LONG-TERM PRESCRIBED FIRE DOES NOT ALTER LITTER DECOMPOSITION AND BIOAVAILABILE NITROGEN IN XERIC OAK FORESTS

By

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DEDICATION

This work is dedicated to my girlfriend, Rachel Snyder. Her love and support throughout my time at Oklahoma State University made it possible to push through those long hours into the night. Listening to practice presentations, proofreading my papers, and encouraging me to work harder are a few of the many ways she has helped make me a better scientist.

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Abstract: The Cross Timbers is a patchwork of grassland, savanna, and xeric oak forest that stretch across Kansas, Oklahoma, and Texas. Historically a pyric ecosystem, burning of the Cross Timbers became infrequent. Currently, land managers are increasingly using prescribed fire as a tool to increase biodiversity, reduce woody encroachment, and decrease wildfire risk. Understanding the effects fire has on litter decomposition is important due to its impacts on carbon storage, nutrient cycling, and erosion. Nitrogen volatilizes in fire and this can reduce the bioavailable nitrogen that, in turn, lowers litter quality. Previous studies have shown that lower litter quality can slow decomposition. Fire can also affect decomposition environment, resulting in altered microbial communities, arthropods, litter depth, moisture, and temperature in the litter layer that can change the rate of decomposition. The objective of our study was to determine whether fire frequency effects on litter quality and decomposition environment alter the rate of decomposition. Litterbags were installed at three wildlife management areas in Oklahoma that have been periodically burned for at least 24 years. Litterbags were collected every three months for a period of 15 months. Major findings of our study were decomposition environment did not affect the rate of decomposition under a closed canopy with fire frequency between 0 and 4.6 fires per decade, and differences observed in litter quality decomposition rates were not due to fire, but some other unexplored mechanism.

TABLE OF CONTENTS

Section Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

LONG-TERM PRESCRIBED FIRE DOES NOT ALTER LITTER DECOMPOSITION AND BIOAVAILABILE NITROGEN IN XERIC OAK FORESTS

1. Introduction

1.1. Cross Timbers

Stretching across portions of Kansas, Oklahoma, and Texas, the Cross Timbers Ecoregion encompasses 7,991,900 hectares (McArthur and Ott 1996). Representing a landscape-sized ecotone where the eastern forests meet the Great Plains, the Cross Timbers is characterized as a patchwork of grassland, savanna, and xeric forest. The forests are predominately composed of post oak (*Quercus stellata*) and blackjack oak *(Quercus marilandica)* and to a lesser extent black hickory (*Carya texana*), shumard oak (*Quercus shumardii*), winged elm (*Ulmus alata*), and eastern redcedar (*Juniperus virginiana*). Post oak and blackjack oak comprise 68% of the total basal area in the Oklahoma Cross Timbers (DeSantis 2010). Typical understory species include greenbrier (*Smilax spp.*), little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerardii*), buckbrush (*Symphoricarpos orbiculatus*), and fish-on-a-fishing-pole grass (*Chasmanthium latifolium*).

Historically, the Cross Timbers was subjected to periodic burning (mean fire return interval=4.1-4.4 years) (Clark 2003; Stambaugh et al. 2009) by Native Americans for communication, warfare, and to aid in the hunting of the American bison (*Bison bison*) (Courtwright 2007). As Euro-American settlement ensued, human populations within the Cross Timbers increased and anthropogenic fires increased to a mean fire return interval of 2.0 years (Clark 2003; DeSantis 2010). Most (97%) fires were ignited in the dormant season (September-March) (Stambaugh et al. 2009) and were of low-intensity. Currently, much of the Cross Timbers is increasingly becoming fragmented by roads, agriculture, and urban areas (Bidwell et al. 2003). Public perception of fire is generally negative and periodic burning is not as commonplace as it was in the past (Collins and Wallace 1990; Morton et al. 2010).

Recently, a renewed interest in prescribed fire has taken hold as a beneficial tool to manage the Cross Timbers (Bidwell et al. 2003). Land managers and private owners are using fire to increase biodiversity, reduce fuel loads that can result in catastrophic wildfires, and reduce woody encroachment of eastern redcedar. Increasing prescribed burning has been shown to have a positive linear relationship on herbaceous biodiversity in the Cross Timbers (Burton 2009). Through regular burning, the quantity of fuel is reduced and the potential for wildfires that destroy homes and infrastructure is lower (Bidwell et al. 2003). Burning can reduce woody encroachment by eastern redcedar, a native tree, which has been increasing its abundance in the Cross Timbers due to the absence of fire. From 1985 to 1994 redcedar extended its range throughout Oklahoma by 79% (Bidwell and Oklahoma Cooperative Extension Service 2009). This profound increase has widespread ecological effects for forested systems including reduced litter C, shifts in soil microbial communities, increased actual evapotranspiration, and reduced understory cover and species richness (Pierce and Reich 2010; Williams 2010; Hung 2012; van Els et al. 2010).

1.2. Fires and Nitrogen Volatilization

Though studied elsewhere (Grigal and McColl 1977; Ferran and Vallejo 1992; Hernández and Hobbie 2008; Silveira et al. 2009), the effects of fire on litter decomposition and bioavailable nitrogen has never been studied in the Cross Timbers. Nitrogen has been shown to volatilize during fires with temperatures above 200°C. Typical maximum ground surface temperatures of a forest fire are between 200-300°C (Knicker 2007). Research in a chaparral ecosystem observed losses of 146 kg/ha N during a controlled burn (Debano and Conrad 1978). Within the Cross Timbers, Williams (2010) observed total N in the entire litter layer was reduced by 20% and 21% in units that were subjected to 2.5 fires per decade and 5 fires per decade, respectively, as compared to an unburned control. This increased the C:N ratio by 25% and 28%, correspondingly. One of the main drivers of the rate of litter decomposition is C:N (Hernández and Hobbie 2008; Kurka et al. 2000; Silveira et al. 2011). Another driver of decomposition is lignin:N and a strong correlation has been reported for hardwood litter decomposition decreasing as lignin:N increased (Melillo et al. 1982). In the Cross Timbers, lignin:N was found to increase with an increase in fire frequency (Williams 2010).

A similar study to our study was located at Cedar Creek Ecosystem Science Reserve in Minnesota that examined how northern pin oak (*Quercus ellipsoidalis*) litter decomposed in response to varying burn frequencies. Hernández and Hobbie (2008) found that as fire frequency increased, litter C:N ratio increased resulting in slower decomposition. Their research demonstrated that immobilization was greatest in litter originating from the high burn unit (greater than 8 fires per decade) and this reinforced the feedback loop of low N availability in the stands (Figure 1). Additionally, ion exchange resin bags were used in their study and they showed that N availability in the soil decreased with increasing fire frequency.

1.3. Objectives

The goal of our study was to determine how litter quality (total N concentration, C:N, and lignin:N) and decomposition environment (canopy cover and basal area) affect litter decomposition and bioavailable N (ammonium and nitrate) in post oak-blackjack oak forests under different long-term prescribed burning regimes. To accomplish this goal, measurements were performed on litter mass loss; litter and soil chemistry; and decomposition environment characteristics.

The research objectives included:

1. Determine whether prescribed burning effects on litter quality alter the rate of decomposition.
2. Determine whether prescribed burning effects on decomposition environment alter the rate of decomposition.
3. Determine the relative importance of decomposition environment and litter quality on the rate of decomposition.

4. Determine how prescribed fire affects the bioavailable N in the soil.

Decomposition environment was defined as the physical structure of the forest measured through canopy cover and basal area, though decomposition environment can also comprise litter depth, microbial community, litter layer temperature and moisture, and arthropod population. These variables were not explored in their relation to fire frequency. A significant finding of a decomposition environment effect might require additional measurements to discover the mechanism responsible for decomposition rate differences.

1.4. Hypotheses

Hypotheses addressing the preceding objectives, respectively, are as follows:

1. Litter TN will decrease as fire frequency increases due to the volatilization of N from fire. It follows that C:N and lignin:N will increase as fire frequency increases; the change in these litter quality variables will slow the rate of decomposition as compared to unburned control units.
2. Decomposition environments with high burn frequencies will be more open and warmer, consequently increasing microbial activity. This increase in microbial activity will result in slightly higher decomposition rates as compared to unburned, shadier, cooler control units.
3. Litter quality will be the main driver controlling the rate of decomposition with decomposition environment playing a minor role.

4. The soil ammonium and nitrate concentrations will decrease as fire frequency increases as compared to an unburned control due to volatilization and immobilization of the N in the soil by microbes to decompose the lower quality litter.

1.5. Purpose of Study

The litter layer and its associated nitrogen dynamics are fundamental ecosystem components. With the increasing popularity of using prescribed fire as a management tool, understanding the effects fire has on the rate of decomposition of litter and the nitrogen cycle is valuable. Decomposition in fire driven ecosystems can have broad implications for climate change as carbon storage is affected (Knicker 2007). From a wildlife management perspective, nitrogen dynamics play a role in the forage quality for ungulates, fowl, and other wildlife (Hensley 2010). Burning the litter layer and altering decomposition can increase the rate of erosion leading to water quality issues and a loss of soil fertility (O'Dea and Guertin 2003; Cawson et al. 2012). Litter N and annual litterfall cycling has been found to decrease with an increase in fire frequency leading to a decrease in aboveground net primary productivity (Reich et al. 2001). Burning the litter layer has been demonstrated to have a positive effect on avian and arthropod species (Boyd and Bidwell 2001; Howard and Hill 2007), though it undoubtedly reduces the richness of species intolerant to fire. Understanding the varied effects of fire on litter decomposition and bioavailable N is crucial for land managers to make educated decisions on C storage, N storage, forage quality, productivity, and habitat.

Some might argue that studying the rate of decomposition is of no use if the litter is burned frequently and consumed. However, the time between burns can vary from as little as one year to greater than 37 years. Even if burned every year, research shows that litter can lose approximately 25% of its mass before the next burn (Hernández and Hobbie 2008). Therefore, altering the decomposition rate can have profound impacts on nutrient cycling and other ecosystem processes despite periodic consumption by fire.

2. Methods

2.1. Study Locations

Our study was conducted at three wildlife management areas (WMAs) in Oklahoma that are situated within the Cross Timbers Ecoregion: Okmulgee WMA, Cherokee WMA, and Lexington WMA (Figure 2). All three WMAs are managed by the Oklahoma Department of Wildlife Conservation (ODWC).

Okmulgee WMA is located in east-central Oklahoma (35°38’N, 96°02’W). Elevations range from 195-288 meters. Soils are characterized by well-drained, stony fine sandy loam on slopes of 5-30% (Soil Survey Staff, 2013). Mean annual temperature is 15.2°C with an average monthly low of 2.1°C in January and an average monthly high of 27.0°C in July. Mean annual precipitation is 107.1 cm with an average monthly low of

4.3 cm in January and an average monthly high of 14.0 cm in May (Oklahoma Climatological Survey, 2000).

Cherokee WMA is located in eastern Oklahoma (35°40'N, 95°03'W). Elevations range from 170-311 meters. Soils are characterized by well-drained, stony fine sandy loam on slopes of 8-30% (Soil Survey Staff, 2013). Mean annual temperature is 15.5°C with an average monthly low of 2.7°C in January and an average monthly high of 26.9°C in July. Mean annual precipitation is 122.2 cm with an average monthly low of 6.1 cm in January and an average monthly high of 14.5 cm in May (Oklahoma Climatological Survey, 2000).

Lexington WMA is located in central Oklahoma (35°03'N, 97°11'W). Elevations range from 323-378 meters. Soils are characterized by well-drained, fine sandy loam on slopes of 3-8% (Soil Survey Staff, 2013). Mean annual temperature is 15.6°C with an average monthly low of 2.4°C in January and an average monthly high of 27.8°C in July. Mean annual precipitation is 95.5 cm with an average monthly low of 3.8 cm in January and an average monthly high of 13.5 cm in May (Oklahoma Climatological Survey, 2000).

The ODWC performs periodic prescribed burning on all three WMAs in an effort to increase the quality of habitat for wildlife. These low-intensity surface fires occur in the dormant season, typically February or March. To ensure a safe and effective burn, prescribed burning only takes place under the following weather conditions: wind speed less than 25 kph, relative humidity between 30-50%, and temperature below 27°C (Weir, 2009).

2.2. Experimental Design

Each WMA was divided into numbered management units with varying burn frequencies (Table 1). At each WMA three units were selected: a high burn frequency, medium burn frequency, and control/no burn. High burn frequency was defined as greater than 2.5 fires per decade. Medium burn frequency was defined as less than 2.5 fires per decade and greater than 1.4 fires per decade. Control/no burn units have not been burned for at least 24 years. Within each unit, four sites (samples) were randomly selected using ArcMap 9.2 for a total of 12 sites at each WMA or 36 total sites among all three WMAs. Extra care was taken to ensure that no points fell within a clearing or within 50 meters of the edge of a unit.

Recently fallen post oak and blackjack oak litter was collected in March 2012 and dehydrated in a drying oven at 70°C until no mass loss. Equal amounts of litter from the four sites within each unit were combined and mixed to create a homogenized mixture for each unit at every WMA. In addition, three 10 gram samples from each homogenized litter mixture were weighed to determine the proportion of blackjack oak to post oak.

Litterbags were constructed from gray 1 mm mesh fiberglass screen and were 26 cm by 26 cm. Litterbags were filled with approximately 10 grams of homogenized litter. Our study employed a reciprocal transplant treatment of the litterbags at each WMA. In simplest terms, this means that all of the sites had litter from the other two units as well as their own unit. The purpose of using a reciprocal transplant treatment was to simultaneously assess how decomposition environment and litter quality affect decomposition.

