.46
Electrical conductivity (dS m^{-1} yr^{-1})	< 0.01	0.84	0.16
Soil organic matter (% yr^{-1})	0.64	0.48	0.65
Soil organic matter (Mg ha^{-1} yr^{-1})	0.35	0.88	0.07
Total nitrogen (% yr^{-1})	0.27	0.23	0.63
Total nitrogen (Mg ha^{-1} yr^{-1})	0.29	0.25	0.14
Total carbon (% yr^{-1})	0.48	0.13	0.89
Total carbon (Mg ha^{-1} yr^{-1})	0.19	0.17	0.03
C:N ratio (yr^{-1})	0.06	0.14	0.22
Total nitrogen in organic matter (% yr^{-1})	0.39	0.32	0.18
Total carbon in organic matter (% yr^{-1})	0.01	0.07	0.28

Table 3. Summary of mean soil property changes by treatment (i.e., ecosystem, soil moisture regime, or their interaction) over a 12-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 a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Treatment	Soil properties								
	BD ($g\ cm^{-3}\ yr^{-1}$)	pH (yr^{-1})	EC ($dS\ m^{-1}\ yr^{-1}$)	SOM ($Mg\ ha^{-1}\ yr^{-1}$)	TN ($Mg\ ha^{-1}\ yr^{-1}$)	TC ($Mg\ ha^{-1}\ yr^{-1}$)	C:N (yr^{-1})	N/SOM ($\%\ yr^{-1}$)	C/SOM ($\%\ yr^{-1}$)
Ecosystem									
PR15†	0.003	0.001	0.001*	−0.26	0.06	−0.16	0.15	0.25	−0.10
PR16	−0.004	0.000	−0.001*	−0.54	−0.03	−0.07	0.18	−0.04	0.28*
PR17	0.000	−0.004	−0.003*	−0.22	−0.02	−0.01	0.20	−0.04	0.24
PR38	0.001	0.035	0.000*	−0.22	−0.03	−0.21	0.17	−0.06	−0.32*
NP	0.003	0.014	−0.003*	−0.36	0.46	0.23	−0.09	0.93	0.81*
Soil moisture regime									
Aquic	−0.002	0.015	−0.001	−0.37	0.21	0.08	0.05	0.44	0.51
Udic	0.001	0.004	−0.001	−0.34	< 0.01	−0.12	0.17	0.05	0.02
Ecosystem x soil moisture regime									
PR15-Aquic	0.003	0.014	0.002	0.03	−0.04	−0.06	0.23	−0.09	−0.15
PR15-Udic	0.003	−0.005	0.001	−0.40	0.11	−0.21	0.11	0.42	−0.08
PR16-Aquic	−0.006	−0.001	−0.002	−0.86	−0.01	−0.07	0.06	0.03	0.61
PR16-Udic	−0.004	0.001	0.000	−0.43	−0.03	−0.07	0.23	−0.06	0.17
PR17-Aquic	−0.011*	0.016	−0.003	−0.58	−0.02	−0.14	0.06	0.01	0.29
PR17-Udic	0.011*	−0.023	−0.003	0.13	−0.03	0.12	0.33	−0.09	0.19
PR38-Udic	0.001	0.035	0.000	−0.22	−0.03	−0.21	0.17	−0.06	−0.32
NP-Aquic	0.005	0.032	−0.002	−0.07	0.92	0.60*	−0.14	1.83	1.28
NP-Udic	0.001	−0.004	−0.004	−0.66	< −0.01	−0.13	−0.04	0.03	0.34

† 15-, 16-, 17-, and 38-yr-old prairie restorations (PR) and native prairie (NP).

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

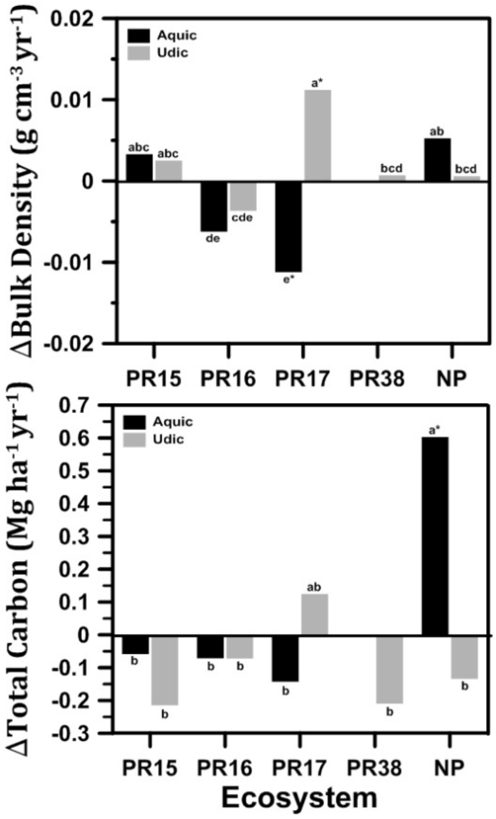

Figure 1. Ecosystem-soil moisture regime effects on the change in soil bulk density and total carbon in the top 10 cm over the 12-yr sampling period in a chronosequence of four prairie restorations (PR; 15-, 16-, 17-, and 38 years old) and an undisturbed native prairie (NP) in northwest Arkansas. An asterisk (*) indicates mean value is greater than 0 ($P < 0.05$).

