EFFECTS OF PRESCRIBED FIRE ON DEAD WOODY

MATERIAL IN UPLAND XERIC OAK FORESTS OF

OKLAHOMA

By

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DEDICATION

This work is dedicated to Brandy Niemann. Her encouragement was important and endless, as demonstrated by her willingness to accompany me somewhere neither of us had been to before, listen to my repeated practice presentations, proofread just about anything I wrote (which probably would have put a committee member in an asylum), and just being a sounding board for any idea I had. Thanks, my love.

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Abstract

The Cross Timbers of Oklahoma is a xeric oak forest adapted to frequent, low
intensity fire. These forests may include tracts of old-growth stands that have been altered
due to changes in fire regimes following European settlement. Dead wood comes from
the death or breakage of trees and is important for wildlife habitat, nutrient cycles, energy
storage, carbon sequestration, and erosion control. Dead wood depends on many factors
such as site productivity, stand age, and disturbance. Fire has the capacity to create and
consume dead wood. The purpose of this study was to determine whether prescribed
burning affected the quantity of standing and down dead wood. We studied three wildlife
management areas (WMAs) in central and eastern Oklahoma where prescribed burning
had been used as one of the primary management practices. At each WMA, we measured
30 transects in each of 8 burn units with fire frequencies ranging 0 to 4.6 fires / decade
over 22 - 26 years. Down woody debris (DWD) was measured by the planar intersect
method on 50-m transects, and snags were measured on 500-m^2 plots along the same
transects. Volume of DWD $\leq$ 7.5 cm diameter was variable across the burn units and sites
(7.2-8.7 m^3 ha^{-1}). Volume of DWD > 7.5 cm diameter was highly variable among burn

units and sites (6.2-9.1 m^3 ha^{-1}). The volume of total DWD (13.5-17.7) was approximately equal to that of snags (14.1-18.0 m^3 ha^{-1}). Linear regression analyses with fires per decade and years since fire as explanatory variables were nearly all nonsignificant for all the metrics of DWD and snags. Multiple regression analyses with site and live basal area as explanatory variables were likewise not significant. The high variability of DWD and snag volume among burn units suggested that stand structure and local disturbances such as wind, ice, and disease may determine dead wood volumes.

1. Introduction

While generally living in excess of 150 years, trees in the upland, xeric forests of the Cross Timbers of Kansas, Oklahoma, and Texas do not finish their ecological roles with their deaths (Clark *et al.*, 2003; Johnson and Risser 1975; Therrell and Stahle, 1998). Dead woody material from dead trees and tree pieces has numerous roles in ecology including habitat, forage, fuel for fire, nutrient cycling, and erosion control (Brown *et al.*, 2003; Harmon, 2002; Harmon *et al.*, 1986). These functions impart an important role for dead wood in the conservation of forests. Prior to the sea change in forest conservation that took place around the middle 20th century to recognize the importance of all parts of an ecosystem, dead wood was considered a nuisance and removed at earliest convenience. Now, its value is recognized, and it is the focus of expanded research (Thomas, 2002).

Forests in Oklahoma's Cross Timbers have been described as a mosaic of closed canopy stands, savannas, and prairie openings. The Cross Timbers is situated between eastern deciduous forests and the Great Plains of North America, encompassing 4.5

million hectares. The forest's two main species are *Quercus stellata*, post oak, and *Q. marilandica*, blackjack oak (Johnson and Risser, 1975; Rice and Penfound, 1959). Various species of *Carya* are subdominant in the canopy, and the understory layer contains numerous shrub, forb, and graminoid species (Burton *et al.*, 2010; Hoagland, 2000; Stambaugh *et al.*, 2009). Other trees species are found throughout the Cross Timbers as minor components, and *Juniperus virginiana*, eastern redcedar, is becoming more widespread as it encroaches into these forests (DeSantis *et al.*, 2010a).

The Cross Timbers is located along a steeply declining precipitation gradient from east to west. The resulting annual precipitation throughout the Cross Timbers is less than precipitation in the rest of the eastern deciduous forests. The upland sandy soils on which these forests are found, the high summer temperatures, and the low precipitation make for harsh conditions for supporting trees. Although tolerant of harsh conditions, oaks in these forests are described as "stunted", probably due to the conditions just mentioned (Burton *et al.*, 2010; Clark *et al.*, 2005; Therrell and Staley, 1998). Because these factors have mostly resulted in minimal systematic harvesting, the Cross Timbers may contain old-growth stands (Clark *et al.*, 2003; DeSantis *et al.*, 2010b; Therrell and Stahle, 1998).

Historically, fire has been an important disturbance to the Cross Timbers (DeSantis *et al.*, 2010a; DeSantis *et al.*, 2010b; Stambaugh *et al.*, 2009). Studies have concluded that most of the fires in the region were of anthropogenic origin. Native Americans used fire for many purposes (Moore, 1972; Guyette *et al.*, 2002). After widespread settlement by Europeans, fire regimes changed to accommodate property owners and human safety (Guyette *et al.*, 2002). Before European settlement, the historical fire regime was low severity and frequent fires, at 0-10 year intervals (Brown,

2000). The common season for burns was early spring, while most vegetation was still dormant (Allen and Palmer, 2011; Clark *et al*., 2005, DeSantis *et al*., 2010b; Stambaugh *et al*., 2009). Fires at this time of the year have low severity and leave woody plants and trees > 5 cm diameter at breast height (dbh) generally untouched (Burton *et al.*, 2010). While it is generally thought that fire frequency has declined since the late 19th century, recent studies found that it might have increased in some Cross Timbers forests (Allen and Palmer, 2011; Clark *et al.*, 2005; DeSantis *et al.*, 2010b). In addition to fire, windstorms and hail also cause disturbances in the Cross Timbers (Brooks, 2011a, 2011b) (Figures 1 and 2).

Dead wood is normally referred to as coarse woody debris (CWD), a term often used for both standing dead and down pieces of wood. In this study, CWD refers to just down, large pieces of wood. Smaller pieces of down woody material are called fine woody debris (FWD), CWD and FWD collectively are referred to as down woody debris (DWD). Standing dead is referred to as snags. The literature classification for CWD ranges from 5-10 centimeters diameter (Fraver and White, 2005; Miehs *et al.*, 2010); this study classifies pieces > 7.5 cm as CWD. Snags, CWD, and FWD are collectively called dead wood.