Ion exchange resin bags were assembled from nylon/lycra fabric cut into 15 cm by 15 cm squares and filled with 4.5 grams of mixed bead ion exchange resins (Sigma-Aldrich Dowex Marathon MR-3 hydrogen and hydroxide form). Resin bags were secured with a zip tie and trimmed of excess fabric. A 1.2 M solution of HCl was used to soak the resin bags for 1 hour. Afterwards, the resin bags were rinsed with deionized water until the rinse water was a neutral pH. Resin bags were refrigerated in sealed plastic bags until installation in the field.

2.3. Sampling Collection and Processing

In March 2012, each site received a total of 18 litterbags that were arranged in a 3 by 6 grid (Figure 3). At every site, three litterbags were collected each time representing the litter quality of all three units. The litterbags were collected approximately every three months for a total of five collections over 15 months with an extra set constructed in case of any lost or unidentifiable litterbags. When collecting the litterbags, a random number was generated and that number was used to determine which column to pick up to eliminate bias. In addition to the litterbags, one resin bag was installed at each site 10 cm below mineral soil at the beginning of the study. Each collection, a resin bag was removed and a new resin bag was installed in an adjacent location.

Within each unit at all three WMAs, four 10 gram samples of homogenized litter were ground to a fine powder prior to installation to establish initial nutrient values. These samples were analyzed by the Soil, Water, and Forage Analytical Laboratory (SWFAL) at Oklahoma State University for total nitrogen concentration (TN), total carbon concentration (TC), and lignin concentration. Dry combustion in a LECO TruSpec Carbon and Nitrogen Analyzer was used to quantify TN and TC (Bremner, 1996; Nelson and Sommers, 1996). Acid detergent fiber was determined using an Ankom Fiber Analyzer and subsequently dissolved by 72% sulfuric acid by weight to quantify lignin (ANKOM Technology, 2011; ANKOM Technology, 2013). Each collection of the litterbags was dried in the same way as the initial litter and carefully cleaned of any soil or organic matter that was present on the leaves. Each collection was similarly ground and analyzed by SWFAL for TN, TC, and lignin.

To process the resin bags, they were first rinsed in deionized water to remove loose soil on the exterior. To extract ammonium and nitrate from the beads, resin bags shook on a shaker table for 1 hour in 25 mL of 1 M KCl. After shaking, the extractant was filtered and neutralized by adding a 0.1 M NaOH solution to each sample until a neutral pH was reached. After neutralizing, samples were analyzed for ammonium and nitrate by SWFAL using a Lachat Flow Injection Auto-analyzer. Ammonium was measured using the salicylate method and nitrate was measured using the cadmium reduction method (Gavlak et al., 2003).

Additionally, each site was measured for canopy cover during the growing season using a spherical densiometer and basal area using a basal area 10 factor prism.

2.4. Post-Burn Experiment

In March 2013, the medium burn unit at Lexington was burned by the ODWC. This coincided at the time of the fourth collection. Due to the extra set of litterbags that were constructed at the beginning of the study, an opportunity presented itself to split the remaining litterbags between the recently burned unit and a similar unit, medium (post-burn) (Table 1). Litterbags were removed prior to the burn and replaced afterwards, half in the burned unit and half in the unburned unit. Although the litter had already been decomposing for a year, this smaller experiment allowed a glimpse into how the environment of a recently burned unit can affect litter decomposition rates and N dynamics in the soil.

2.5. Analysis

PROC MIXED in SAS 9.3 software was used for all statistical analyses. Each WMA was separately analyzed due to different burn frequencies. Mass remaining, TN, C:N, and lignin:N were analyzed using a split-split plot design with decomposition environment as the main plot, litter quality as a sub plot, and collection date as the sub-sub plot. Ammonium and nitrate were analyzed as a split plot design with decomposition environment as the main plot and collection date as the sub plot. If an interaction effect by collection date was found significant, then each collection date was further analyzed separately. Basal area, canopy cover, and initial litter quality variables were analyzed as a randomized complete block design. Mass remaining, TN, and C:N were also averaged across treatments for each WMA to examine overall trends at the WMA scale. These WMA variables were analyzed as a completely randomized design. PROC MEANS was used to compute means and standard errors for all variables. The least significant difference (LSD) test was used to determine if means were significantly different at $P < 0.05$. Linear regressions of TN, C:N, lignin:N, and percentage of blackjack oak compared against mass remaining were created in Sigma Plot 11.0 using the linear regression tool.

3. Results

3.1. Initial Litter Quality

Initial litter quality differences among treatment units were inconsistent among WMAs. Prescribed fire did not significantly affect initial litter TN, C:N, and lignin:N at Okmulgee WMA (Table 2). At Cherokee WMA, TN was significantly lower at the medium burn unit than the other treatments, C:N was significantly higher at the medium burn unit than the other treatments, while lignin:N was significantly lower at the control unit than the other treatments. At Lexington WMA, the high burn unit had significantly higher TN and significantly lower C:N than the other treatments. The control unit had significantly higher lignin:N compared to all other treatments.

3.2 Decomposition Environment

Very few decomposition environment differences were observed among WMAs. Canopy cover and basal area were not significantly different among treatments at Okmulgee WMA (Table 3). At Cherokee WMA, the medium burn unit had significantly lower canopy cover than the control unit with the high burn unit not significantly different from either. Basal area was not significantly different among treatments. At Lexington WMA, the medium (post-burn) unit had significantly lower canopy cover and basal area. The high burn unit's basal area was not significantly different from any treatments.

3.3. Litter Decomposition

Litter decomposition did not exhibit any high-order interactions. There was no significant three-way interaction between decomposition environment, litter quality, and collection date at all three WMAs (Tables 4, 5, and 6).

Overall, decomposition environment exhibited few differences in litter decomposition among treatments. Okmulgee WMA had a significant interaction for decomposition environment by collection date whereas the other WMAs had no significant interactions or decomposition environment main effects. The high burn environment litter at Okmulgee WMA decomposed significantly faster than the medium burn environment litter for the third and fourth collections while the control environment litter decomposed significantly faster for the fifth collection than the other two treatments (Figure 4).

Litter quality showed a few trends though they were conflicting at different WMAs. A significant interaction between litter quality and collection date was observed at Okmulgee WMA and Lexington WMA while Cherokee WMA was non-significant for both interaction and litter quality main effect (Tables 4, 5, and 6). At Okmulgee WMA, the high burn litter decomposed at a significantly slower rate from the second through the fourth collection while the medium burn litter decomposed significantly faster on the fifth collection (Figure 5). At Lexington WMA, on the second collection, the control litter decomposed significantly slower than the other two litters. On the third and fourth collection, the control litter decomposed significantly slower than only the high burn litter. For the final collection, the high burn litter decomposed significantly faster than the other litters.

Additionally, to ensure that the proportions of post oak to blackjack oak in the litter was not a confounding factor in decomposition, final mass remaining versus percentage of blackjack oak was analyzed by linear regression to determine if a relationship exists. No significant relationship was observed (Figure 6).

Another confounding factor that was examined is the home-field advantage which is defined as litter decomposing at a faster rate in its own decomposition environment or where the litter originated. This effect would have been indicated by a three-way interaction between decomposition environment, litter quality, and collection date. The three-way interaction was non-significant at all three WMAs (Tables 4, 5, and 6).

3.4. Litter Chemistry

All litter quality variables displayed no high-order interactions. At all three WMAs, there were no significant three-way interactions between decomposition environment, litter quality, and collection date for TN, C:N, and lignin:N (Tables 4, 5, and 6).

Decomposition environment had no effect on litter TN. All three WMAs showed no significant interactions between decomposition environment and collection date as well as no significant decomposition environment main effects (Tables 4, 5, and 6).

Litter quality had an effect on litter TN. A significant interaction between litter quality and collection date was observed at Okmulgee WMA and Lexington WMA while Cherokee WMA was non-significant (Tables 4, 5, and 6). The medium burn litter at Okmulgee WMA had a significantly higher TN than the high burn litter on the first collection and a significantly higher TN than the other two litters for the second through the fifth collection (Figure 8). At Lexington WMA, the high burn litter had significantly higher TN than the control litter on the fifth collection. At Cherokee WMA, medium burn litter TN had a significant main effect of being lower than the other two litters.

Litter C:N showed a lack of response to decomposition environment. At all three WMAs, there were no significant interactions between decomposition environment and collection date, in addition to no significant decomposition environment main effects (Tables 4, 5, and 6).

Litter quality exhibited several trends for litter C:N. An interaction between litter quality and collection date was significant at only Cherokee WMA and the other two WMAs it was non-significant (Tables 4, 5, and 6). At Cherokee, the medium burn litter had significantly higher C:N than the other two litters for the first through third collection. At Okmulgee WMA, the main effect was significant for all litter qualities being different from each other in the following order of decreasing C:N: high burn, control, medium burn (Figure 10). At Lexington WMA, there was a significant litter quality main effect of the high burn litter C:N being lower than the other two litters.

Decomposition environment affected litter lignin:N in only a few cases. An interaction between decomposition environment and collection date was observed only at Lexington WMA with the other two WMAs non-significant (Tables 4, 5, and 6). At Lexington WMA, the high burn litter lignin:N was significantly lower than the other two litters on the third collection and the high burn litter lignin:N was significantly higher than the medium burn litter on the fourth collection (Figure 11). No significant decomposition environment main effects were found at Okmulgee WMA or Cherokee WMA.

Litter quality played a major role in litter lignin:N differences among treatments. All three WMAs had a significant interaction between litter quality and collection date (Tables 4, 5, and 6). At Okmulgee WMA, the high burn litter lignin:N was significantly higher than the other treatments for the first through fourth collection (Figure 12). The medium burn litter lignin:N was significantly lower than the other treatments for all collections, except for the second collection. At Cherokee WMA, the medium burn litter lignin:N was significantly higher than the other treatments for all collections except the fifth collection where it was only significantly higher than the control litter. At Lexington WMA, the control litter lignin:N was significantly higher than the other treatments for the second collection and higher than only the high burn litter for the third and fifth collections.

3.5. Resin Bags

Bioavailable N was highly variable within treatment units and few differences were observed among treatment units. At all three WMAs, no significant interactions between decomposition environment and collection date were detected for soil ammonium as well as no significant decomposition environment main effects (Figure 13). For nitrate, Lexington WMA had the only significant interaction between decomposition environment and collection date while the other two WMAs were non-significant (Figure 14). At Lexington WMA, the medium burn unit had significantly higher nitrate than the other treatments on the second collection. Cherokee WMA had a significant main effect with the control unit nitrate higher than the high burn unit. Okmulgee WMA had a non-significant decomposition environment main effect.

3.6. Post-Burn Experiment

Comparing litterbags placed in an unburned unit with the same historical burn frequency to those in a recently burned unit at Lexington WMA, no significant differences were observed (Table 7). Mass remaining, TN, C:N, and lignin:N all showed no significant differences between the two treatments. Soil ammonium was over 6 fold greater in the burned unit than the unburned unit. Soil nitrate was not significantly different among the two treatments.

3.7. Regression Analysis

Results of the linear regressions indicated strong relationships of litter mass remaining to litter quality variables. Mass remaining showed a strong negative relation to TN (Figure 15), a strong positive relation to C:N (Figure 16), and a positive relation to lignin:N (Figure 17). Mass remaining was most strongly related to C:N and least to lignin:N.

3.8. General Trends

When litter data was averaged across treatments within WMAs, the results yielded interesting comparisons. Mass remaining was 3% lower at Okmulgee WMA than the other two WMAs after 15 months (Table 8). Initially before litterbag installation, Lexington WMA litter had significantly higher TN and significantly lower C:N than the other WMAs. At the end of the study, all three WMAs had converged to very similar non-significant values for TN and C:N.

Across all WMAs, litter TN increased over 60% from an initial content of 0.80% to 1.29% while litter C:N decreased from 60 to 35 and litter lignin:N decreased from 33 to 26 (Figures 7-12). Litter mass loss decreased linearly other than during the period of the fourth collection (December-March) when mass loss was flat; this corresponded with the period when temperatures were at their lowest (Figures 4, 5, and 18). Soil ammonium and nitrate spiked during the second collection (June-September) and a smaller spike during the fifth collection (March-June) that coincided with the warmer periods of the year (Figures 13, 14, and 18). Despite fairly consistent overall trends in ammonium and nitrate, the magnitude over WMAs is quite different. Lexington WMA had a huge spike on the second collection compared to the other two WMAs and Okmulgee WMA had much higher nitrate than the other WMAs on the fourth and fifth collections.

4. Discussion

4.1. Decomposition Environment

Across all WMAs and all collections, decomposition environment generally had no effect on decomposition or litter quality variables. The absence of a treatment environment effect on decomposition can be explained when comparing the treatment unit's canopy cover and basal area in Table 3. Very few differences exist suggesting that the low-intensity and low-severity of these prescribed fires are not modifying the structure of the forest. Therefore, the litter microclimate is similar at all treatment units regardless of fire frequency. Thus, the hypothesis of treatment units becoming more open and warmer as fire frequency increases is not supported.

The finding of an absence of a decomposition effect by decomposition environment was similar to what Hernández and Hobbie (2008) observed in a study conducted in Minnesota even though they found differences in the canopy cover along a fire frequency gradient. They speculated the lack of decomposition response to more open, higher fire frequency sites was the opposing forces of higher temperature and lower moisture in the litter layer that together equaled no net effect. Another study in semi-arid Africa found increasing canopy cover slowed decomposition suggesting photodegradation was a major factor in differences observed (Mlambo and Mwenje 2010). Conversely, research in British Columbia saw decreased pine litter decomposition in areas that were in a clearcut opening (Prescott et al. 2000). Mixed results of previous research demonstrate the multitude of environmental factors affecting decomposition and the site specific responses.

4.2. Litter Quality

Initial litter quality did not show evidence of being affected by increasing fire frequency. A high fire frequency would be expected to show reduced litter TN. This effect was not observed suggesting these low-intensity prescribed fires were not hot enough to volatilize measurable amounts of N. As a result, fire was not the primary driver for the differences observed in initial litter quality.