Among a variety of landuses from native undisturbed grasslands to poorly managed rangelands, global soil C sequestration rates have been reported to range from 0 to approximately 8 Mg SOC ha^{-1} yr^{-1} within the upper 30 cm [28]. It has been estimated that between 40 and 60% of the original SOC can be lost following the conversion of lands from tallgrass prairie to cultivated agriculture [29]. The soil C sequestration results of this study are similar to past reports, where global soil C sequestration rates ranged from 0.1 to 0.4 Mg C ha^{-1} yr^{-1} and averaged 0.33 Mg C ha^{-1} yr^{-1} for soils converted from agricultural management to grassland [16]. Christiansen and Thompson [30] followed the progression of a grassland restoration in eastern Iowa and concluded that fluctuations in soil C dynamics did not change linearly over time, but rather decreased within the first two years after initiating restoration activities, increased in the subsequent years, and then began to decrease between 15 and 24 years after initiating restoration activities, highlighting the difficulty in interpreting soil C dynamics in natural grassland ecosystems. Kucharik [13] reported a declining average annual soil C sequestration rate in the top 5 cm as prairie restorations in southern Wisconsin matured from 4- to 16-yrs old, while the rates of soil N sequestration were more varied. Kucharik et al. [31] also suggested that short-term SOC and TN increases with conversion from agricultural management to prairie restoration could be lost with time. In comparison, a longer grassland restoration study conducted on previously cultivated clay soils (Udic Haplusterts) in central Texas showed that SOC contents in the top 60 cm in a 60-yr-old restoration had not yet reached the level of stored SOC of a native prairie and, at a sequestration rate of 0.45 Mg C ha^{-1} yr^{-1}, it would require nearly an additional century for the 60-yr-old restoration site to reach a stored-C pool equivalent to that of the native prairie [32].

Changes in soil pH, EC, and the TC fraction of SOM in the top 10 cm over time differed ($P < 0.02$; Table 2) among ecosystems. Averaged across SMRs, soil pH increased the most over time in the 38-yr-old prairie restoration (0.034 yr^{-1}) compared to the other four prairie ecosystems, but the change did not differ from a change of zero, while changes in soil pH over time did not differ among any of the other four ecosystems and did not differ from a change of zero (Table 3; Figure 2). Brye et al. [27] also reported that there were no differences in soil pH from year to year when assessing the progress of a prairie restoration in southern Wisconsin. In contrast to soil pH, averaged across SMRs, soil EC increased the most over time in the 15-yr-old prairie restoration (0.001 dS m^{-1} yr^{-1}), while soil EC decreased the most over time in the 17-yr-old prairie restoration and native prairie, but did not differ and averaged −0.003 dS m^{-1} yr^{-1} (Table 3; Figure 2). However, although all soil EC changes over time differed from zero, the changes in soil EC were relatively minor, but demonstrate how uniform soil EC was for the slight fluctuations over time to be significant.

In relation to the timing of prescribed burning, a study of sequential burning effects was conducted on a grassland restoration in the mid-Atlantic coast in eastern Maryland to compare changes in soil chemistry following spring and fall burns [33]. A greater increase was observed in pH in the top 20 cm following the spring burn, compared to a less significant pH increase observed only in the top 2.5 cm of soil following the fall burn [33].

Similar to soil TC content, averaged across SMR, the increase in TC fraction of SOM over time was numerically largest in the native prairie (0.81% yr^{-1}; Table 3; Figure 2), but the increase did not differ from that in the 16- or 17-yr-old prairie restorations and did not differ from a change of zero. The decrease in TC fraction of SOM over time was numerically largest in the 38-yr-old prairie restoration (−0.32 % yr^{-1}; Table 3; Figure 2), but the decrease did not differ from that in the 15- or 17-yr-old prairie restorations and also did not differ from a change of zero. These results indicate that differential enrichment of the SOM pool with C is not occurring among the prairie restorations or native prairie, which suggests to some degree that the functions associated with soil C dynamics in the prairie restorations achieved a similar level as those in the native prairie by only 15 years after initiation of restoration efforts. These results also underscore the influence of similar loamy soil parent materials on ecosystem functioning among tallgrass prairies in the Ozark Highlands region of northwest Arkansas.