Dead wood has several functions in a forest. One of the most obvious is as shelter or refuge for the fauna and flora. Fauna, including birds, mammals, and invertebrates, rely on snags and DWD for shelter (Braccia and Batzer, 2008; Goodburn and Lorimer, 1998). A study of midwestern hardwoods found 26 bird species, 11 mammal species, and 20 species of herptofauna relied on dead wood for habitat purposes (Spetich *et al.*, 1999). Endangered species, such as *Myotis sodalis*, the Indiana bat, rely on snags for roosting

(Humphrey *et al.*, 1977). The DWD also provides nutrition for some invertebrates and other organisms, such as fungi, bacteria, and some plants, (for example, *Corallorhiza wisteriana*, spring coralroot, a saprophytic orchid, Figure 3) (Braccia and Batzer, 2008; Goodburn and Lorimer, 1998; Harmon *et al.*, 1986). Since the recognition of dead wood's importance to ecological processes in a forest, some have expressed concern that foresters are not adequately considering it in management plans. Efforts are underway to change management practices to accommodate dead wood as an integral part of managed forest planning (Hicks and Stabins, 2002; Pawson, 2011). A study of snag use by wildlife in Oklahoma forests found that wildlife used snags > 25 cm dbh. Snags > 25 cm dbh were broken into 2 size classes, those between 25-50 cm and those >50 cm dbh. These snags were considered "wildlife trees" (Rafferty *et al.* 1996).

Among less obvious roles, dead wood serves as reservoirs of nutrients and energy that play roles in nutrient cycling and energy transfer to other trophic levels. Wood ties up a lot of carbon in the forest; carbon is a paramount topic for study because of its effect on climate (Birdsey *et al.*, 2006; Birdsey and Heath, 1995). Numerous studies seeking to balance the global carbon budget have considered what role dead wood plays in the carbon cycle (Ambrose and Conkling, 2007; Birdsey *et al.*, 2006; Birdsey and Heath, 1995; Bois *et al.*, 2009; Krankina and Harmon, 1995). One study found that dead wood could hold up to 17% of global carbon in forests (Bradford *et al.*, 2009). Other important nutrients, such as nitrogen and potassium, also are found in dead wood and the decay of dead wood will have some influence on how much of those elements are available for the biological processes of other organisms (Harmon *et al.*, 1986).

The quantity of dead wood ranges widely and depends on several variables, such as climate, forest structure, tree species, and size distribution of the forest (Goodburn and Lorimer, 1998; Harmon *et al.*, 1986). Mortality events that affect inputs of dead wood in forests include pests and diseases, competition and suppression, and disturbance, both man-made (logging) and natural (fire and wind storms) (Harmon *et al.*, 1986; Van Lear, 1993). Dead wood leaves a system by processes such as fragmentation, leaching, decomposition, and combustion (Figure 4). Much of the decomposition relies on the activity of microbes, bacteria, and fungi that break down the wood, and this decomposition can begin before a tree is actually dead (Boddy and Rayner, 1983a; Boddy and Rayner, 1983b; Harmon *et al.*, 1986). As a very general statement, forests with large, slow-growing trees found in cool and humid climates probably will provide greater amounts of dead wood than forests in other conditions due the effect these conditions have on the organisms that carry out decomposition (Richardson *et al.*, 2009).

Fire is important to dead wood dynamics of oaks. Since the heartwood is protected by the sapwood and bark, wounds in these layers are crucial to invasion by heart rot fungi, e.g. *Armillaria mellea* and *Fomes ignarius* (Berry, 1973). Broken branches offer one form of ingress, but there are some fungi that can invade intact trees (Boddy and Rayner, 1983). A study in the central hardwood region of North America found that fire scars were the starting point for 25% of infections by rot-inducing fungi. With more than 40% of decay volume associated with these wounds, fire was most important for decomposer invasion (Berry and Beaton, 1973).

Fire causes a variable amount of added CWD to a forest system. High-impact disturbances can contribute large quantities of biomass to dead wood volumes. In the pine

forests of western Oregon, large fires can occur every 500 years. Such a fire can add 1000

Mg ha^{-1} of CWD, although the average addition of dead wood is 500 Mg ha^{-1}. In

undisturbed forests, normal mortality will increase dead wood amounts by 1200-2200 Mg

ha^{-1} over 500 years (Harmon and Hua, 1991). When stands go unburned, there is an

increase in snags as they mature (Morrison and Raphael, 1993; Youngblood et al., 2005).

Almost no new snags were added to stands that were burned in a study in California

(Morrison and Raphael, 1993). It was indicated that snags created by fire fell over and

became DWD quickly, so the net effect from fire ended up being indiscernible.

Along with wildfires, other natural causes of tree mortality include windstorms

and pest outbreaks (Harmon et al., 1986). These events affect large portions of the stands

in which they occur. In a study of old-growth stands of conifers in the North Carolina

Piedmont, Peet and Christensen (1987) found that 32% of tree deaths were attributable to

windthrow and that 21% of tree death in a beech-magnolia, *Betula-Magnolia*, forest in

Texas was the result of windstorms.

Conservation efforts in Oklahoma's natural areas by land managers from the state

government have relied on prescribed fire to maintain natural processes and biological

diversity. Land managers utilize fire for controlling fuel loads, reducing encroachment of

undesirable species, improving grazing, and maintaining productive wildlife habitat.

Nevertheless there are few data about the effects of fire on the quantity of dead wood in

Cross Timbers forests. Fire can create snags and lead to DWD creation; it can also reduce

these amounts through combustion (Harmon et al., 1986). The objective of this study was

to quantify dead wood pools in the Cross Timbers and evaluate the relationships between

frequency of prescribed fire and the dead wood quantities. Given the fire-resistant

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features of the dominant trees and the low-intensity fires that normally occur in the Cross Timbers, I hypothesized that frequent fire decreased the amount of dead wood found in a forest, because consumption of the dead materials should increase with fire frequency. Infrequent fires could result in a build up of dead wood materials.

2. Methods

2.1. Study Sites

The study was conducted in three WMAs in the Cross Timbers of eastern and central Oklahoma: Okmulgee WMA (OWMA), Lexington WMA (LWMA), and Cherokee WMA (CWMA) (Figure 5). Prescribed fire had been used to manage the vegetation for wildlife for at least 22 years at these WMAs and every fire had been documented relative to its location and timing. At each site, we sampled eight management units with varying fire frequencies. The burn frequencies ranged from 0 to 4.55 fires per decade (FPD) and 0 to 7 years since the last fire (YSF) (Tables 1, 2, and 3). The non-burned units had not been burned for at least 22 years.

Prescribed burns normally took place in February or March. Conditions for burning were: relative humidity from 30-50%, temperature < 27 °C, and wind speed < 25 kph. These conditions were considered ideal for achieving the goals of fuel and vegetation management and for fire containment (Weir, 2009). Over the 22 years, there was one wild fire at OWMA and two at CWMA that occurred under conditions similar to those used for the prescribed burns.