Decomposition exhibited responses to litter quality though the responses varied depending on the WMA. The high burn unit litter at Okmulgee WMA decomposed the slowest while the control unit litter at Lexington WMA decomposed the slowest (Figure

5). These inconsistent trends suggest a factor other than initial litter quality was responsible for the differences observed.

Despite fire not being a clear driver in the rate of decomposition, litter quality may explain the differences in rates of decomposition observed at Okmulgee WMA. The high burn unit at Okmulgee WMA decomposed the slowest and also had the lowest litter quality over time (Figures 5, 8, 10, and 12). The linear regressions of mass remaining by litter quality variables revealed mass remaining had a strong negative relation with TN and a strong positive relation with C:N suggesting that as decomposition proceeds litter quality improves and this may have positive implications for further decomposition (Figures 15 and 16).

Pinpointing the litter quality variable most important in the rate of decomposition is useful because different drivers are found across different ecosystems. Melillo et al. (1982) found lignin:N to be the main driver in decomposition in a Northeast hardwood forest. Another study in Minnesota found that C:N was the primary driver in decomposition (Hernández and Hobbie 2008). In the Missouri Ozarks, research showed that lignin:N and TN had the strongest relationship with mass loss (Li et al. 2009). A large synthesis of 110 litter decomposition studies found that N, P, K, Ca, Mg, and C:N explained 70.2% of the variation in litter decomposition rates (Zhang et al. 2008). A study in the southeast United States found TN and C:N to be the main drivers in decomposition (Silveira et al. 2011). Clearly, determining a general primary driver for rates of decomposition is difficult and each ecosystem has drivers that are unique to its environment. In our study, the lack of a clear effect of litter quality determining decomposition rates underscores the strong likelihood that another mechanism is responsible for decomposition rate differences observed.

4.3. Bioavailable Nitrogen

Soil available ammonium and nitrate showed no clear differences among treatment units across WMAs. It was predicted that a lower amount of ammonium and nitrate would be observed as fire frequency increased. Observing no long-term effect on bioavailable N further reinforces the implication that fire is not affecting this system in any profound way. This finding also supports the lack of differences observed in the initial litter quality; if there are no differences in the soil N between treatments then no differences would be expected with tree uptake and subsequently litter N.

One resin bag was present at each sample site for a total of four per treatment unit; this may have been too few samples to accurately depict the bioavailable N in each unit, especially with the high variability among resin bags. This was further exacerbated as some resin bags were unearthed throughout the study, presumably by small mammals, and these resin bags were not included in the mean calculations.

Other studies have reported mixed results in bioavailable N as a result of fire. A study in Kruger National Park, South Africa reported no change in soil N with varying fire frequencies (Coetsee et al. 2010). Their explanation was the relatively low amount of N volatilized in fire was balanced by N fixation and wet deposition resulting in no net long-term change. In research conducted at Cedar Creek Long-Term Ecological Research

Station in Minnesota, bioavailable N was shown to decrease as fire frequency increased (Hernández and Hobbie 2008). A study in a southwestern Oregon conifer forest observed substantial soil N loss during fire and noted that burn severity was strongly correlated with the magnitude of N loss (Homann et al. 2011).

Despite not finding differences in bioavailable N between treatments, differences were observed in the post-burn experiment. The flush of ammonium in the recently burned unit appears to not have an effect on long-term litter quality; therefore, more examination is needed to determine the fate of the soil N increase. Possible explanations include, but are not limited to: leaching from the soil, uptake by the herbaceous layer or trees, and/or bonding with soil organic matter and clay particles rendering the N inaccessible to plants.

4.4. Fire's Impact

The fire regime was expected to influence the ecosystem in a similar way that Hernández and Hobbie (2008) observed in Minnesota (Figure 1). Nitrogen volatilizes in fire, reducing tree uptake and litter N. This lower litter quality causes greater immobilization that results in less soil N available and more N consumed when a fire returns. This process is a positive feedback loop further intensifying N loss than just N volatilization alone. In our study, none of these processes were observed indicating that either fire is not volatilizing measurable amounts of N from this system or that any N volatilized is offset by microbial fixation or nitrogen-fixing legumes.

Examining the results, it becomes clear that fire does not strongly influence decomposition. Prescribed fires at the three WMAs are conducted under very mild weather conditions: moderate temperatures, low wind speed, and moderate relative humidity. As a result of these conditions, fires are of low-intensity and low-severity. When fires are of low-intensity the flame temperatures are lower, resulting in less N volatilized (Knicker 2007), or in the case of our study, an undetectable amount. Another potential reason N loss might not have been detected is because N volatilization could have been offset by microbial N fixation as was speculated in a South African study (Coetsee et al. 2010) or by the increased presence of nitrogen-fixing legumes in higher fire frequency units as was observed in a prior Cross Timbers study (Burton 2009). These low-severity fires may also not reach the temperatures needed to cause mortality in trees. If the fires are not altering tree recruitment rate, then the canopy cover and basal area would be expected to remain the same as was observed in Table 3 with decomposition consequently unaffected.

Fire is often thought of as a homogenous force that moves across the landscape unchecked, but in current prescribed burning that is far from the truth. Fire is inherently patchy (Turner 2010), yet in our study the assumption was made that all units burned completely and homogenously. The problem in doing this was some sample points that were thought to be a high burn, for example, might have had some fires not burn that sample point, in effect, skewing the results. A higher sampling size might have ameliorated this effect.

Another consideration is the length of fire regime. These WMAs have had a prescribed burning regime for 24-29 years. The study by Hernández and Hobbie (2008) at Cedar Creek Long-Term Ecological Research Station observed strong relationships among soil N, immobilization rates, and decomposition along an increasing fire gradient. The difference between their study and our study is the prescribed burning regime was a decade longer at Cedar Creek Long-Term Ecological Research Station. Perhaps prescribed fire has not been present in these Oklahoma WMAs long enough for a measurable amount of N to be volatilized from the system to affect processes.

4.5. Lexington WMA Land Use History

Lexington WMA had a few unexpected results: the initial litter N at the high burn unit was very high, the control litter decomposed the slowest, and the initial lignin:N started out much lower than the subsequent collections. These might be explained by land use history. Compared to Okmulgee and Cherokee WMAs (old-growth Cross Timbers), Lexington WMA has much younger trees and more even-aged stands, suggesting relatively recent disturbances (personal observation).

In the late 1800s, the area where Lexington WMA sits was settled in the Oklahoma Land Run. Cotton was primarily farmed in this region with possible tillage and fertilizing effects. Fertilizer applications could have increased N availability. Tillage could have increased mineralization of N (Lupwayi et al. 2006). In 1941, 2/3 of the current WMA was condemned by the United States War Department for use as a Naval Bombing Range during World War II. This included the high burn unit that had very high initial litter TN values. In 1949, the majority of the Naval Bombing Range was deeded to ODWC for use as a WMA. The medium burn unit was a ranch that was later acquired in the 1960s (Rex Umber, personal communication). Grazing has been shown to increase soil organic matter C:N resulting in an N limited system (Piñeiro et al. 2010). The control unit has always been private land making it difficult to determine land use history, but similar land use is likely because of the prevalence of even-aged stands and young trees.

A report containing an erosion map of Oklahoma showed that Lexington WMA is located in the most severely eroded area in the entire state (Oklahoma Conservation Commission 2002). When the topsoil layer is lost, fundamental changes can take place with nutrient cycling as well as plant uptake responses. Recent research found soil carbon at 0–20 cm was 40% higher at Okmulgee WMA and 90% higher at Cherokee WMA than at Lexington WMA. The same study found soil nitrogen at 0–20 cm was 50% higher at Okmulgee WMA and 80% higher at Cherokee WMA than at Lexington WMA (Dustin Logan, personal communication). If the soils at Lexington WMA were degraded by agriculture as the historical record and these data suggest, that may explain the seemingly inconsistent results.

4.6. Management Implications

Due to prescribed fire's lack of effect on the rate of decomposition observed in our study, land managers in the Cross Timbers should be able to manipulate fire frequency with no effect on decomposition rates, though this statement has a few caveats. The highest burn frequency in all of the WMAs was at Okmulgee WMA where burns occurred approximately every other year. An increase in the burn frequency to annual burning might begin to alter the rate of decomposition. The low-intensity and low-severity of these fires could also be a factor in the lack of a response. If land managers increased the intensity of prescribed fires through lower moisture fine fuel loads and changing the seasonality to growing season burns, decomposition rates could greatly differ due to stand modifications as well as increased fire temperatures (Twidwell et al. 2013).

4.7. Further Research

The hypothesis that fire was the mechanism driving changes in decomposition was not supported by the results, though fire could be affecting decomposition in an unexplored indirect way. One suggested avenue of further research would be to determine the mechanism for differences observed in litter quality decomposition rates. Potential variables that could explain differences include abundance of saprophytic fungi on litter, differences in initial litter P, and differences in microbial colonization on litter.

Second, exploring the fate of the nitrogen flush observed at Lexington WMA in the post-burn experiment would help elucidate nutrient cycling in this ecosystem. Possible outcomes for the nitrogen flush include uptake by the herbaceous layer, leaching from the system, and/or forming bonds with soil organic matter and clay particles becoming inaccessible to plants.

A final direction for subsequent research would be examining the responses of litter decomposition under a more intense or severe burning regime. The lack of responses observed in our study could be a function of the fires simply not being hot enough or frequent enough to elicit a response. Burning at lower fuel moisture, burning in the growing season, or under higher wind speeds could change the decomposition environment as well as litter quality resulting in a decomposition rate change.

4.8. Conclusion

Even at 4.6 fires per decade, prescribed fire does not modify the decomposition environment or the litter quality enough to affect decomposition in this system. The low-intensity of these fires might not create the heat needed to volatilize measurable amounts of nitrogen or modify the structure of the forest. The effect of litter quality on decomposition rates could be explained by some other unexplored variable such as saprophytic fungi, litter P, or soil microbial communities.

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TABLES

Table 1. Burn history of selected units in three wildlife management areas.

Unit	Total Fires	Fires Per Decade	Years Since Last Fire
Okmulgee WMA			
High	11	4.6	1
Medium	5	2.1	1
Control/no burn	0	0	24+
Cherokee WMA			
High	8	2.8	1
Medium	5	1.7	3
Control/no burn	0	0	29+
Lexington WMA			
High	7	2.7	4
Medium (post-burn)[1]	5	1.9	4
Medium (pre-burn)[2]	4	1.5	4
Control/no burn	0	0	26+

[1] The litterbags from Medium (pre-burn) were relocated to Medium (post-burn) for the final collection due to a prescribed burn.
[2] Burn history shown does not reflect the burn that occurred near the end of the experiment.

Table 2. Initial litter quality of homogenized units prior to installation of litterbags. Values shown are means ± 1 standard error. Means followed by different letters in columns are significantly different (P<0.05, LSD) for each respective wildlife management area.

Unit	TN (%)	C:N	Lignin:N
	Okmulgee WMA		
High	0.78 ± 0.04	61.06 ± 3.57	34.40 ± 2.43
Medium	0.78 ± 0.05	60.29 ± 3.63	30.24 ± 1.79
Control	0.76 ± 0.03	62.64 ± 2.74	38.28 ± 4.01
	Cherokee WMA		
High	0.79 ± 0.03 a	60.34 ± 2.35 b	38.63 ± 2.02 a
Medium	0.70 ± 0.02 b	67.35 ± 1.27 a	41.17 ± 1.20 a
Control	0.83 ± 0.02 a	57.45 ± 1.85 b	31.71 ± 0.82 b
	Lexington WMA		
High	0.94 ± 0.04 a	50.93 ± 1.88 b	24.13 ± 1.41 b
Medium	0.78 ± 0.01 b	60.64 ± 0.96 a	27.80 ± 0.76 b
Control	0.79 ± 0.03 b	59.68 ± 1.55 a	33.75 ± 1.96 a

Table 3. Decomposition environment characteristics of units. Values shown are means ± 1 standard error. Means followed by different letters in columns are significantly different (P<0.05, LSD) for each respective wildlife management area.

Unit	Canopy Cover (%)	Basal Area (m^2/ha)
	Okmulgee WMA	
High	81.8 ± 1.3	29.3 ± 2.7
Medium	87.2 ± 2.6	30.5 ± 3.8
Control	85.6 ± 1.3	25.9 ± 0.6
	Cherokee WMA	
High	86.4 ± 2.1 ab	29.9 ± 1.9
Medium	84.5 ± 1.0 b	21.3 ± 3.4
Control	90.6 ± 1.2 a	28.8 ± 4.5
	Lexington WMA	
High	83.7 ± 3.0 a	25.9 ± 2.2 ab
Medium (pre-burn)	84.1 ± 1.3 a	29.3 ± 0.6 a
Medium (post-burn)	75.8 ± 2.7 b	21.3 ± 2.0 b
Control	87.5 ± 0.9 a	27.6 ± 2.3 a

Table 4. Results of litterbag split-split plot analysis for Okmulgee WMA. DE=decomposition environment, LQ=litter quality, CD=collection date

		Mass Remaining	TN	C:N	Lignin:N
Source of Variation	**DF**	**P-value**	**P-value**	**P-value**	**P-value**
DE	2	0.1282	0.6246	0.1643	0.2720
LQ	2	<0.0001	<0.0001	<0.0001	<0.0001
CD	5	<0.0001	<0.0001	<0.0001	<0.0001
DE*LQ	4	0.4150	0.9378	0.9715	0.9998
DE*CD	10	0.0004	0.5616	0.8525	0.3330
LQ*CD	10	0.0265	0.0158	0.0729	0.0069
DE*LQ*CD	20	0.9894	0.9004	0.9842	0.9531

Table 5. Results of litterbag split-split plot analysis for Cherokee WMA. DE=decomposition environment, LQ=litter quality, CD=collection date

		Mass Remaining	TN	C:N	Lignin:N
Source of Variation	**DF**	**P-value**	**P-value**	**P-value**	**P-value**
DE	2	0.1302	0.0670	0.1050	0.2238
LQ	2	0.2136	<0.0001	<0.0001	<0.0001
CD	5	<0.0001	<0.0001	<0.0001	<0.0001
DE*LQ	4	0.4248	0.1849	0.1743	0.2635
DE*CD	10	0.0594	0.3444	0.3944	0.2011
LQ*CD	10	0.5369	0.8283	0.0266	<0.0001
DE*LQ*CD	20	0.8423	0.5551	0.7820	0.9379

Table 6. Results of litterbag split-split plot analysis for Lexington WMA. DE=decomposition environment, LQ=litter quality, CD=collection date

		Mass Remaining	TN	C:N	Lignin:N
Source of Variation	**DF**	**P-value**	**P-value**	**P-value**	**P-value**
DE	2	0.8639	0.8956	0.8868	0.8120
LQ	2	0.0002	0.0159	0.0157	<0.0001
CD	5	<0.0001	<0.0001	<0.0001	<0.0001
DE*LQ	4	0.2011	0.5766	0.6473	0.2195
DE*CD	10	0.7779	0.4109	0.2567	0.0182
LQ*CD	10	0.0170	0.0102	<0.0001	0.0023
DE*LQ*CD	20	0.0729	0.9610	0.8968	0.7702

Table 7. Litterbag and resin bag comparison of burned and unburned units at Lexington WMA during final three month period. Values shown are means ± 1 standard error. Means followed by different letters in columns are significantly different (P<0.05, LSD).