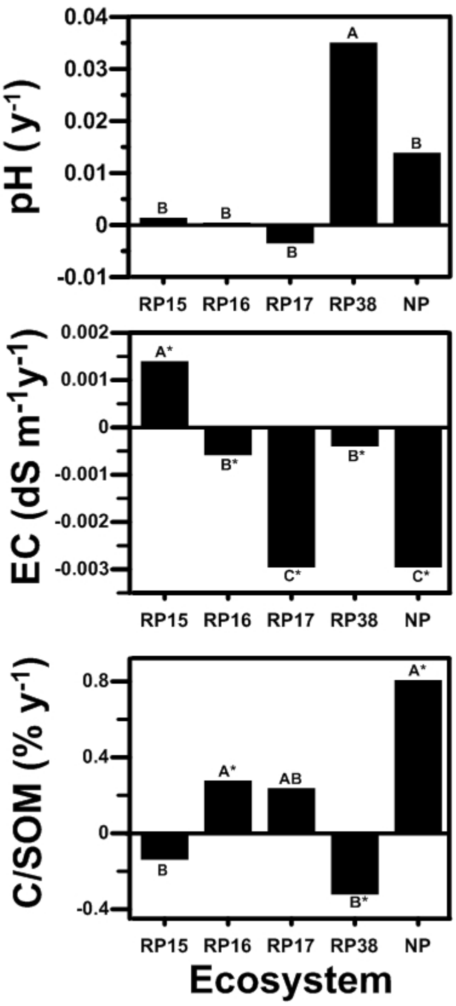

Figure 2. Ecosystem effects on the change in soil pH, electrical conductivity (EC), and the carbon fraction of soil organic matter (C/SOM) in the top 10 cm over the 12-yr sampling period in a chronosequence of four prairie restorations (PR; 15-, 16-, 17-, and 38 years old) and an undisturbed native prairie (NP) in northwest Arkansas. An asterisk (*) indicates mean value is greater than 0 ($P < 0.05$).

Averaged across ecosystems, soil pH increased ($P = 0.03$) more over time in the aquic (0.015 yr^{-1}) than in the udic (0.004 yr^{-1}) SMR, but both changes did not differ from a change of zero (Table 3). Changes in SOM and TN concentration and content, soil C:N ratio, and the TN fraction of SOM in the top 10 cm over the 12-yr time period were generally quite small, where many changes over time did not differ from a change of zero (Table 4) and, consequently, were unaffected ($P > 0.05$) by ecosystem, SMR, or their interaction (Table 2). In contrast, Brye et al. [27] reported a significant TN content increase in the top 30 cm of soil from 1995 to 1999 when assessing the progress of a prairie restoration also on fine-textured, predominantly silt-loam soils, in southern Wisconsin. The differential TN results suggest that less decomposition is occurring in the upper Midwest, which is relatively cooler, as evidenced by the storage and sequestration of more soil N, compared to in the mid-southern United States, which is relatively warmer, where, in this study, there was no significant increase in total soil N.

Table 4. Summary of mean soil property changes by treatment (i.e., ecosystem, soil moisture regime, or their interaction) over a 12-year sampling period for soil organic matter (SOM), total nitrogen (TN), total carbon (TC) concentrations in a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Treatment	Soil properties		
	SOM (% yr^{-1})	TN (% yr^{-1})	TC (% yr^{-1})
Ecosystem			
PR15[†]	−0.03	−0.004	−0.02
PR16	−0.03	−0.002	0.00
PR17	−0.01	−0.001	0.01
PR38	−0.02	−0.002	−0.02
NP	−0.05	0.000	0.00
Soil moisture regime			
Aquic	−0.02	−0.001	0.01
Udic	−0.03	−0.002	−0.01
Ecosystem x soil moisture regime			
PR15-Aquic	−0.01	−0.004	−0.01
PR15-Udic	−0.04	−0.004	−0.02
PR16-Aquic	−0.05	0.000	0.01
PR16-Udic	−0.02	−0.002	0.00
PR17-Aquic	0.01	0.000	0.02
PR17-Udic	−0.02	−0.003	−0.00
PR38-Udic	−0.02	−0.002	−0.02
NP-Aquic	−0.03	0.000	0.02
NP-Udic	−0.06	0.000	−0.01

[†] 15-, 16-, 17-, and 38-yr-old prairie restorations (PR) and native prairie (NP).