The OWMA headquarters was located at 35° 18' 15.5" N, 96° 3' 12." W. Elevation was 220-280 meters above mean sea level. The mean annual temperature was

16° C, with mean summer temperature of 34° C and mean winter temperature of -4° C (Oklahoma Climatological Survey, 2005). Annual precipitation averaged 111 cm, with extremes as low as 54.5 cm and as high as 156.2 cm (Oklahoma Climatological Survey, 2005). Soils in OWMA were primarily from the Hector-Endsaw complex (Sparwasser *et al.*, 1968). These soils were described as well-drained, non-arable, shallow fine sandy loam with bedrock at a depth of about 30 cm on hilly or mountainous topography of 5-30% slopes. All OWMA samples were located within this soil type. The area of the 8 management units was 47 to 386 ha.

The LWMA headquarters was located at 35° 05' 11.9" N, 97° 14' 04.9" W. Elevation was 324-374 m above mean sea level. The mean annual temperature was 16° C, with mean summer temperature of 34° C and mean winter temperature of -2.2° C (Oklahoma Climatological Survey 2005). Precipitation averaged 102 cm, the lowest yearly total was 46 and the highest yearly total was 144 cm per year (Oklahoma Climatological Survey 2005). Sampling took place on soils in the Stephensville-Darnill complex. These soils were found on slopes from 1-45% and were characterized as excessively drained, loamy fine sand with depths 25-50 cm (NRCS, 2011). The area of the 8 management units was 33-79 ha.

The CWMA headquarters was located at 35° 46' 13.5" N, 95° 04' 04.7"W. The elevation was 178-318 m above mean sea level. The mean annual temperature was 16° C, with a mean summer temperature of 33° and mean winter temperature of -3° C (Oklahoma Climatological Survey 2005). Mean annual precipitation was 122 cm with low and high annual values of 64-187 cm (Oklahoma Climatological Survey 2005). Soils were from the Hector complex. They were fine sandy loams on 1-30% slopes. The

distance to the bedrock was 38-76 cm (NRCS, 2011). The area of the 8 management units was 122-744 ha.

2.2. Sampling Design

Forty sample points were located randomly in each management unit using ArcMap 9.2 (ESRI, 2007). Only 30 points were sampled and the excess points provided the opportunity to reject preselected plots when they fell in an unacceptable location such as a clearing. I sampled in summer in order to differentiate live trees from dead. The measurements at each sample plot took place in three phases: DWD and litter, snags, and live trees (Figures 6 and 7). Measurements for DWD were done on a 50-m randomly oriented transect by the plane intersect method. The plane intersect method is a probability based survey method modified from the line intersect method (Williams and Gove, 2003). The line intersect method is a survey method founded on the principle that a DWD piece will intersect a survey line with a probability based on the DWD piece's length and orientation to the survey line. The research on this method also found that the volume of one piece surveyed was correlated with sum of the volume of pieces. This meant that pieces did not need to be measured for all the dimensions of volume, just getting the diameter and tally of pieces in diameter classes permitted suitable estimation of the volume of DWD pieces (Van Wagner, 1968; Warren and Olsen, 1964). Brown modified this practice from intersection with a line to intersection with a vertical plane (Brown, 1982). The height of the plane used in this study was 2-m as modified by Brown (1982).

Tallies for small, fine woody debris (SFWD, dia. < 1 cm); medium, fine woody debris (MFWD, 1 cm < dia. < 2.5 cm); large, fine woody debris (LFWD, 2.5 cm < dia. < 7.5 cm); and coarse woody debris (CWD, dia. > 7.5 cm) were taken on each transect for DWD. These size classes correspond to fuel class ratings based on drying time lag (Brown, 1982). The SFWD tallies were taken in four 2-m segments at 10, 20, 30, and 40 m on the transect. The MFWD and LFWD tallies used the same four segments and an additional 2-m segment at the 48-m. Measurements for CWD were taken along the entire 50-m transect.

Minimum dimensions for CWD were 7.6 cm diameter at intersection and 50 cm length. Measurements taken for CWD were diameter at intersection, diameter at the opposite end of the piece down to 3 cm, length between the diameters, and condition of the bark and condition of the wood. Condition classes were between one and five, one being least decayed to almost dust for five (Table 4). Pieces had to be > 45° from vertical and detached at the base.

Litter depth was measured to the nearest centimeter at every 10 m along the transect starting at 10-m. A trowel with measurement increments in the blade was maneuvered through the leaf litter to disturb it as little as possible until it hit the mineral soil and then the litter was cleared enough to assure that the spade was on soil and the litter depth along the blade was recorded.

The second phase of sampling used the transect again as the midline of a 50 x 10 m plot. Two people walked in the same direction, reverse to the previous direction of the transect, on both sides of the transect looking for all dead trees that were at least 1.4 m

tall, attached at the base to the roots, and less than 45° from vertical. In order to be considered inside the plot, the centerline of the stem had to be within the 5-m boundary from the transect. For each snag, we recorded: species, dbh, height, bark condition, wood condition, crown whole or broken, distance along the transect, obvious signs of animal use (e.g. excavations or animals perched or climbing on snags), and signs of fire or injury. Height was measured with an extendable pole up 10.67 m in OWMA and LWMA. In CWMA, the trees were much taller than the pole, and we used a laser rangefinder (Laser Technology Inc., Centennial, Colorado).

Finally, after completing the snag plot we used a basal area factor (BAF) 10 prism plot for a point count. The center of the prism plot was the 50-m mark of the snag plot. All live trees were identified to species and measured for dbh.

2.3. Analysis

Values for each unit's respective DWD transect measurements were calculated on a per hectare basis for three FWD classes and one CWD class. FWD volume (m^3 ha^{-1}) was calculated as follows:

$$FWD_i = \frac{kc}{L} n d_i^2 \qquad (Eq.1)$$

where k was a conversion factor for estimation of area values from individual piece volumes ($k = 1.234$), c was an adjustment factor for slope, L was the transect length in m, n was the number of pieces in size class i, d was the diameter in m of the pieces in class i. The diameters for each size class were: $i = 1$, dia. $= 0.59$ cm; $i = 2$, dia. $= 1.75$ cm; $i = 3$,

dia. = 5.05 cm. The correction for slope only was included when the slope was over 20% (Woodall and Williams, 2005).

Volume for a single piece of *CWD* (v in m^3) was calculated using Smalian's formula:

$$v = \left(\frac{\pi d_i^2}{4} + \frac{\pi d_s^2}{4}\right) l \quad \text{(Eq. 2)}$$

where d_i^2 was the intersect diameter and d_s^2 was the second diameter, and l was the length of the piece (all measurements in meters). The following equation was used to calculate *CWD* volume on an area basis (m^3 ha^{-1}) for each transect:

$$CWD = \frac{f\pi}{2L}\sum_{j=i}^{n}\left(\frac{v_j}{l_j}\right) \quad \text{(Eq. 3)}$$

where f was a factor to convert *CWD* to a per hectare value ($f = 10,000$), L was the length of the transect ($L = 50$ m), v_j and l_j were the volume and length of the jth piece in the transect (Woodall and Williams, 2005).