Unit	Mass Remaining (%)	TN (%)	C:N	Lignin:N	Ammonium (ppm)	Nitrate (ppm)
Burned	72.36 ± 0.90	1.29 ± 0.02	33.70 ± 0.65	25.75 ± 0.48	16.57 ± 4.37 a	37.27 ± 22.20
Unburned	71.46 ± 1.07	1.27 ± 0.03	35.22 ± 0.74	25.24 ± 0.69	2.58 ± 0.46 b	6.41 ± 1.19

Table 8. Litter mass remaining and initial/final litter quality variables averaged over all treatment units for each wildlife management area. Values shown are means ± 1 standard error. Means followed by different letters in columns are significantly different (P<0.05, LSD).

	Mass Remaining (%)	Initial TN (%)	Final TN (%)	Initial C:N	Final C:N
Okmulgee WMA	69.93 ± 0.69 b	0.77 ± 0.01 b	1.26 ± 0.03	61.33 ± 0.99 a	35.53 ± 0.75
Cherokee WMA	73.37 ± 0.68 a	0.78 ± 0.01 b	1.30 ± 0.02	61.72 ± 0.89 a	35.09 ± 0.51
Lexington WMA	72.29 ± 0.97 a	0.84 ± 0.02 a	1.30 ± 0.02	57.08 ± 0.86 b	34.53 ± 0.53

FIGURES

Figure 1. Diagram of a positive feedback loop for nitrogen that demonstrates through the use of fire, nitrogen reduction is reinforced and becomes less bioavailable to the system. Adapted from Hernández and Hobbie 2008.

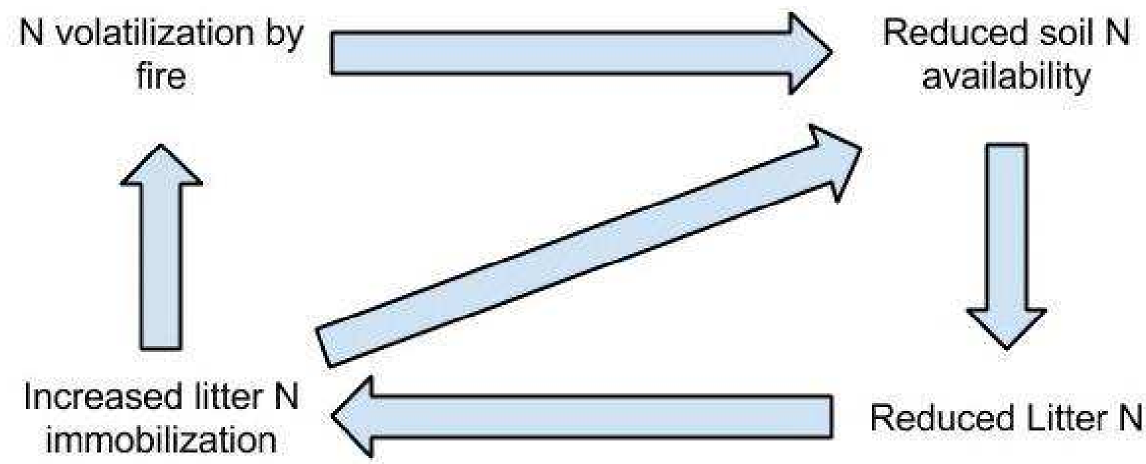

Figure 2. Map of Oklahoma Cross Timbers showing locations of three study areas.

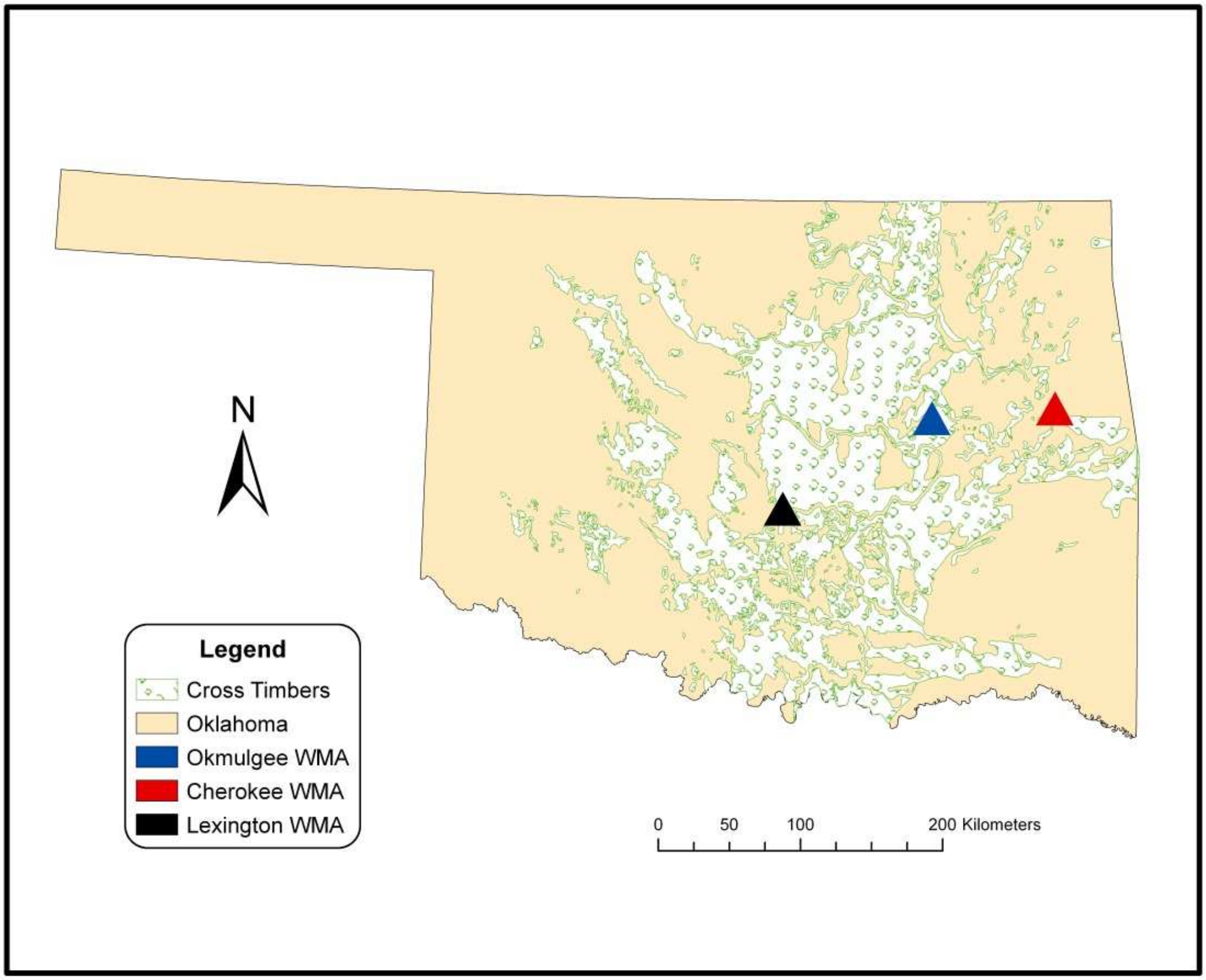

Figure 3. Diagram of litterbag and resin bag site establishment. High, Medium, and Control indicate the litter origin. Numbered columns denote randomly selected collections.

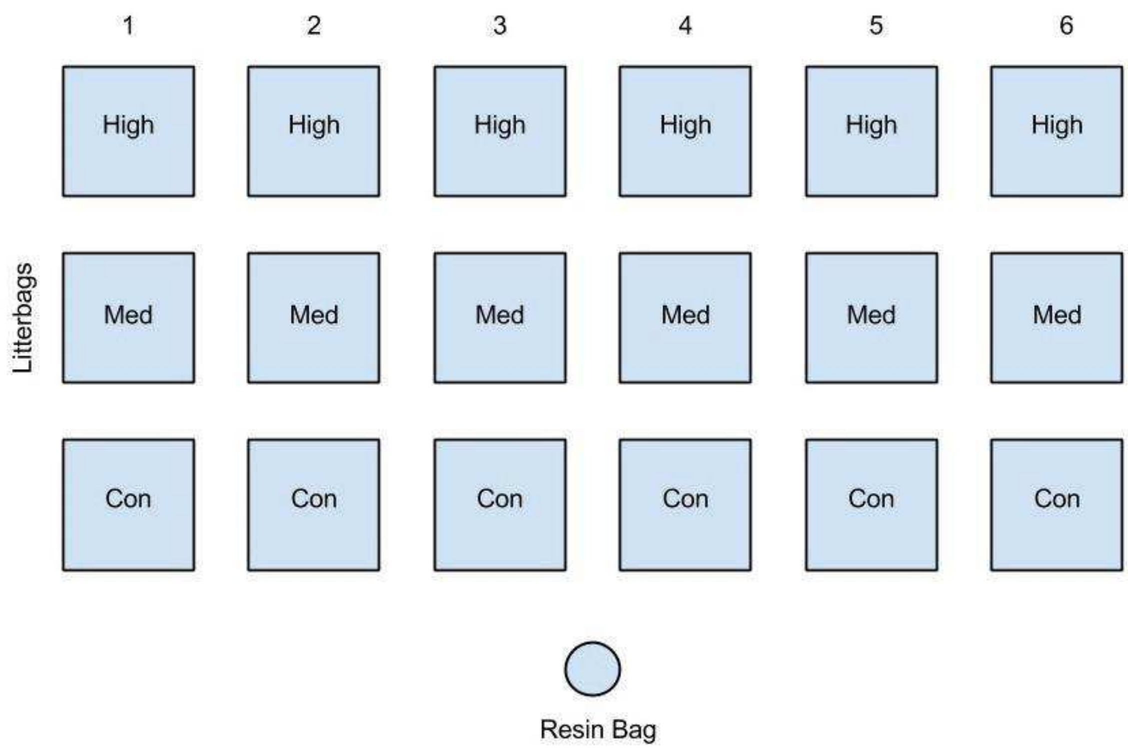

Figure 4. Litter mass remaining by decomposition environment over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

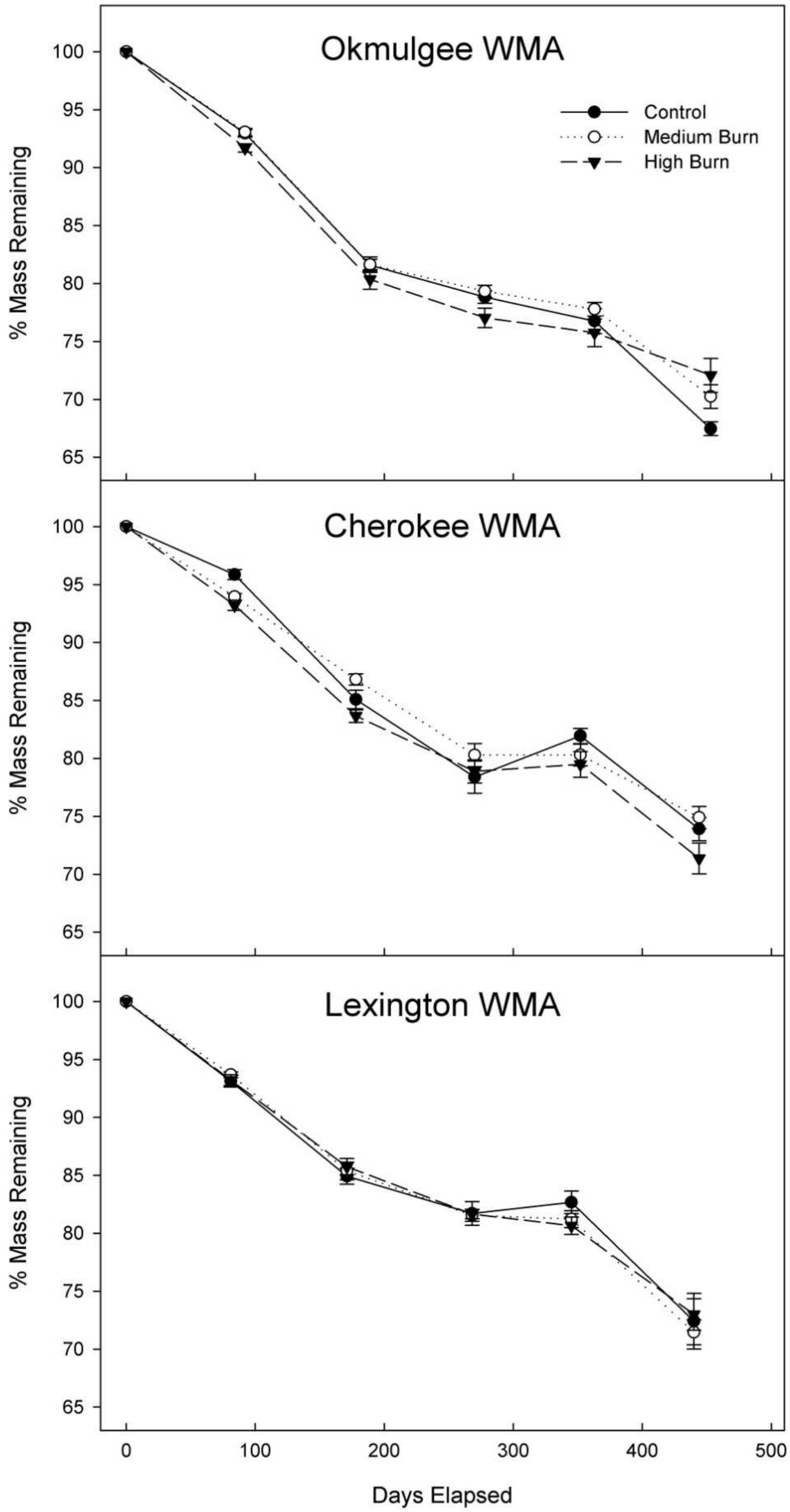

Figure 5. Litter mass remaining by litter quality over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