3.2. Soil property differences after 12 years

Though five of nine measured soil property changes over time in the top 10 cm were affected, while the other four were unaffected, by ecosystem, SMR, or their interaction, all measured soil properties differed ($P < 0.05$) among ecosystems, between soil moistures regimes, or among treatment combinations in 2017 after 12 years of consistent management or natural time progression (Table 5). With the exception of soil C:N ratio and TC and TN fraction of SOM, all other soil properties differed ($P < 0.01$) between SMRs among ecosystems (Table 5). The regression analysis conducted resulted in significant trends only in the udic SMR, where BD, SOM and TC contents and concentrations were the only soil properties that significantly changed ($P < 0.05$) as ecosystem age increased. With the exception of the C:N ratio, which was averaged across SMR and analyzed by prairie restoration only, excluding the native prairie, all other soil properties did not change over time. Soil BD in the top 10 cm was greater in the udic-17-, udic-38-, and 15-yr-old prairie restorations in both SMRs, which did not differ and averaged 1.25 g cm^{-3}, than that in the 16- and 17-yr-old prairie restorations in the aquic SMR, which did not differ and averaged 1.01 g cm^{-3} (Table 6; Figure 3). A similar study conducted in fall 2005 by Brye et al. [15] on the same prairie restoration sites when the sites were 3, 4, 5, and 26 years old, but not separated by SMR, concluded that the oldest prairie restoration had the greatest bulk density (1.23 g cm^{-3}) in the top 10 cm, while the soil bulk density was lowest in the native prairie (1.07 g cm^{-3}).

Table 5. Analysis of variance summary of the effects of ecosystem, soil moisture regime (SMR), and their interaction on soil bulk density, pH, electrical conductivity, organic matter, total nitrogen, and total carbon concentration and content, C:N ratio, and the nitrogen and carbon fractions of soil organic matter from the 2017 sampling in a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Soil property	Ecosystem	SMR	Ecosystem x SMR
		P	
Bulk density (g cm^{-3})	< 0.01	< 0.01	< 0.01
pH	< 0.01	0.68	< 0.01
Electrical conductivity (dS m^{-1})	0.15	< 0.01	< 0.01
Soil organic matter (%)	< 0.01	< 0.01	< 0.01
Soil organic matter (Mg ha^{-1})	< 0.01	< 0.01	< 0.01
Total nitrogen (%)	< 0.01	< 0.01	< 0.01
Total nitrogen (Mg ha^{-1})	< 0.01	< 0.01	0.02
Total carbon (%)	< 0.01	< 0.01	< 0.01
Total carbon (Mg ha^{-1})	< 0.01	< 0.01	< 0.01
C:N ratio	< 0.01	0.46	0.15
Total nitrogen in organic matter (%)	< 0.01	0.81	0.15
Total carbon in organic matter (%)	< 0.01	< 0.01	0.17

Regression analysis determined a strong trend in soil BD ($P = 0.05$, $r^2 = 0.71$) among prairie ecosystems in the udic SMR, where BD decreased by 0.00005 g cm^{-3} yr^{-1} as restoration age increased. An overall decrease in soil BD as restoration age increases could be the result of the adaptation of the soil as grazing cattle were removed from these ecosystems to initiate the restorations and establish the perennial grasslands. However, Derner and Shuman [34] reported no relationship between the change in SOC content and the longevity of a grazing management practice in native rangelands of the North American Great Plains. Brye and Riley [3] concluded the same when results showed a general decrease in soil BD with restoration age that tended toward the native prairie. Kucharik et al. [31] also reported greater soil BD in a 65-yr-old prairie restoration compared to that in an adjacent remnant prairie ecosystem in east-central Wisconsin. However, in contrast, Brye and West [5] reported greater soil BD in the top 10 cm of an ungrazed grassland compared to a grazed grassland on silt-loam soils in the Ozark Highlands, where the ungrazed grasslands included a native prairie and several hayed/mowed grasslands. Brye and West [5] attributed the difference to low and inconsistent cattle stocking rates on the grazed grassland that led to the wheel traffic from the cutting of the ungrazed meadows to have a greater impact on soil BD than periodic animal traffic. Soil pH was greater in the 16- and 17-yr-old prairie restorations in the aquic SMR, which did not differ and averaged 6.5, than that in the native prairie in the aquic SMR (pH = 5.2), which was more acidic than all other ecosystem-SMR combinations (Table 6; Figure 3). Similarly, Brye et al. [15]

reported the lowest soil pH in the native prairie as well, along with low soil pHs in the oldest prairie restoration. Contrary to these results, in a study also conducted on the same restoration sites (aged 3, 4, 5, and 26 years old), Brye and Riley [3] reported an increase in soil pH as restoration age increased, which was attributed to the cessation of N fertilization and the influence of nitrification as an acidifying process from the previous managed grassland land use. Similar to pH, soil EC was greater in the 16- and 17-yr-old prairie restorations in the aquic SMR, which did not differ and averaged 0.111 dS m^{-1}, than that in all other ecosystem-SMR combinations, which did not differ and averaged 0.075 dS m^{-1} (Table 6; Figure 3).