Snags measurements were calculated to per hectare values. The basal area (BA) calculation applied to snags was

$$BA = \left(\frac{d}{2}\right)^2 \pi \quad \text{(Eq. 4)}$$

where d was the dbh and given in meters. Snag volume was determined by multiplying the BA by the height of the respective stem. I did not use a form factor for snag volume calculation because they were rather short and the taper along the tree was not large.

Basal areas for all snags in a transect were summed and then multiplied by 20 for a per hectare estimate of BA. The per hectare BA for each transect were averaged for a unit estimate of BA. This same approach was taken with snag volumes. Transect means of bark and wood conditions were averaged for a mean bark and wood condition in the unit.

Basal area for live trees in $m^2 \, ha^{-1}$ was calculated as 2.2957 times the tree count with the BAF 10 prism. The diameters of the counted trees were used to calculate tree frequency by diameter class.

To detect relationships of dead wood measurements to fire effects, the unit means were used in univariate linear regression with either FPD or YSF as explanatory variables. Multiple regression was also used. Significance for all regressions was $\alpha = 0.05$. The explanatory variables in multiple regression models were either of FPD or YSF combined with BA of live trees and a dummy variable for site, represented as either 1 or 0 for OWMA and LWMA (Crawley, 2005). Control plots were not used in any regression with YSF as an explanatory factor because it was unknown when those plots had last burned. Seven years since fire was the longest time without fire in the burned plots. All regressions were completed with the R statistics package (R Development Core Team, 2010).

Carbon was calculated for dead wood pieces by using the value 0.46 kg m^3 for specific gravity to determine mass and then multiplying by 0.50 to figure mass of carbon (Bois *et al.* 2009; MacMillan, 1981). For litter, I used a bulk density of 0.03 kg m^3 to calculate mass, which I then multiplied by a ratio of 0.46 for the mass of carbon in the litter (Chojnacky *et al.*, 2009).

3. Results

The mean BA of live trees was 19.3 m^2 ha^{-1} in OWMA, 21.37 m^2 ha^{-1} in LWMA, and 20.34 m^2 ha^{-1} in CWMA and was not affected by prescribed burning frequency. The diameter distributions of the live trees we measured in each site approached that of a reverse-J shape, indicating an uneven-aged stand (Figure 8).

3.1. Down woody debris

The volume of DWD was 13.45 m^3 ha^{-1} in OWMA, 16.16 m^3 ha^{-1} in LWMA, and 17.68 m^3 ha^{-1} in CWMA. The volume of CWD was 6.24 m^3 ha^{-1} in OWMA, 7.44 m^3 ha^{-1} in LWMA, and 9.1 m^3 ha^{-1} in CWMA (Figures 9, 10, and 11). The ranges of CWD values within each management area were 4.76-11.43 m^3 ha^{-1} in OWMA, 3.06-13.49 m^3 ha^{-1} in LWMA, and 2.76-17.18 m^3 ha^{-1} in CWMA (Figures 9, 10, and 11). At the CWMA, the volume of *Q. marilandica* CWD decreased as the fire frequency increased (Figure 12). In LWMA, the volume of *Q. stellata* CWD increased when the years since last fire increased (Figure 13). The volumes for small FWD were 0.39 m^3 ha^{-1} in OWMA, 0.42 m^3 ha^{-1} in LWMA, 0.30 m^3 ha^{-1} in CWMA (Figures 9, 10, and 11). The medium FWD volumes were 2.47 m^3 ha^{-1} in OWMA, 2.40 m^3 ha^{-1} in LWMA, and 2.10 m^3 ha^{-1} in CWMA (Figures 9, 10, and 11). The volumes of large FWD were 5.07 m^3 ha^{-1}, 5.90 m^3 ha^{-1}, and 6.14 m^3 ha^{-1} in OWMA, LWMA, and CWMA, respectively (Figures 9, 10, and 11). CWD was < 50% of DWD in all of the burn units in all 3 WMAs. The next largest component was the large FWD, which was approximately one third of the DWD volume. The volume of small FWD declined with increasing fire frequency in CWMA (Figure 14). Generally, fire's effect on the DWD was minimal and linear regression with FPD or

YSF as the independent variable was not significant. Multiple regression analyses with BA of live trees and fires per decade or years since fire as explanatory variables was not significant with any of the dependent variables. When site was included in the regression model, it was not significant either.

The volume of pieces of CWD with a diameter over 15 cm at the transect intersect was approximately 44% of average volume of CWD. Fifteen centimeters was chosen because 13.6 cm was close to the 75th percentile of intersect diameters among all three sites. Of the CWD pieces that could be identified to species, *Q. stellata* comprised 31% of the CWD volume. *Q. marilandica* was 33% of CWD volume across all sites. Fine woody debris pieces were not identified to species. Most of the CWD pieces were covered by less than 50% of bark, and the mean condition class of wood was 2.21 at OWMA, 1.56 at LWMA, and 1.94 at CWMA (Table 5).

3.2. Litter

The litter depth was 3.81 cm in OWMA, 3.49 cm in LWMA, and 4.02 cm in CWMA. These would be equivalent to volumes of 381 m^3 ha^{-1}, 349 m^3 ha^{-1}, and 402 m^3 ha^{-1} in OWMA, LWMA, and CWMA, respectively. There was one significant relationship; in CWMA, as FPD increased, litter depth decreased (Figure 15). Fires per decade or YSF did not have any other significant effects on litter depth.

3.3. Snags

The number of snags per hectare in each site was 99-139 ha^{-1} (Table 6, Figures 16, 17, and 18). Snag BA was 1.77-2.25 m^2 ha^{-1} (Table 6, Figures 19, 20, and 21). The volume of snags ranged was 11.27-18.05 m^3 ha^{-1} (Table 6, Figures 22, 23, and 24). On

average, snags were covered by > 50% bark and lacked branches < 7.5 in all sites. Means

of the wood decay classes were 1.21 in OWMA, 1.45 in LWMA, and 1.49 in CWMA,

indicating that wood in the snags was firm, but could be penetrated with a probe (Table

5). The density of snags 25-50 cm dbh was 12/ha in OWMA, 8/ha in LWMA, and 10/ha

in CWMA (Table 6, Figures 16, 17, and 18). In LWMA, *Q. stellata* BA increased when

YSF increased (Figure 25). In CWMA, the bark coverage class increased, meaning that

bark coverage decreased, as FPD increased (Figure 26). Multiple regression analyses

with BA of live trees and fires per decade or years since fire as explanatory variables was

not significant with any of the dependent variables. When site was included in the

regression model, it was not significant either.