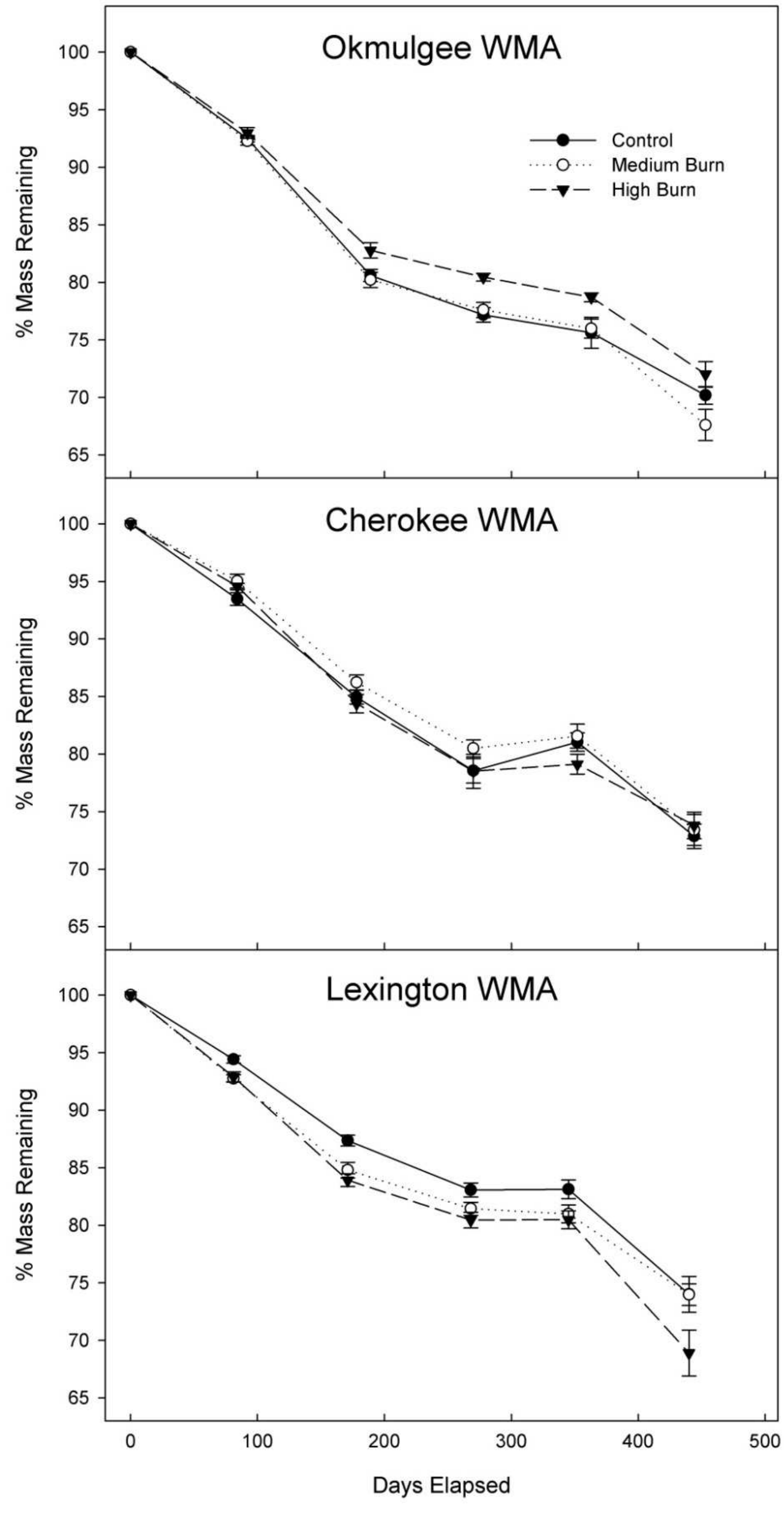

Figure 6. Relation of litter mass remaining after 15 months to percentage blackjack oak in litterbags at three wildlife management areas. Regression line not shown due to non-significance.

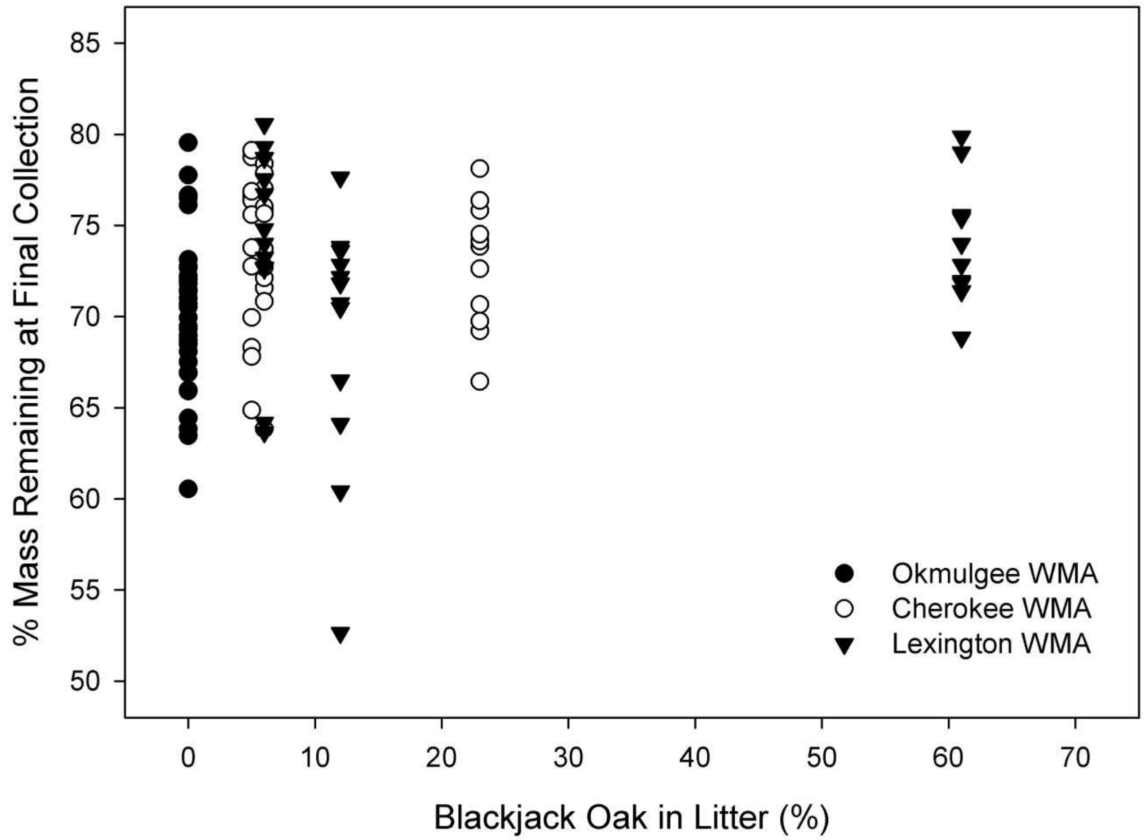

Figure 7. Litter total N by decomposition environment over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

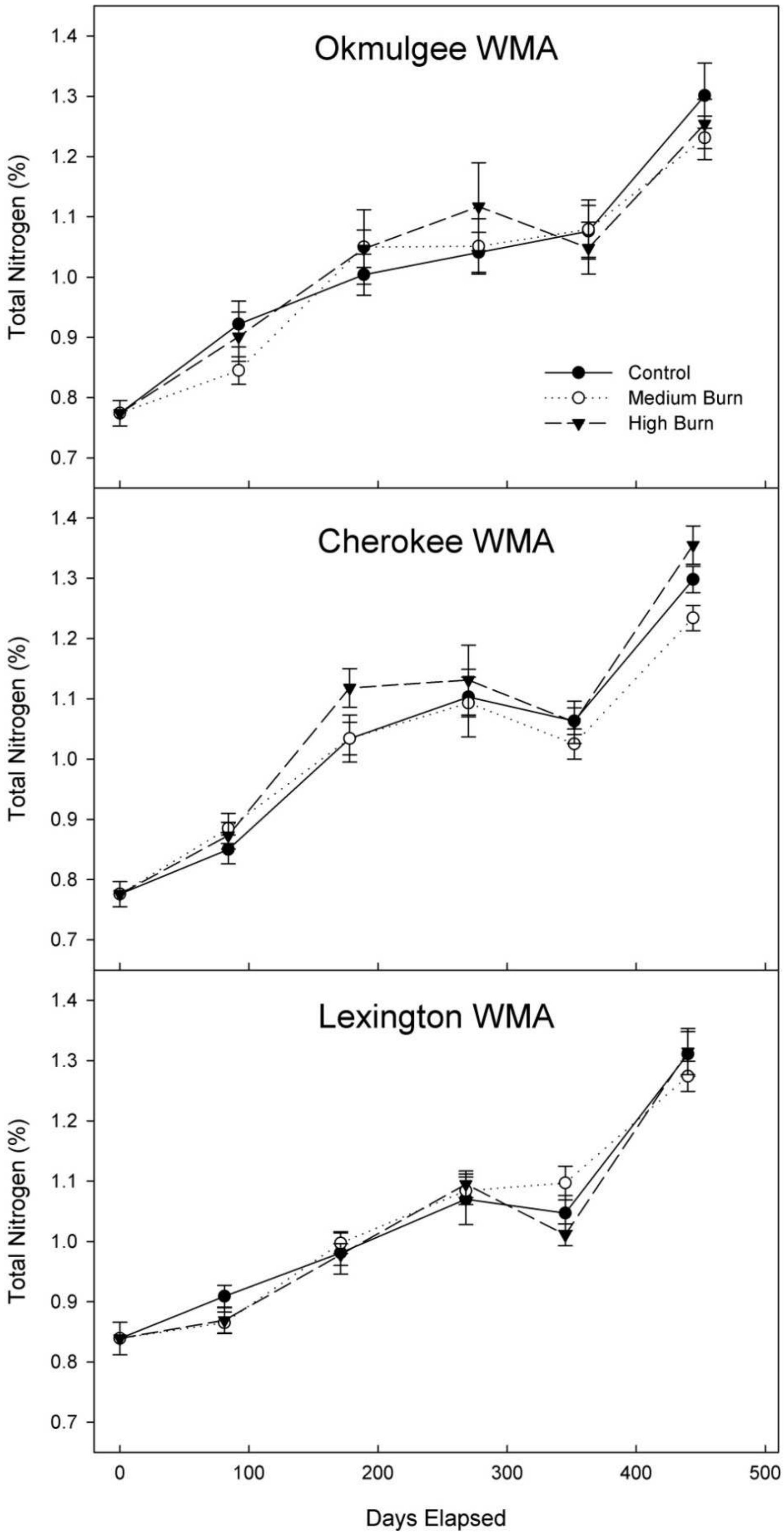

Figure 8. Litter total N by litter quality over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