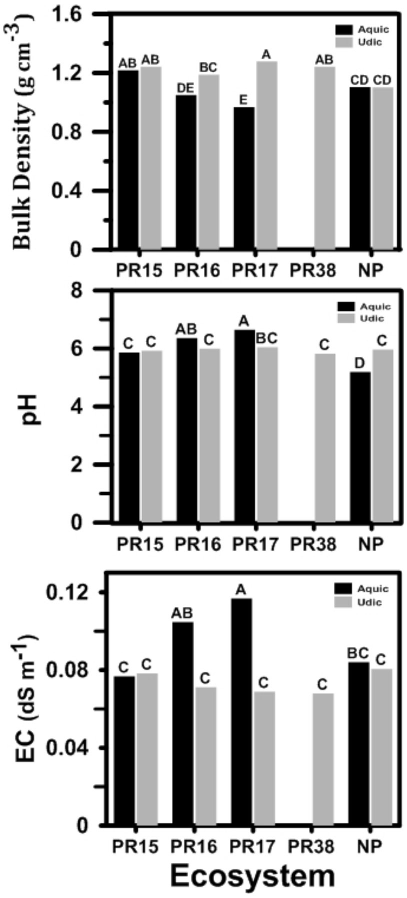

Figure 3. Ecosystem-soil moisture regime effects on soil bulk density, pH, and electrical conductivity (EC) in the top 10 cm from the 2017 sampling in a chronosequence of four prairie restorations (PR; 15-, 16-, 17-, and 38 years old) and an undisturbed native prairie (NP) in northwest Arkansas.

Soil organic matter concentration and content were greater in the 16- and 17-yr-old prairie restorations in the aquic and native prairie in the udic SMR, which did not differ and averaged 5.3% and 29.1 Mg ha^{-1}, respectively (Table 6 and 7; Figure 4). Soil organic matter concentration was lowest in the four prairie restorations in the udic SMR, which did not differ and averaged 2.9% (Table 7; Figure 4), while SOM content was lowest in 15-, 17-, and 38-yr-old prairie restorations in the udic SMR, which did not differ and average 34.2 Mg ha^{-1} (Table 6; Figure 4). Although not separated by SMR, similar results were reported by Brye et al. [15], when the restorations were 3, 4, 5, and 26 years old, where

SOM content was greatest in the native prairie, which did not differ to that in the 4- and 5-yr-old restorations. In addition, Brye et al. [15] also reported SOM content to be lowest in the oldest restoration, which was 26-year-old at the time of sampling. Regression analysis also determined a strong trend in SOM concentration (P = 0.02, r^2 = 0.82) and content (P = 0.03, r^2 = 0.81) among prairie ecosystems in the udic SMR, where SOM concentration and content increased by 0.0006% yr^{-1} and 0.006 Mg ha^{-1} yr^{-1}, respectively, as restoration age increased. The trend of increasing SOM over time was most likely the result of greater above- and belowground biomass growth, as root systems of the prairie vegetation expand through the soil over time. However, it is unclear why the trend of significantly increasing SOM concentration and content over time was not observed within the aquic SMR.

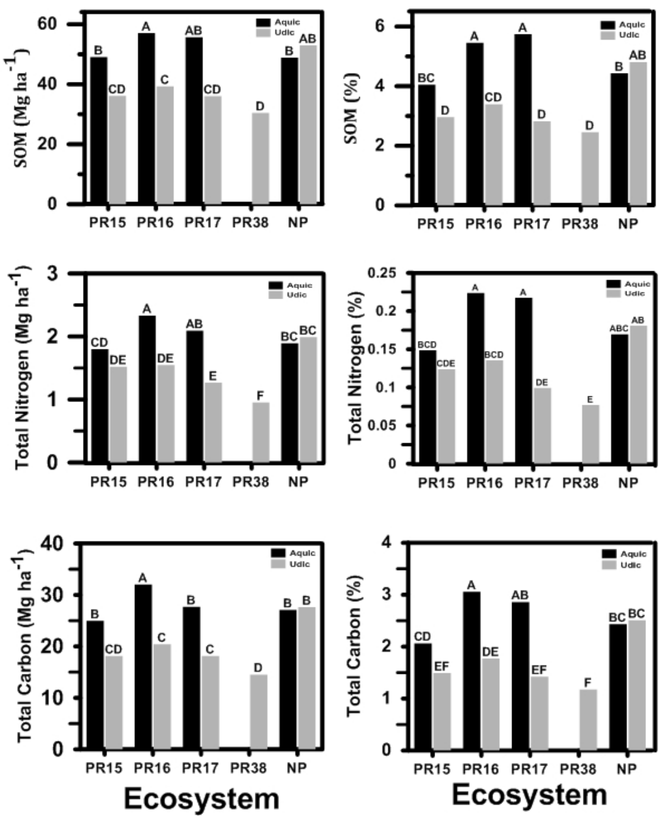

Figure 4. Ecosystem-soil moisture regime effects on soil organic matter (SOM), total nitrogen (TN), and total carbon (TC) concentrations and contents in the top 10 cm from the 2017 sampling in a chronosequence of four prairie restorations (PR; 15-, 16-, 17-, and 38 years old) and an undisturbed native prairie (NP) in northwest Arkansas.