The mean number of large wildlife trees, > 50 cm dbh, was less than one tree per

hectare in all three sites. Mean BA of all wildlife trees was 1.1 m^2 ha^{-1} in OWMA, 0.55

m^2 ha^{-1} in LWMA, and 0.95 m^2 ha^{-1} in CWMA (Figures 19, 20, and 21). All wildlife trees

were covered by > 50% bark in LWMA, and between 25-50% bark in OWMA and

CWMA. Means of wood decay class were 2.12 in OWMA, 1.42 in LWMA, and 1.74 in

CWMA. There were no significant relationships of wildlife tree quantities to FPD or

YSF.

The ratio of standing dead to live trees was over 0.10 across all three WMAs. The

plot of the standing dead to live ratio for dbh classes told a more complicated story

(Figure 27). The pattern of change was similar across all three WMAs. The ratio had a

minor peak of 0.10 at 10-14 cm dbh, declined to a plateau near 0.08 at 14-28 cm dbh, and

increased sharply above 0.10 at 40 cm dbh while becoming erratic up to 50 cm dbh.

We noted that moths used loose bark for shelter. Fourteen snags were found in Okmulgee with the distinctive rectangular excavations of *Dryocopus pileatus*, Pileated Woodpecker. Twenty-seven sampled snags had what appeared to be excavations by primary excavators, but these holes were usually well out of reach of any examination without special equipment. *Melanerpes erythrocephalus*, red-headed woodpecker, was viewed perched on one snag that was located outside of the sampling plots.

4. Discussion

The major finding was the amount of dead wood and litter in these three Cross Timbers sites was not related to the frequency of prescribed fires in the sites. This was the case even when the fire frequency was as high as 10 fires in 22 years. The distribution of tree sizes indicated these forests were approaching equilibrium for recruitment and mortality, which is associated with high quantities of dead wood, but volumes of snag and DWD varied from 8.2 to 37.9 m^3 ha^{-1}. For example, variability of CWD volume in each of the three sites was between three to six fold. Snag densities, volumes and basal areas also had comparable differences. This kind of variability could probably be linked to other factors, such as pests, wind, or ice storms. The large differences in dead wood from the various processes could have made it difficult to detect prescribed burning's effect on dead wood.

4.1. Down woody debris

The CWD volumes found in the three sites were approximately twice that found in a recent study in similar Cross Timbers forests (3.1 m^3 ha^{-1}, Clark *et al.*, 2005). A study in a mesic hardwood forest type in Indiana had a much greater quantity, 44 m^3 ha^{-1}

(Idol *et al.*, 2001). Another study in Indiana that included DWD pieces > 5 cm had a mean of approximately 17 m^3 ha^{-1}, which was similar to the highest unit mean, 17.2 m^3 ha^{-1} in a CWMA unit (MacMillan, 1988). The Cross Timbers forests were on upland, sandy soils, and most likely were less productive than mesic oak forests and could not produce as much dead wood (Rosson, 1994; Spetich *et al.*, 1999). In a study of CWD amounts across mesic sites in four states from Missouri to Indiana, volume increased from west to east, which probably reflected a gradient of increasing productivity (Spetich *et al.* 1999). That study also found that stand age and size distribution affected production of dead wood. There was three times as much dead wood in old-growth sites when compared to second-growth sites (60 vs. 20 m^3 ha^{-1}, Spetich *et al.*, 1999).

Clark *et al.* (2005) concluded that the Cross Timbers in Osage county Oklahoma did not fit traditional population structure models for an uneven-aged stand. This is mentioned because the lack of a steady state for the stands in which I sampled could also explain the large variation in dead wood volumes. Johnson and Risser (1974) concluded that a Cross Timbers stand in central Oklahoma was still undergoing a phase of rapid growth. It can be expected that dead wood quantities are low until a forest matures and will then increase when the mature trees begin to senesce, unless a major disturbance takes place causing an early pulse in dead wood (Harmon *et al.*, 1986; Ter-Mikaelian *et al.*, 2008). Since some parts of the Cross Timbers have sections that could be considered old-growth due to the old age of trees, gap dynamics, and the lack of harvesting, while other parts appear to be younger forests with higher density of smaller stems, there appears to be a mixture of structures (Johnson and Risser, 1974; Therrell and Stahle,

1998). This mixture could be part of the cause for variable amounts of dead wood volumes.

While oak species are rated as resistant to heartwood rots when they are alive, there are fungal and other decomposer organisms just as suited to oak as any other wood (Scheffer and Cowling, 1966). The warm, subhumid climate of the Cross Timbers is not suited to slow decomposition of DWD (Highley, 1995; Rose *et al.*, 2001). Therefore, it is likely the decomposition of DWD is likely to be similar to other oak forests throughout eastern North America.

Fine woody debris volumes were as variable as CWD volumes. While fire was a regular disturbance, it did not seem to affect the quantities we found. The smallest pieces, those less than a centimeter in diameter, were the pieces most likely to be consumed by the low intensity fires that occurred in the study areas (Agee, 1996; Brown *et al.*, 1982). However, if these pieces were exiting more rapidly due to combustion, there should have been a smaller amount in the most recently burned units or the units burned most frequently than in the units subjected to less fire, but there was not. This result did occur in CWMA, but only with respect to small FWD. The significance of fire frequency's effect on one category of FWD in only one of the sites suggests that decay processes were more important than combustion in the departure of fine woody debris from the Cross Timbers.

The lack of an effect of prescribed burning frequency on CWD was exemplified by the more than 6-fold difference in CWD volume (2.8 m^3 ha^{-1} and 17.2 m^3 ha^{-1}) between two management units at CWMA that had the same burn frequency of 1.9 FPD

and similar living basal areas of 18.9 and 20.2 m^2 ha^{-1}. The lack of a prescribed burning effect can be shown a different way by looking at the volume of most frequently burned and least frequently burned units in OWMA, also the most and least frequently burned units among the three sites. The most frequently burned had approximately 4.6 fires per decade and a CWD volume of 4.61 m^3 ha^{-1}. The least frequently burned unit had 0.9 fires per decade and a volume of CWD that was 6.37 m^3 ha^{-1} which was a difference that was less than 50% of smaller volume (Figure 11).

The 2- to 6-fold difference in the amount of CWD can result from at least a couple of situations. In one scenario, differences in CWD creation occur among units, while the wood exits the system at a similar rate in all of the units (Harmon *et al.* 1986). In the other scenario, CWD is added at a constant rate, but it leaves the units at different rates. In the first scenario, differences in productivity or disturbance could explain difference in amount of dead wood (Harmon *et al.*, 1986). It would seem that productivity is relatively constant across the study areas, so differences in processes that create dead woody materials would determine dead wood inputs. Various disturbances, e.g. wind, ice, and disease, occur in these stands unevenly in space and time with uneven generation of CWD. This scheme is one possible explanation for large differences in CWD.