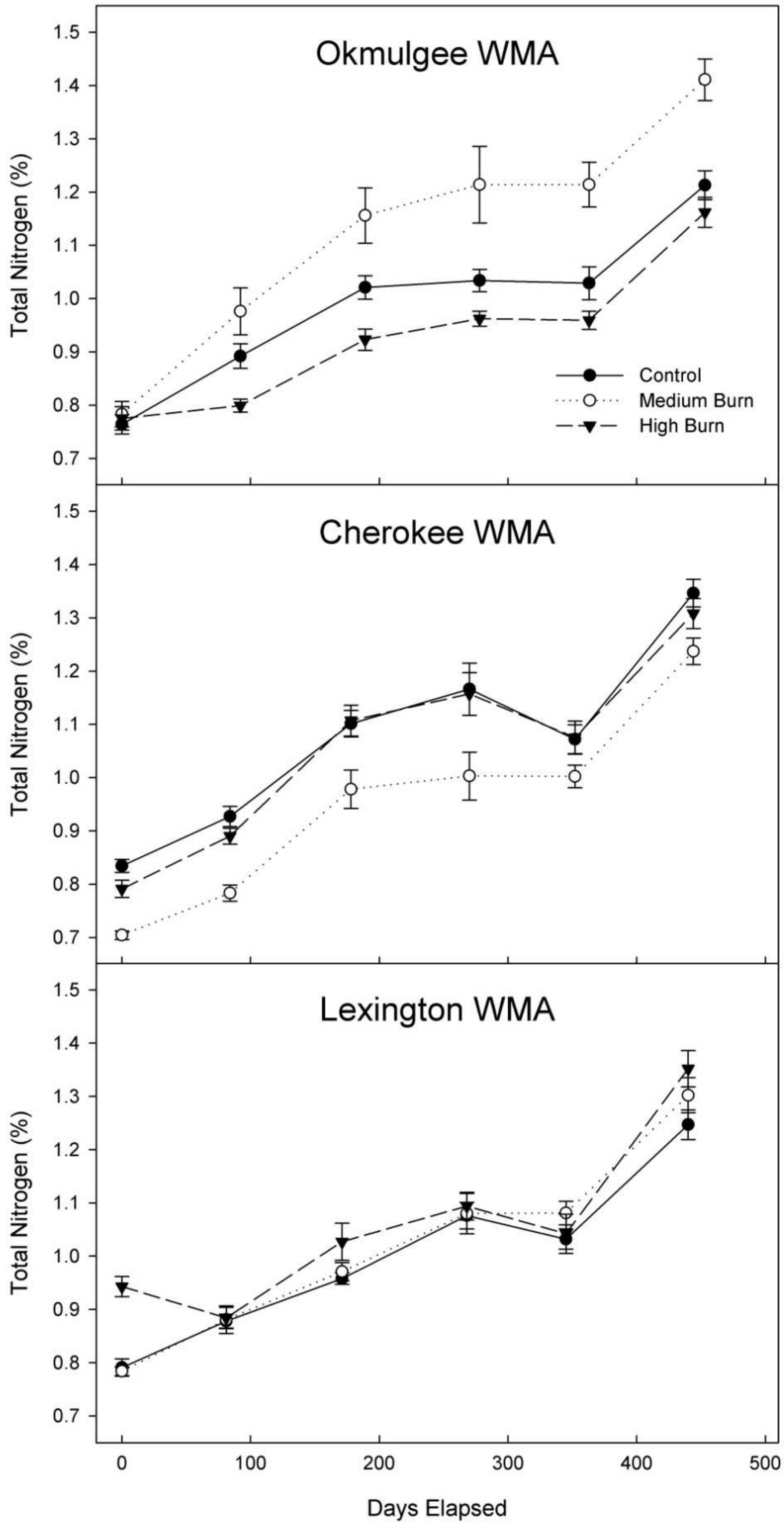

Figure 9. Litter C:N by decomposition environment over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

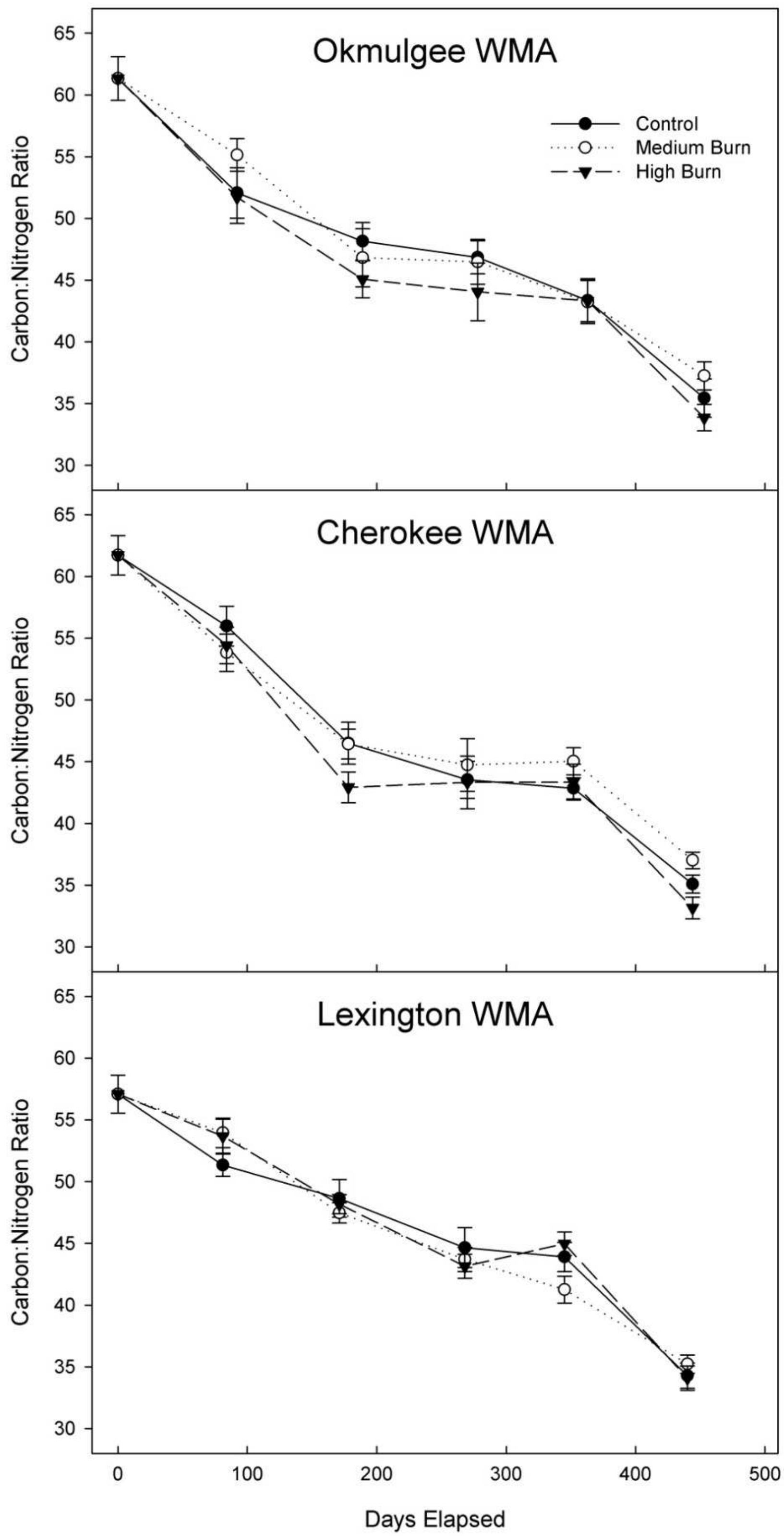

Figure 10. Litter C:N by litter quality over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

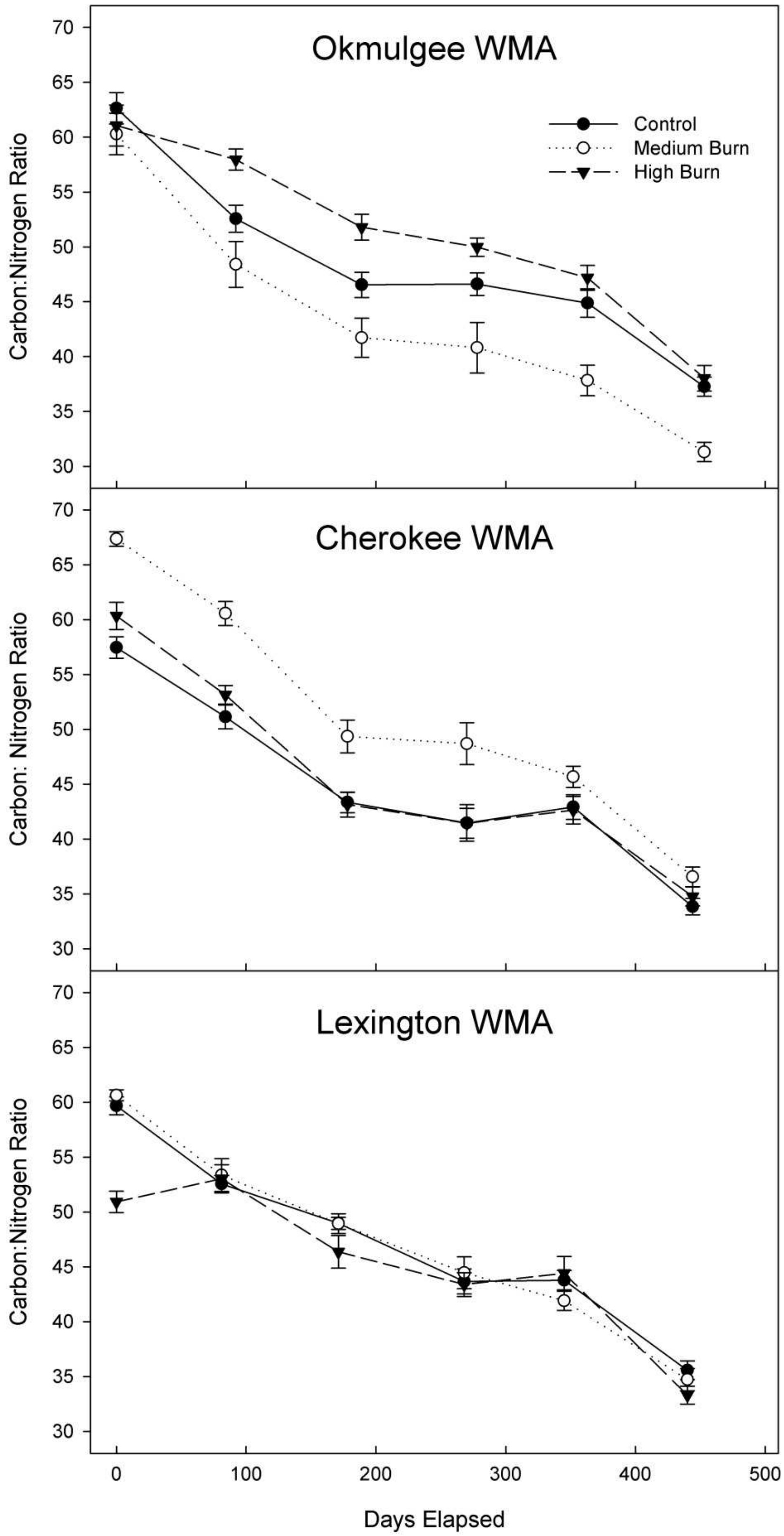

Figure 11. Litter lignin:N by decomposition environment over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

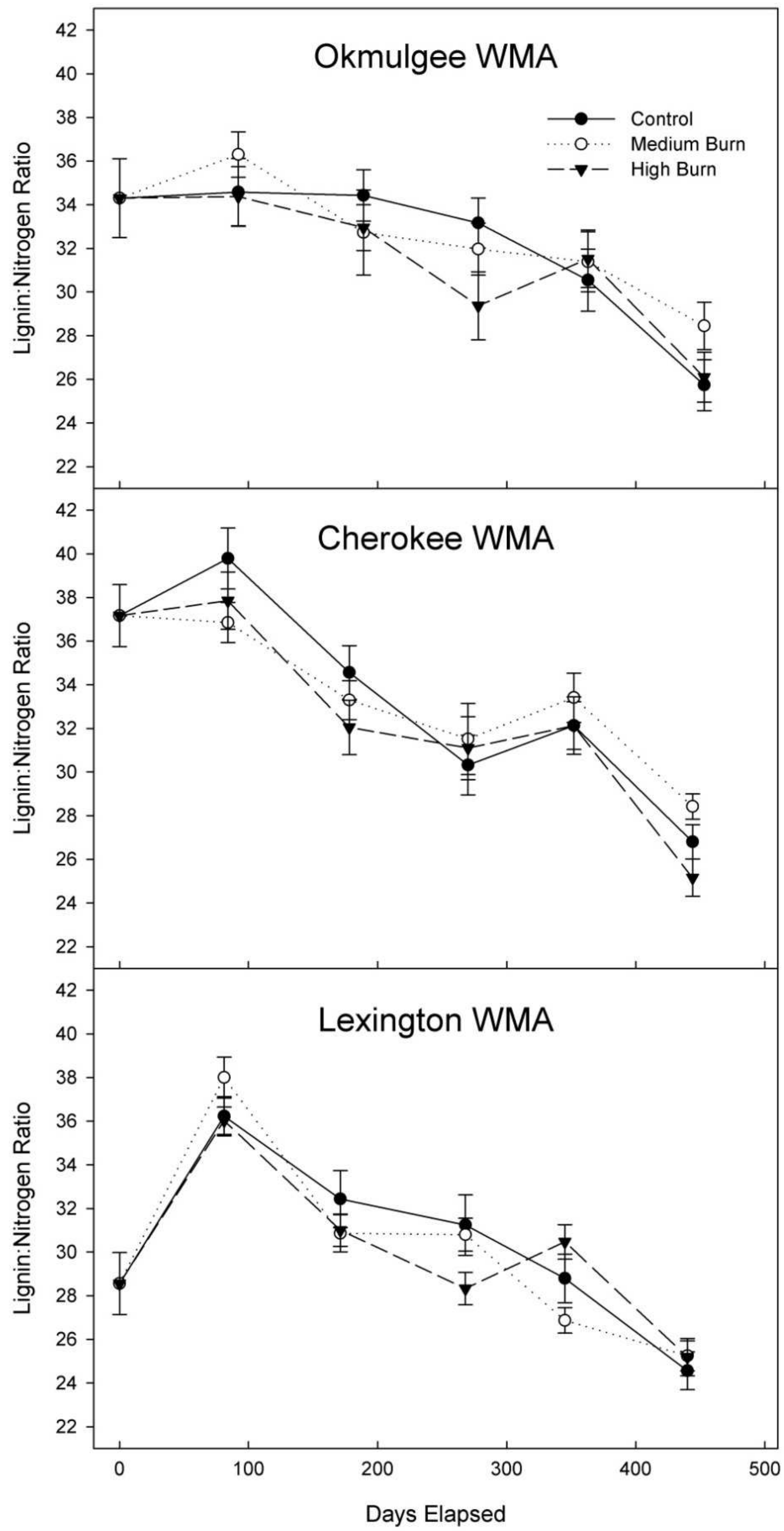

Figure 12. Litter lignin:N by litter quality over five collections at three wildlife management areas. Values shown are means ± 1 standard error.