Table 6. Summary of mean soil properties by treatment (i.e., ecosystem, soil moisture regime, or their interaction) from the 2017 sampling 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 a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Treatment	Soil properties								
	BD ($g\ cm^{-3}$)	pH	EC ($dS\ m^{-1}$)	SOM ($Mg\ ha^{-1}$)	TN ($Mg\ ha^{-1}$)	TC ($Mg\ ha^{-1}$)	C:N	N/SOM (%)	C/SOM (%)
Ecosystem									
PR15†	1.23	5.9	0.078	40.40	1.61	20.40	12.81	4.0	50.1
PR16	1.15	6.1	0.080	43.70	1.74	23.30	13.60	3.9	52.7
PR17	1.12	6.3	0.093	45.85	1.68	22.89	13.82	3.7	50.3
PR38	1.24	5.8	0.068	30.45	0.95	14.52	15.35	3.1	47.7
NP	1.10	5.6	0.082	50.91	1.94	27.35	14.10	3.8	53.7
Soil moisture regime									
Aquic	1.08	6.0	0.096	52.65	2.03	27.93	13.82	3.9	53.1
Udic	1.21	5.9	0.073	37.75	1.43	19.13	13.80	3.7	50.2
Ecosystem x soil moisture regime									
PR15–Aquic	1.22	5.9	0.077	49.02	1.80	24.97	13.89	3.7	50.9
PR15–Udic	1.24	5.9	0.078	36.09	1.52	18.11	12.27	4.2	49.7
PR16–Aquic	1.05	6.4	0.105	57.04	2.33	31.99	13.78	4.1	56.1
PR16–Udic	1.19	6.0	0.071	39.25	1.55	20.41	13.58	3.8	51.5
PR17–Aquic	0.97	6.6	0.117	55.65	2.09	27.66	13.27	3.8	50.3
PR17–Udic	1.28	6.0	0.069	36.05	1.27	18.12	14.37	3.5	50.3
PR38–Udic	1.24	5.8	0.068	30.45	0.95	14.52	15.35	3.1	47.7
NP–Aquic	1.10	5.2	0.084	48.88	1.89	27.08	14.35	3.9	55.3
NP–Udic	1.10	6.0	0.081	52.94	1.99	27.62	13.84	3.8	52.1

† 15-, 16-, 17-, and 38-yr-old prairie restorations (PR) and native prairie (NP).

Soil C concentration was greater in the 16- and 17-yr-old prairie restorations in the aquic SMR, which did not differ and averaged 3.0%, while soil C concentration was lowest in the 15-, 17-, and 38-yr-old prairie restorations in the udic SMR, which did not differ and averaged 1.4% (Table 7; Figure 4). These results are likely the result of the periodic water-logging and anaerobic conditions typical of an aquic SMR, which would tend increase the amount of stored C within the soil, as SOM decomposition is generally slowed during persistent anaerobic conditions, that occurred with the slightly older prairie restorations. In contrast to soil C concentration, and again highlighting the effect soil BD differences have on TC measurements, soil C content was greater in the 16-yr-old prairie restoration in the aquic SMR (32.0 Mg ha^{-1}) than in all the other ecosystem-SMR treatment combinations, while soil C content was lowest in the 15- and 38-yr-old prairie restorations in the udic SMR, which did not differ and averaged 16.3 Mg ha^{-1} (Table 6; Figure 4). Regression analyses support an increasing trend among ecosystems in the udic SMR in both TC concentration and content, where TC concentration (P = 0.03, r^2 = 0.77) and content (P = 0.04, r^2 = 0.74) increased by 0.0003 % yr^{-1} and 0.003 Mg ha^{-1} yr^{-1}, respectively, with restoration age, in which the changes over time in both soil C properties were tending towards those in the native prairie. A study using the same chronosequence of humid-temperate tallgrass prairie restorations in Ozark Highlands showed soil C content, in the top 20 cm, increased with restoration age and tended towards the observed levels in a nearby native prairie after four years [3]. In southern Wisconsin, Kucharik [13] reported that, when compared, the soil properties of agricultural fields to adjacent prairie restorations of varying ages separated by soil order (i.e., Mollisol or Alfisol), the SOC content increased in the top 5 cm of young (4- to 6-years old) and middle-aged (6- to10-years old) prairie restorations in the Alfisol soil order following the conversion from agricultural land use to prairie restoration. However, on average, Mollisols contained 8.6% more SOC in the 0- to 25-cm depth range than the Alfisols [13].