The other explanation assumes differences in quantities of CWD would have to result from uneven decomposition or combustion. This situation seems less likely. Differences in fire frequency did not seem to explain difference in quantity of dead wood. Although decomposition is probably variable in the landscape, a six-fold variation of decomposition rates at the spatial scale of a burn unit in stands of similar species and

conditions is possible, but seems unlikely. It is possible fire had an indirect effect by influencing the community of decomposers (Harmon *et al.*, 1986, Sippola and Renvall, 1999), but this is only conjecture, since decay rates of DWD and detritivore communities were not measured in this study. Considering the two suggested explanations for high variability in DWD volumes, the one focusing on input seems more likely (Harmon *et al.*, 1986; Monserud, 1976; Yin, 1999).

While there was no clear effect of fire frequency on the quantities of DWD, that is not to say that fire did not burn the pieces, even the larger pieces that would seem to be unlikely to burn. A visit to a recently burned unit found evidence of CWD that was completely combusted (Personal observation). Ash outlines remained that indicated what appeared to be large pieces that had been totally consumed by fire (Figures 28 and 29). There is no way to know exactly how big the debris pieces were, but photographs are indicative of pieces up 20 cm diameter.

4.2. Litter

The amounts of litter we measured were comparable to other values given in the literature. A study of mixed broad-leaved forests in the Appalachians averaged 6 t ha^{-1} (Hubbard *et al.*, 2004) and another study of oak stands had more than 2 t ha^{-1} (Jonard *et al.*, 2008) (Table 7). Given that leaf litter is the dead material most sensitive to prescribed fire, it is surprising the litter depth was not responsive to fire frequency or time since fire. A recent study at OWMA concluded that litter cover increased two-fold and litter depth increased three-fold in the three years after a prescribed burn (Burton *et al*., 2011). The depth of litter declined in CWMA as FPD increased. Besides that result, there were no

significant results for FPD or YSF's effect on litter. A larger study in the same sites as this one found that litter mass increased in the three years following a prescribed burn then flattened out (Hallgren, Oklahoma State University, personal communication). This could explain the lack of an effect of YSF on litter depth, since many of the units had YSF that were close to 3 or greater. It appears the low intensity prescribed burns consumed some of the litter and the normal leaf fall from the closed canopy rapidly replaced it in two of the sites.

4.3. Snags

Snag volumes at all three sites were intermediate in comparison to volumes of old-growth and second-growth mesic oak forests, 20 and 10 m^3 ha^{-1}, respectively (Spetich *et al.*, 1999). Only two regressions were significant: in CWMA, subordinate snag species lost bark as FPD increased and in LWMA, *Q. stellata* basal area increased when the time since fire increased. The increase in basal area of *Q. stellata* in response to increasing years since fire could be the result of a delay in mortality after a prescribed burn. Fire might not have caused the deaths of the trees, but it could have been an initiating factor for deaths of *Q. stellata* in LWMA. Density was not significantly affected by fire frequency for these trees, so smaller snags could be falling over and larger snags from trees that took longer to die could be replacing them.

The low severity fires in these sites limit the possibility of them directly killing canopy and subcanopy trees (Agee, 1996; Bagne *et al.*, 2008; Burton *et al.*, 2010; Cutter and Guyette, 1994; Johnson and Risser, 1975). On the other hand, fire may predispose them to other factors leading to death such as disease and insects (Franklin *et al.*, 1987;

Peet and Christensen, 1987). It is likely that some species that are not adapted to fire, such as *Cercis canadensis*, eastern redbud, are killed if the stem is small enough, but even trees of this species beyond 10 cm dbh can probably survive the surface fires.

There are factors beside fire that may affect snag quantities, such as stand age. Compared to stands in the early stages of succession, those with old trees will have more living trees with decay that topple before, or soon after, death (Moroni, 2006). Oaks are resistant to rot when they are alive, but all trees would eventually be invaded by wood decaying fungi. There are fungi and other pathogens that can invade and cause rot and death, especially when disturbances such as fire or wind cause damage and break the barrier to wood rotting fungi (Boddy and Rayner, 1983b; Smith and Sutherland, 1997). In many cases, snags were found that would yield only a few millimeters to probing with a pointed object, but were hollow sounding when struck, implying at least a loss of some of the heartwood. Even though it is rot resistant, the heartwood is generally more susceptible than bark or sapwood to rot-causing organisms. Heartwood could be invaded and start disintegrating, then decay organisms that specialize in butt rots, such as some fungus, could be working down through the heartwood toward the base of the tree. Fire or other factors could cause damage at the base as well, permitting further access for butt rot specialists (Boddy, 2001; Shigo, 1979; Smith and Sutherland, 1997). In the case of a mature tree, if butt rot occurs while the rest of the tree is largely intact, the weakened base has to support a large quantity of material, making the tree a prime candidate for a fall.

Another possibility was that wind was knocking over the snags as well. More than half of the snags had more than half their stems covered by bark and the integrity of the

sapwood was firm for the majority of snags (Table 5). Transition of snags to logs/CWD could be accomplished by a tip-over within probably less than 10 years of death caused by wind damage. Since many of the pieces of down wood had good integrity, that made it appear that when a tree died, it fell over within a few years and most of the decay was taking place in the down position (Harmon *et al.*, 1986). Many of the snags we surveyed were small, suppressed trees. Given that strong winds are a common occurrence, these winds can knock down large and small trees and this can provide the opportunity for DWD input with the pieces consisting of sound wood (Harmon *et al.*, 1986; Rose *et al.*, 2001).

CWMA had the lowest density of snags, but more volume of dead wood compared to the other sites. This indicated that CWMA had larger snags (Table 6). The taller trees in CWMA were probably the reason for this. Better productivity in CWMA probably explained this; CWMA received greater mean precipitation than the other two sites. These taller snags would be beneficial for at least some of the wildlife. Some species of breeding birds, Pileated Woodpecker and Eastern screech-owl, *Otus asio*, for example, prefer to nest in cavities well above the ground (Ehrlich *et al.*, 1988).

The ratio of standing dead to live trees was higher in old-growth than second-growth stands in mesic oak forests (0.10 vs. 0.08, Spetich *et al.*, 1999). The ratio for each WMA was over 0.10, suggesting they had some old-growth characteristics (Figures 27, 28, and 29). The plot of the dead to live ratio for dbh classes told a more complicated story. The ratio was smallest for small trees, increased to an early peak, then dipped a little and leveled. At 30 cm dbh, the plot rose sharply to another peak that was over 0.50 and became more irregular as the density of trees over 50-cm dbh dropped. Spetich *et al.*

(1999) found a somewhat stable ratio for all of the size classes. Normally, stand development patterns showed that small trees were eliminated through self-thinning. Large, old trees senesced or gave way to wind or ice storms (Peet and Christensen, 1987). There was also the possibility that the small trees recently recruited because of fire suppression and were not to the point of density dependent self-thinning. Also, it was possible that the greater dead to live ratio for large trees resulted because large trees persisted longer, since it takes longer for larger trees to fall.