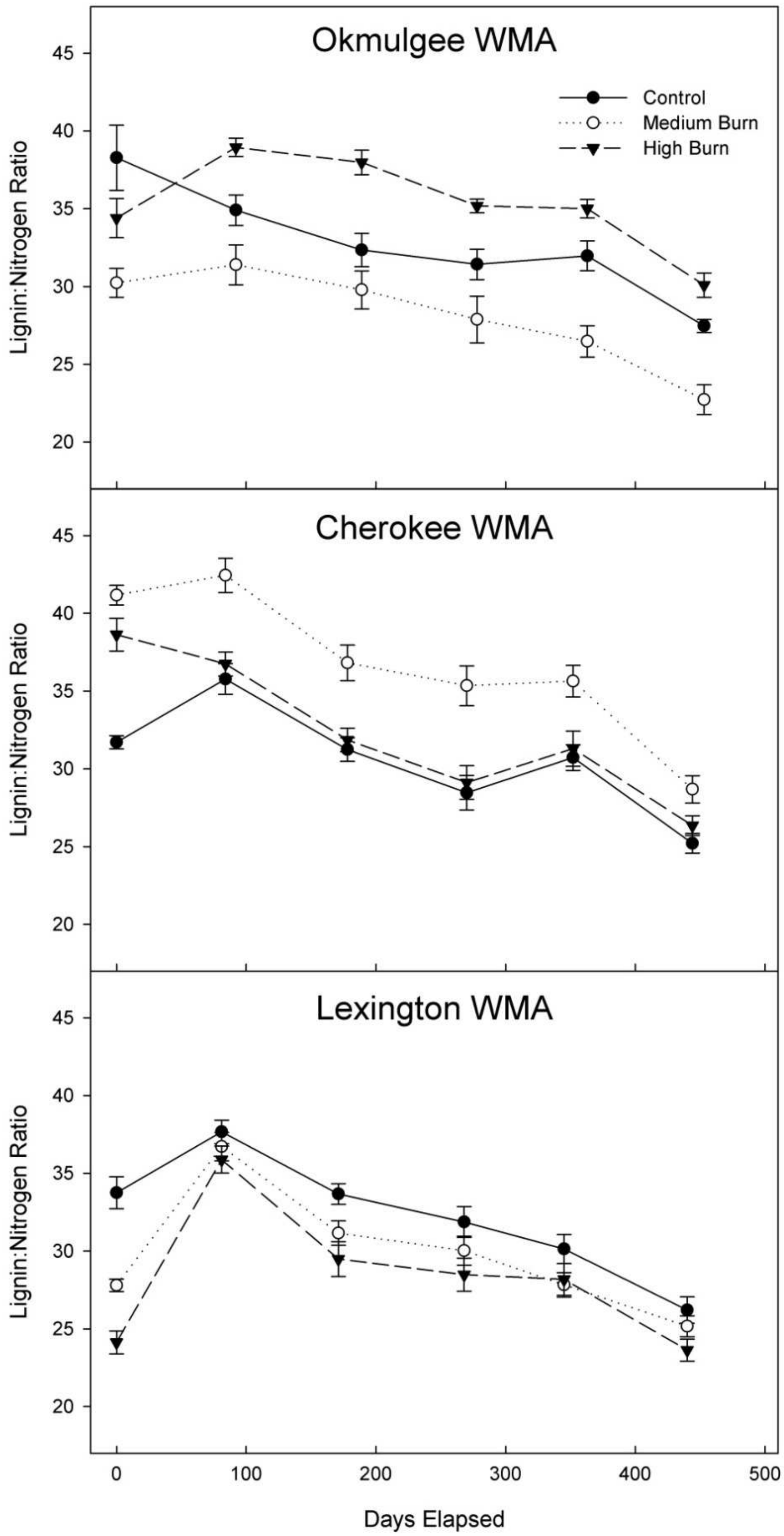

Figure 13. Soil ammonium over five collections at three wildlife management areas. Values shown are means ± 1 standard error. Note y-axes are different.

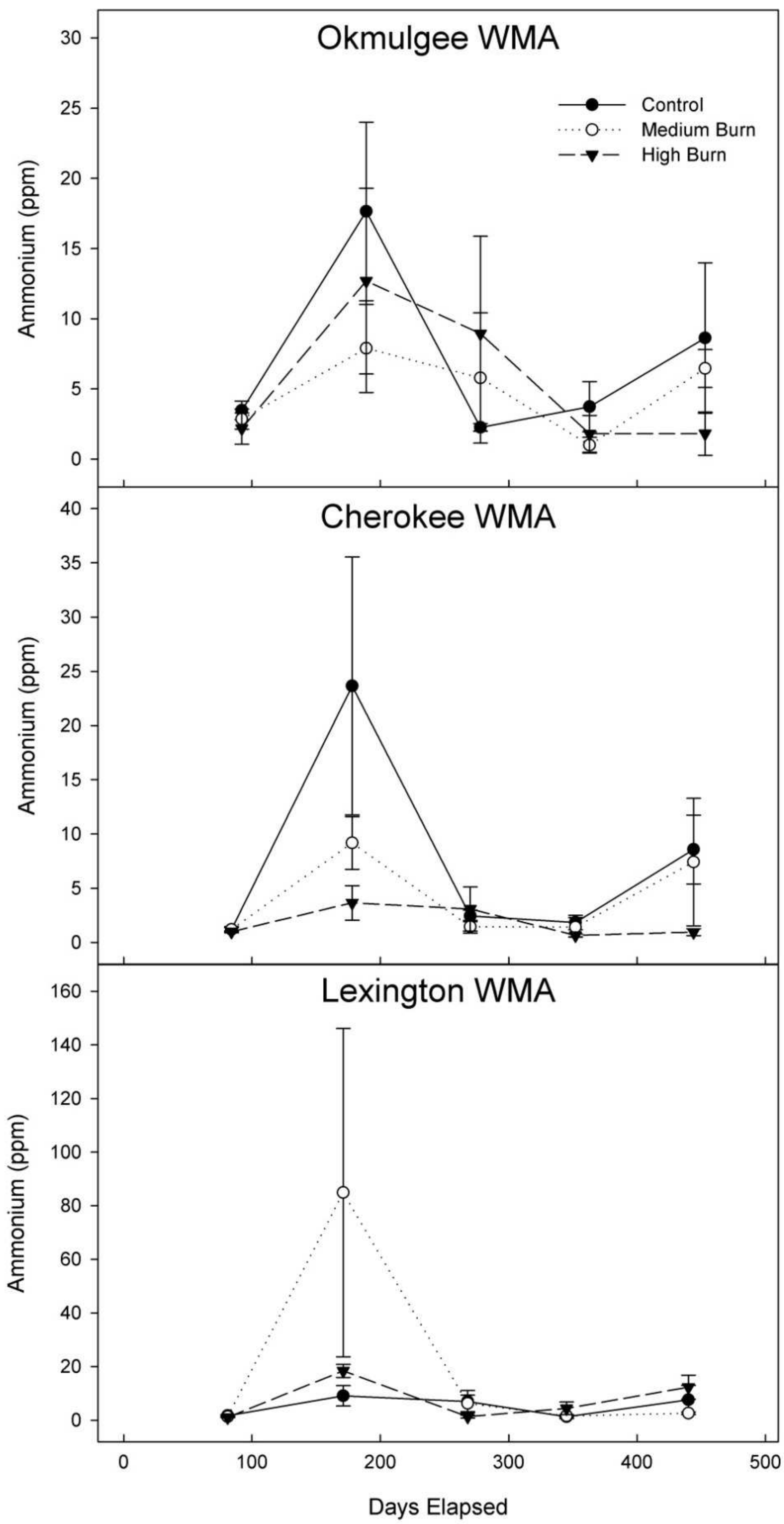

Figure 14. Soil nitrate over five collections at three wildlife management areas. Values shown are means ± 1 standard error. Note y-axes are different.

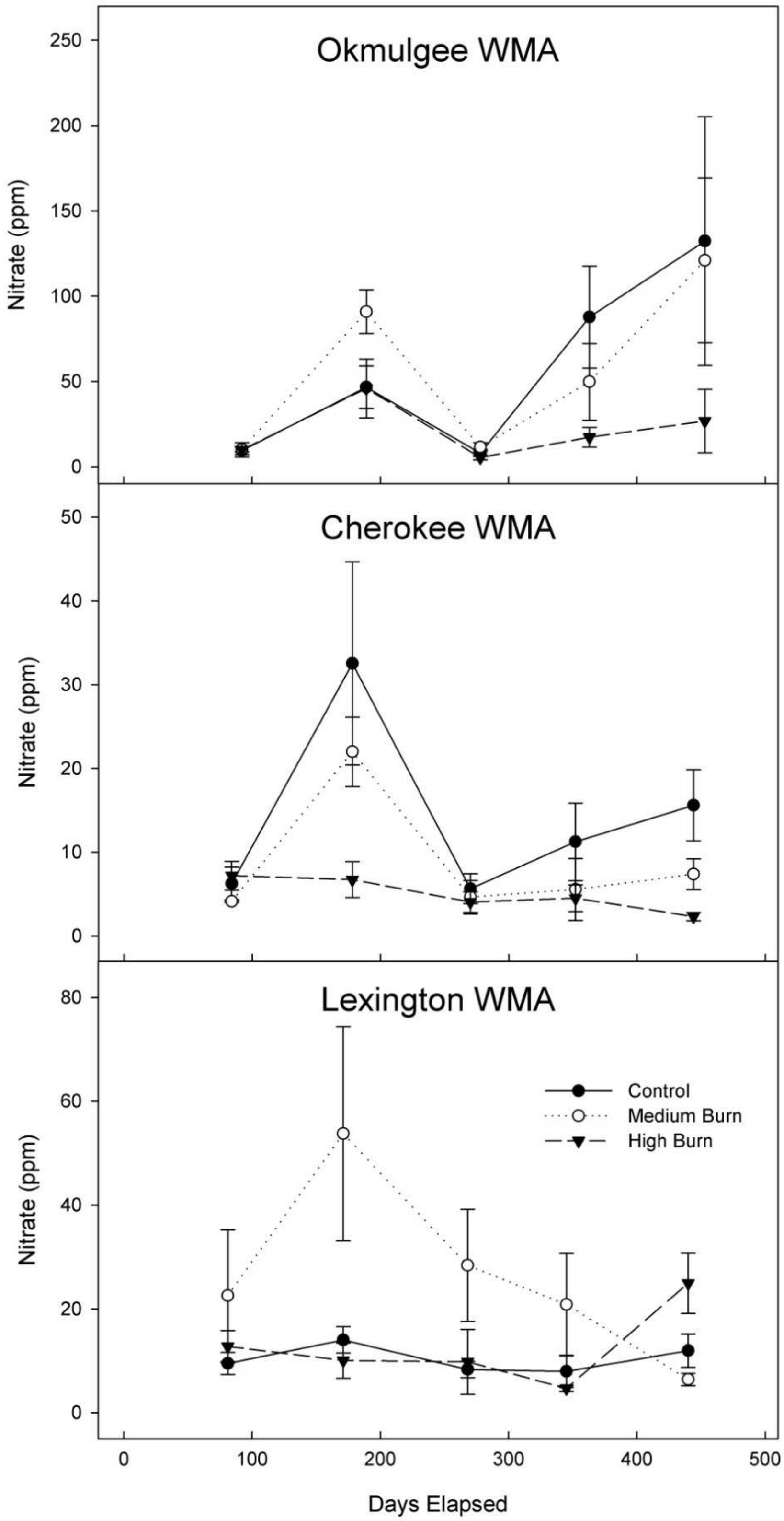

Figure 15. Relation of litter mass remaining to total N at three wildlife management areas.