Similar to SOM concentration, soil N concentration was greater in the 16- and 17-yr-old prairie restorations in the aquic and in the native prairie in both SMRs, which did not differ and averaged 0.2%, while soil N concentration was lowest in the 15-, 17-, and 38-yr-old prairie restorations in the udic SMR, which did not differ and averaged 0.1% (Table 7; Figure 4). The soil N results can be at least partially explained by an increase in N-rich grass species and forbs in the older restorations, excluding the 38-yr-old restoration, which was dominated by woody encroachment from predominantly sumac (*Rhus* spp.) instead of readily decomposable grasses, as well as the increased storage of N in the soil, due to periodic anaerobic conditions in the aquic SMR, that would slow the decomposition of SOM and therefore the mineralization of soil N. The substantially older age was the likely explanation for greater soil N concentration in both SMRs in the native prairie compared to the much younger restorations. In contrast to soil N concentration, soil N content was greater in the 16- and 17-yr-old prairie restoration in the aquic SMR, which did not differ and averaged 2.2 Mg ha^{-1}, while soil N content was lower in the 38-yr-old prairie restoration in the udic SMR (0.9 Mg ha^{-1}) than all other ecosystem-SMR treatment combinations (Table 6; Figure 4). The discrepancy between soil TN concentration and content results was most likely due to the differences in soil BD among the prairie ecosystems. Brye and Riley [3] reported a trend in the relationship between soil N content and restoration age, where the greatest soil N contents were present in the younger restorations and soil N content decreased with restoration age. The trend of decreasing N content with increasing restoration age was attributed to the cessation of inorganic N fertilization for biomass production in the previously managed grassland land use. However, compared to the average C and N contents of 69 and 6.1 Mg ha^{-1}, respectively, reported for a prairie restoration in southern Wisconsin by Brye et al. [27], the average N content of the prairie restorations in this study and others conducted in the past on these same prairie restorations are low. It is important to consider, however, that Brye et al. [27] reported contents measured from the 0–30 cm soil depth range, which is a considerably larger depth range assessed than in the current study.

Table 7. Average soil organic matter (SOM), total nitrogen (TN), and total carbon (TC) concentrations for the 2017 sampling by ecosystem, soil moisture regime, and their interaction from a chronosequence of four prairie restorations and an undisturbed native prairie in northwest Arkansas.

Treatment	Soil properties		
	SOM (% yr^{-1})	TN (% yr^{-1})	TC (% yr^{-1})
Ecosystem			
PR15†	3.33	0.13	1.68
PR16	3.91	0.16	2.09
PR17	4.28	0.16	2.14
PR38	2.46	0.08	1.17
NP	4.62	0.18	2.47
Soil moisture regime			
Aquic	4.92	0.19	2.60
Udic	3.18	0.12	1.62
Ecosystem x soil moisture regime			
PR15-Aquic	4.05	0.15	2.06
PR15-Udic	2.97	0.12	1.49
PR16-Aquic	5.45	0.22	3.06
PR16-Udic	3.39	0.14	1.77
PR17-Aquic	5.74	0.22	2.86
PR17-Udic	2.82	0.10	1.42
PR38-Udic	2.46	0.08	1.17
NP-Aquic	4.43	0.17	2.43
NP-Udic	4.81	0.18	2.51

† 15-, 16-, 17-, and 38-yr-old prairie restorations (PR) and native prairie (NP).

Soil C:N ratio and the TC and TN fractions of SOM differed ($P < 0.01$) among ecosystems but were unaffected by SMR (Table 5). Averaged across SMR, soil C:N ratio was largest in the 38-yr-old prairie restoration and native prairie, which did not differ and averaged 14.7, while soil C:N ratio was lowest and averaged 13.6 among the three youngest prairie restorations and native prairie, which did not differ (Table 6; Figure 5). The soil C:N ratio differences could be indicative of the diversity of grass species decreasing in the native prairie and the eldest prairie restoration, leading to a decrease of N-producing forbs and the aboveground biomass evolving to more woody brush and hardier grasses that have greater C:N ratios that would tend to resist decomposition. In the case of the native prairie, another explanation could be due to a greater SOC sequestration rate within the ecosystem leading to more stored C and less available N within the SOM pool, therefore increasing the C:N ratio within the soil. However, this explanation would likely not pertain to the 38-yr-old prairie restoration, since the oldest restoration had the lowest sequestration rate among the ecosystems evaluated in this study. Regression analysis resulted in a strong positive trend (P = 0.03, r^2 = 0.91) of a 0.08 yr^{-1} increase in C:N ratio with increasing restoration age when analyzed among prairie restorations only and excluding the native prairie. Brye and Riley [3] reported similar results, with soil C:N ratio increasing as restoration age increased. Another similar trend in soil C:N ratio was reported by Brye and Kucharik [12] in the top 10 cm of a prairie restoration in south-central Wisconsin. However, Kucharik [13] reported no trend in soil C:N ratio based on restoration age, but did report a significant effect on soil C:N ratio based on soil order at all measured depths (i.e. 0–5, 5–10, 10–25, and 0–25 cm), where Mollisols had a greater C:N ratio at each depth interval than Alfisols. In contrast to soil C:N ratio, averaged across SMRs, the soil TC and TN fractions of SOM were both largest among the 15-, 16-, and 17-yr-old prairie restorations and native prairie, which did not differ and averaged 51.7 and 3.9%, respectively, and lowest in the 38-yr-old prairie restoration (47.7% C and 3.1% N; Table 6; Figure 5). The cause for the low levels of TC and TN fractions of SOM in the 38-yr-old prairie restoration could stem from the fact that there is only a udic SMR represented in this restoration. Therefore, the more rapid decomposition of the TC and TN, due to the absence of prolonged periodic anaerobic conditions, could be the reason for the lower TC and TN levels within the SOM pool. In contrast to soil TN, averaged across ecosystem, the soil TC fraction of SOM was also greater in the aquic (53.1%) than in the udic (50.2%) SMR (Table 6), which was also likely due to the absence of prolonged water-logging in the udic SMR, leading to a greater rate of mineralization of the available N.