The wildlife trees with dbh 25 – 50 cm exceeded density recommendations, 6 per ha, in all three sites (Table 6). However, for wildlife trees over 50 cm dbh, the densities in all three sites were less than the recommended density, 4 per hectare (Rafferty *et al.*, 1996). With wildlife conservation being of primary concern in these sites, the availability of suitable snags was not ideal. The larger class of snags was important because of the space those trees provide for breeding birds and small mammals, but their densities were insufficient (Loeb, 2002). Bagne *et al.* (2008) noted larger-diameter trees were important to nesting birds as did a study of bats (Johnson *et al.*, 2009). On the other hand, some of the species that require large cavities or hollows might be able to utilize living trees with acceptable hollows. Although we did not survey live cavity trees, personal observation supports the conclusion that there were many live trees with cavities suitable for wildlife. The good coverage of bark was beneficial for bats, as they will roost under loose bark (Loeb, 2002).

4.4. Broader Implications

Another very important implication for DWD and snags is the capacity for carbon storage. The issue of climate change has made carbon storage in natural areas a focus of research (Birdsey *et al.*, 2006). Carbon content was not directly measured, but a rough estimate was made. This study only measured the above ground dead wood and litter, thus living biomass and soil carbon fractions were not estimated at all. The Cross Timbers forests had between 6.5 and 8.4 Mg ha^{-1} of carbon in combined DWD and snag fractions, which was low compared to the combined snag and CWD fractions of 17.3 Mg ha-1 of carbon in a mixed hardwood mesic site in Minnesota (Bradford *et al.*, 2009) (Table 7). On the other hand, these values were comparable to the 7.2 Mg ha^{-1} found in another study of a Cross Timbers forest (Johnson and Risser, 1974) The carbon stored in CWD and FWD in the Cross Timbers was greater than carbon storage in a study of the same components for the forests of the south central region of the U.S. (2.2 Mg ha^{-1}, CWD, 2.8 Mg ha^{-1} FWD, Woodall *et al.*, 2008) The litter storage of carbon, 4.61 to 5.31 Mg ha^{-1}, was also comparable to the study by Johnson and Risser (1974) (Table 7).

The Cross Timbers were relatively undisturbed since the timber was not of commercial value and the soils were too poor for agriculture. Research has shown that it could contain some of the largest tracts of old-growth forest in the eastern United States (Therrell and Stahle, 1998). On the other hand, there was research evidence that in some areas, fire suppression led to changes in forest composition and structure. Parts of the Cross Timbers that were structured like savannas, with scattered trees, have filled in with young oaks where fire was suppressed (DeSantis *et al*., 2010; Johnson and Risser, 1975; Johnson and Risser 1974). A comparison of tree size distributions in a forest and savanna

found the forest resembled a savanna that had filled in with young trees in the early 1900s. The forest and savanna both had similar numbers of trees in the large size classes, while the forest had an excess of trees in the smaller size classes (Johnson and Risser, 1974). It seemed that fire suppression enabled oak recruitment. Aerial photos of the areas illustrated more open stands throughout these sites in the 1930s and 1940s (Unpublished data). Studies going back to the 1970s also supported the theory that the upland forests are becoming denser (DeSantis *et al.*, 2010; Johnson and Risser, 1974; Johnson and Risser, 1975). Several decades of encroachment had probably created a patchwork of open savannas, former savannas filling in from oak recruitment, and dense closed canopy stands. These conditions could have led to variable size class distributions across the landscape, which in turn led to varied volumes of DWD and basal areas of snags in these stands (Miehs *et al.*, 2010).

5. Conclusion

The upland, xeric oak forests of Oklahoma show some signs of old-growth forests, as indicated by old trees, an uneven-aged diameter distribution, and high ratio of standing dead to live trees. Other oak forests have higher amounts of dead wood, most likely because of higher productivity on more mesic sites. The quantities of dead wood components do not have a relationship to prescribed burns over a range of 0 to 5 FPD in the Cross Timbers. However, the fires could be sustaining a steady state process for input and combustion of these materials. The amount of standing dead and down wood in the Cross Timber varies greatly throughout the landscape, probably due to local, severe disturbances, such as wind, hail, ice, and disease. Snag densities of trees >50 cm dbh do

not meet recommendations for wildlife. To improve snag densities, large trees could be girdled so that they can become snags in the future.

Future work on the topic of dead wood material in the Cross Timbers should use permanent plots that map live trees, snags, and CWD to estimate the input and exit of dead wood. Another interesting study would investigate the decay rate for snags and CWD, since there is very little literature available on decay processes in upland, xeric sites. Further study of the large, live old-growth trees would be valuable to determine their demographics and value to wildlife.

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Table 1. The fire history of the eight burn unit sampled in Okmulgee Wildlife Management Area, Oklahoma for the period 1988-2010. All burns took place in spring of the respective year.

Okmulgee Wildlife Management Area burn units								
Year	1	2	3	4	6	7	10	13
2010		1						
2009								
2008				1	1			
2007	1	1						
2006								
2005			1	1		1	1	
2004		1		1				
2003	1						1	
2002				1	1			
2001	1			1			1	
2000	1	1	1					
1999	1							
1998	1							
1997	1		1		1			
1996						1	1	
1995	1							
1994		1		1			1	
1993	1				1			
1992		1		1			1	
1991			1	1				
1990								
1989	1							
1988								
Total fires	10	6	4	8	4	2	6	0
Fires per decade	4.55	2.73	1.82	3.64	1.82	0.91	2.73	0
Years since fire	3	0	5	2	2	5	5	>22

Table 2. The fire history of the eight burn unit sampled in Lexington Wildlife Management Area, Oklahoma for the period 1986-2010. All burns took place in spring of the respective year.

Lexington Wildlife Management Area burn units								
Year	1S	3N	3S	6	9SE	10E	10SW	No Fire
2010								
2009								
2008		1	1		1	1	1	
2007				1				
2006								
2005								
2004	1				1			
2003		1	1			1		
2002								
2001								
2000		1	1	1				
1999	1				1			
1998								
1997								
1996								
1995		1	1	1				
1994	1				1			
1993								
1992				1		1	1	
1991		1	1					
1990								
1989	1				1			
1988		1	1	1		1	1	
1987		1						
1986	1							
Total fires	5	7	6	5	5	4	3	0
Fires per decade	2.1	2.9	2.5	2.1	2.1	1.7	1.3	0
Years since fire	6	2	2	3	2	2	2	>24

Table 3. The fire history of the eight burn units sampled in Cherokee Wildlife Management Area, Oklahoma for the period 1984-2010. All burns took place in spring of the respective year.