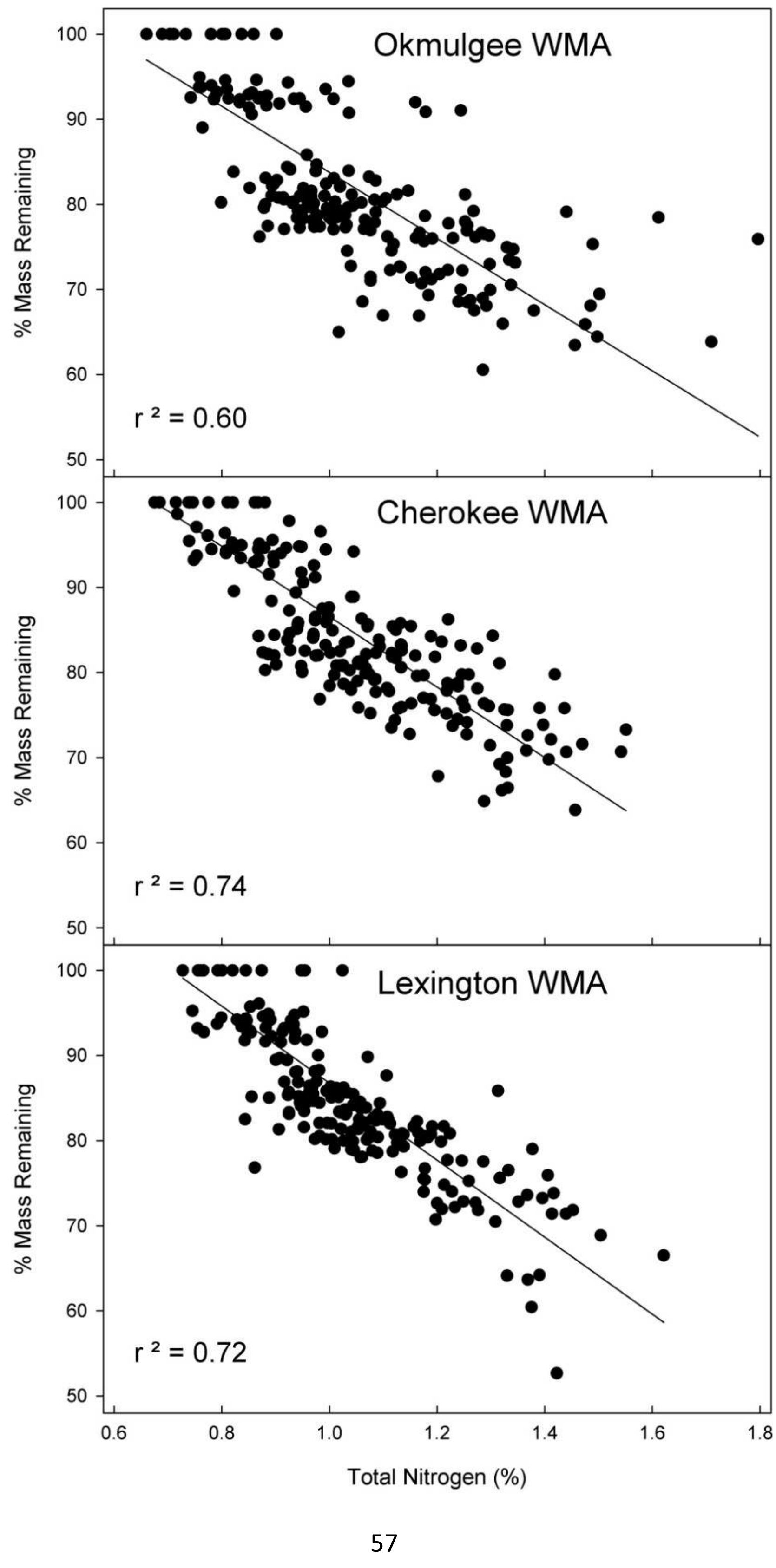

Figure 16. Relation of litter mass remaining to C:N at three wildlife management areas.

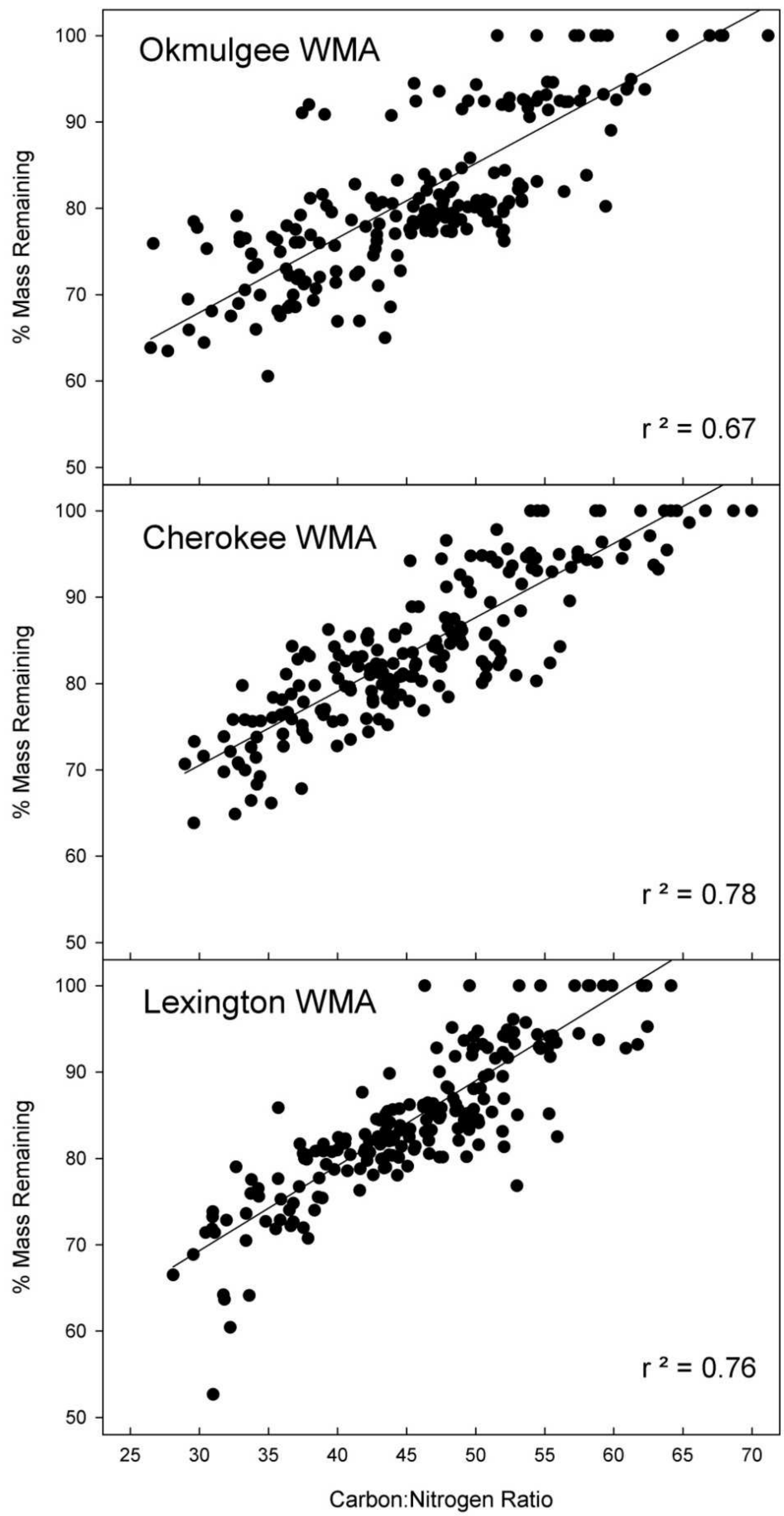

Figure 17. Relation of litter mass remaining to lignin:N at three wildlife management areas.

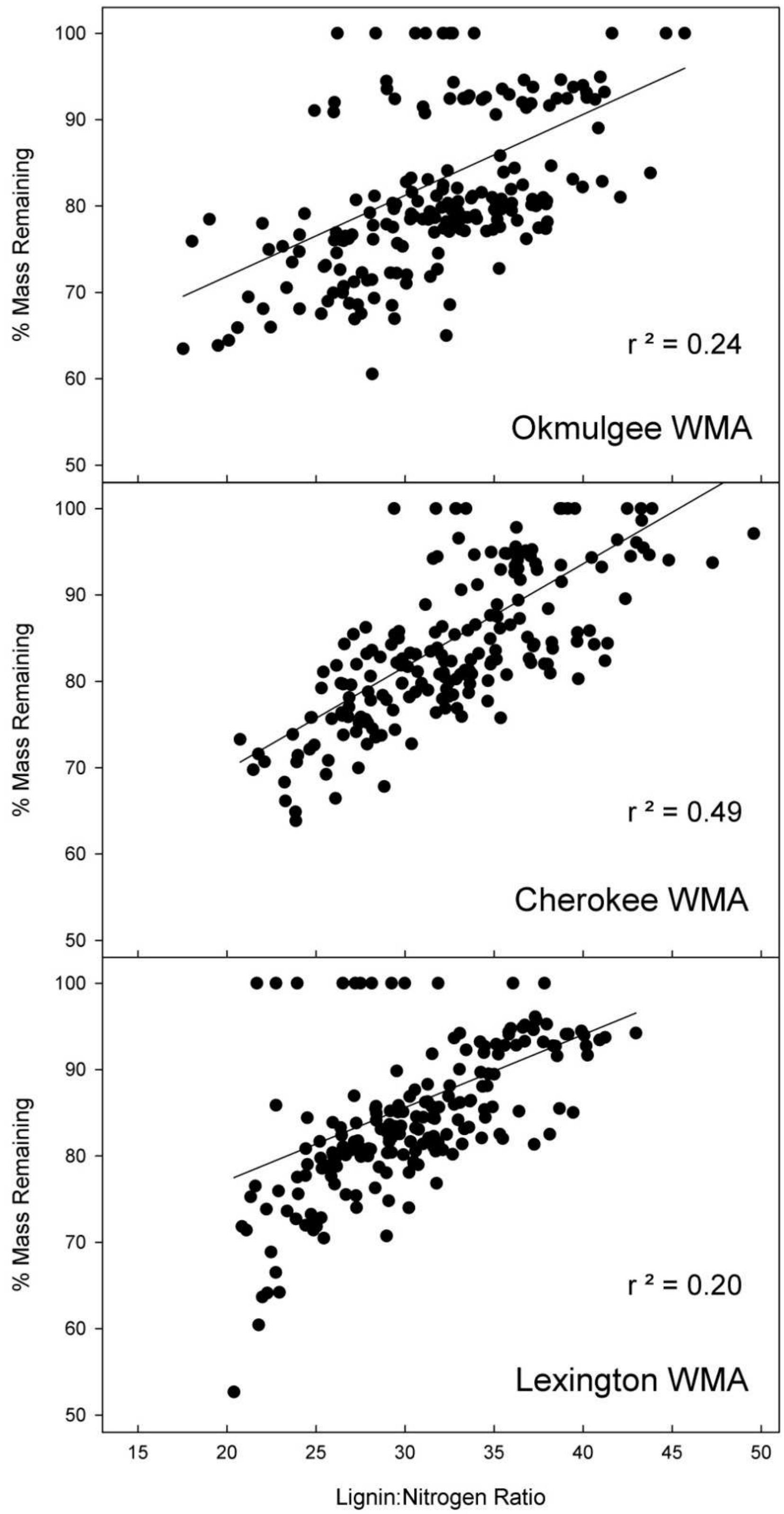

Figure 18. Daily temperature and monthly precipitation over study duration at three wildlife management areas. Line graph is temperature and bar graph is precipitation. Data obtained from the nearest Oklahoma Mesonet station for each wildlife management area.

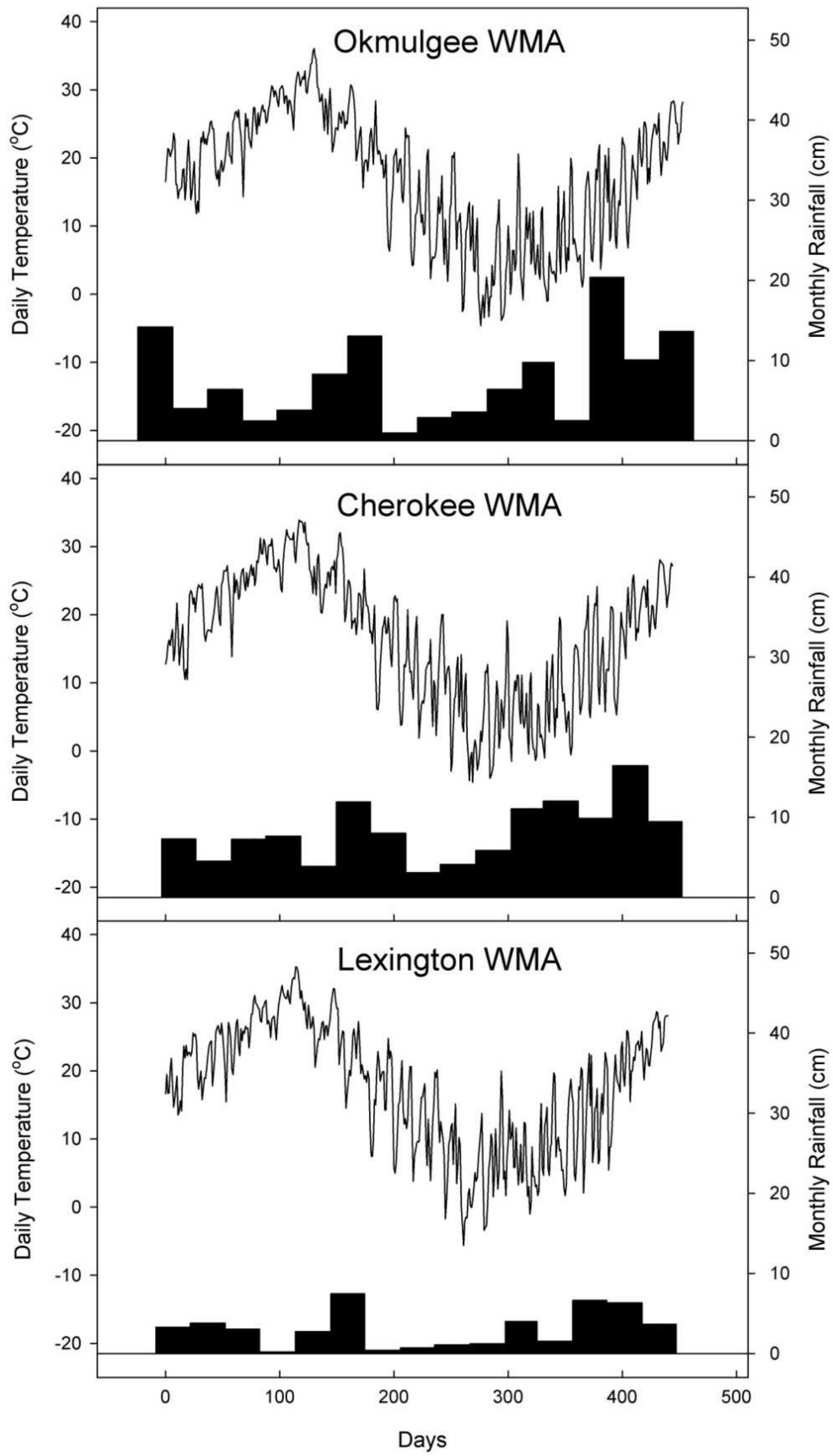

Figure 19. Photo point of the control unit in Cherokee Wildlife Management Area throughout four different seasons. Clockwise from upper left: spring, summer, winter, and fall.

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