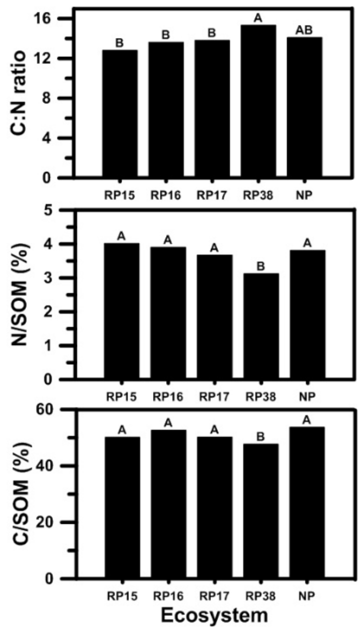

Figure 5. Ecosystem effects on soil carbon: nitrogen (C:N) ratio and the N (N/SOM) and C (C/SOM) fractions of soil organic matter (SOM) in the top 10 cm from the 2017 sampling in a chronosequence of four prairie restorations (PR; 15-, 16-, 17-, and 38 years old) and an undisturbed native prairie (NP) in northwest Arkansas.

4. Conclusions

This field study evaluated the effects of restoration age and SMR (i.e., aquic and udic) on near-surface soil C and other soil property changes over time in a chronosequence of humid-temperate tallgrass prairie restorations (i.e., 15-, 16-, 17-, and 38-years old) in the Ozark Highlands region of northwest Arkansas. The Ozark Highlands region of northwest Arkansas is a unique transition zone between the more arid Great Plains grasslands to the west and northwest and the more humid forests to the east and southeast, where the dynamics of soil C and other C-related soil properties in grasslands have been understudied.

In general, the soil properties evaluated in this study behaved as expected, with decreases in soil BD and increases in SOM, TC, TN, and TC and TN fractions of SOM occurring over time as restoration age increased, which tended towards the values measured in a nearby native prairie. However, the 38-yr-old prairie restoration often possessed the lowest soil property magnitudes and did not fit well within the general trends over time as measured in the three younger restorations. The negative effects of fragmentation and the lack of consistent management leading to woody encroachment have likely contributed to the atypical behavior of the oldest prairie restoration evaluated in this study. The soil C sequestration rates reported for the top 10 cm in this study from direct measurements over a 12-year period, which ranged from −0.21 to 0.12 Mg C ha^{-1} yr^{-1} across four prairie restorations ranging in age from 15- to 38-years old and averaged 0.60 Mg C ha^{-1} yr^{-1} in the aquic SMR of the native prairie, were similar to those reported in other studies. However, soil C sequestration rates determined by regression analysis between soil C contents in the top 10 cm and ecosystem age resulted in much lower rates than those determined from direct measurement. Underestimating soil C sequestration rates based on regression analysis may have negative implications for evaluating the effects of regional or global climate and highlights the importance of using direct measurements for assessing soil property change over time whenever possible. Results of this study also clearly demonstrated the significant effect of the history of internal soil moisture dynamics, as measured through differences in soil properties, particularly for SOC, between soil moisture regimes, indicating that soil moisture regime should be taken into account when attempting grassland restoration activities.

As many soil properties in the prairie restorations evaluated in this study are trending towards those measured in a nearby native prairie on similar soils, continued proper and consistent management of the prairie restorations into the future will be critical for the potential long-term success of the restorations achieving a similar state of functionality and SOC sequestration potential as measured in the native prairie. Continued research on the restoration sites used in this study would be beneficial, due to the unique chronosequence that was created following the staggered implementation of the restoration projects. Expanding the study to include ecological studies and C and N analyses of the dominant vegetative species, as well as the diversity and richness of the microbial population, would further enhance interpretations and implications of restoration activities. Results of this study contribute valuable insights to extrapolate to other prairie restoration projects in the Ozark Highlands, which will help to increase not just biodiversity in prairie vegetation and wildlife and aesthetic appeal in the region, but also lead to greater SOC sequestration to help mitigate global climate change and the rehabilitation of agriculturally disturbed soils.

Acknowledgements

This research study was made possible through the National Parks Service permit number PERI-2016-SCI-0001 and partial funding support from the Arkansas Natural Resource Conservation Service. The authors thank the Park Superintendent and Chief Resource Manager for their support of this research project.

Conflict of interest

The authors declare no conflict of interest.

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