Cherokee Wildlife Management Area burn units								
Year	7	10	14	15	16	17	19	21
2010	1	1						
2009								
2008								
2007	1	1		1	1	1		
2006								
2005							1	
2004					1	1		
2003			1					
2002								
2001						1		
2000								
1999								
1998								
1997								
1996								
1995								
1994			1	1			1	
1993					1	1		
1992	1	1	1	1	1			
1991						1	1	
1990								
1989								
1988								
1987	1	1	1	1		1		
1986					1	1	1	
1985			1					
1984		1						
Total fires	4	5	5	4	5	7	4	0
Fires per decade	1.5	1.9	1.9	1.5	1.9	2.7	1.5	0
Years since fire	0	0	7	3	3	3	5	>26

Table 4. Class descriptions of decay in bark and wood of coarse woody debris and snags.

Decay category	Decay class 1	Decay class 2	Decay class 3	Decay class 4	Decay class 5
Bark	> 90% cover	89 – 50 % cover	49 – 26 % cover	< 25 % cover	Hollow
Wood integrity	Solid	Soft	Chunks missing	Decayed	None

Table 5. Overall means and treatment ranges for bark and wood decay in coarse, woody debris and snags by wildlife management area.

Decay Category	Okmulgee WMA	Lexington WMA	Cherokee WMA
CWD Bark	2.68 (2 – 3.37)	2.2 (1.33 – 2.9)	2.74 (2.02 – 3.15)
CWD Wood	2.21 (1.64 – 2.8)	1.56 (1.08 – 2.32)	1.94 (1.33 – 2.45)
Snag Bark	1.37 (.75 – 1.71)	1.53 (1.12 – 1.99)	1.7 (1.43 – 1.95)
Snag Wood	1.21 (.49 – 1.5)	1.45 (1.28 – 1.61)	1.49 (1.3 – 1.66)

Table 6. Overall means and treatment ranges of snag density, basal area, and volume by wildlife management area.

Category	Okmulgee WMA	Lexington WMA	Cherokee WMA
	Snags ha^{-1}		
Density ha^{-1}	139 (105 – 189)	129 (107 – 192)	99 (55 – 177)
DBH 25 - 50 cm ha^{-1}	12 (5 – 19)	8 (3 – 19)	10 (3 – 17)
DBH > 50 cm ha^{-1}	0 (0 – 1)	0	1 (0 – 1)
	Basal area (m^2 ha^{-1})		
Basal area	2.25 (1.85 -2.77)	1.77 (.9 – 3.18)	2.09 (1.31 – 3.07)
	Volume (m^3 ha^{-1})		
Volume	14.12 (10.44 – 19.79)	11.27 (4.27 – 22.67)	18.05 (10.41 – 31.33)

Table 7. Estimates of volume, biomass, and carbon (C) in each wildlife management area.

	OWMA			LWMA			CWMA		
	Vol. (m³ ha⁻¹)	Mass (Mg ha⁻¹)		Vol. (m³ ha⁻¹)	Mass (Mg ha⁻¹)		Vol. (m³ ha⁻¹)	Mass (Mg ha⁻¹)	
		Biomass	C		Biomass	C		Biomass	C
Snags	14.12	6.50	3.3	11.27	5.18	2.6	18.05	8.3	4.2
DWD	14.13	6.50	3.3	16.26	7.48	3.7	18.32	8.4	4.2
Litter	381	11.43	5.0	349	10.47	4.6	402	12.06	5.3
Total		24.43	11.6		23.13	10.9		28.76	13.7
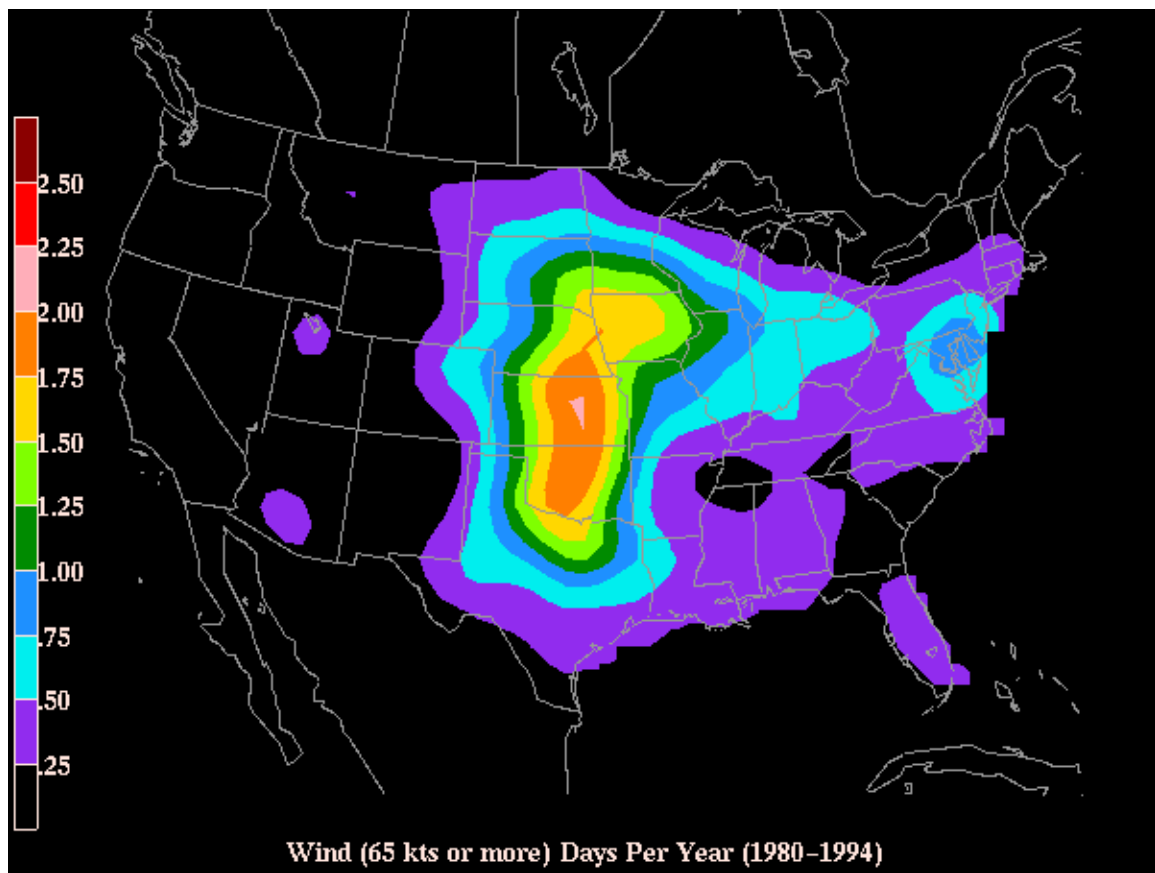
Figure 1. Strong wind days per year in the continental U.S. Oklahoma was among a small group of states that received the most days of strong wind in the country, from Brooks 2011a
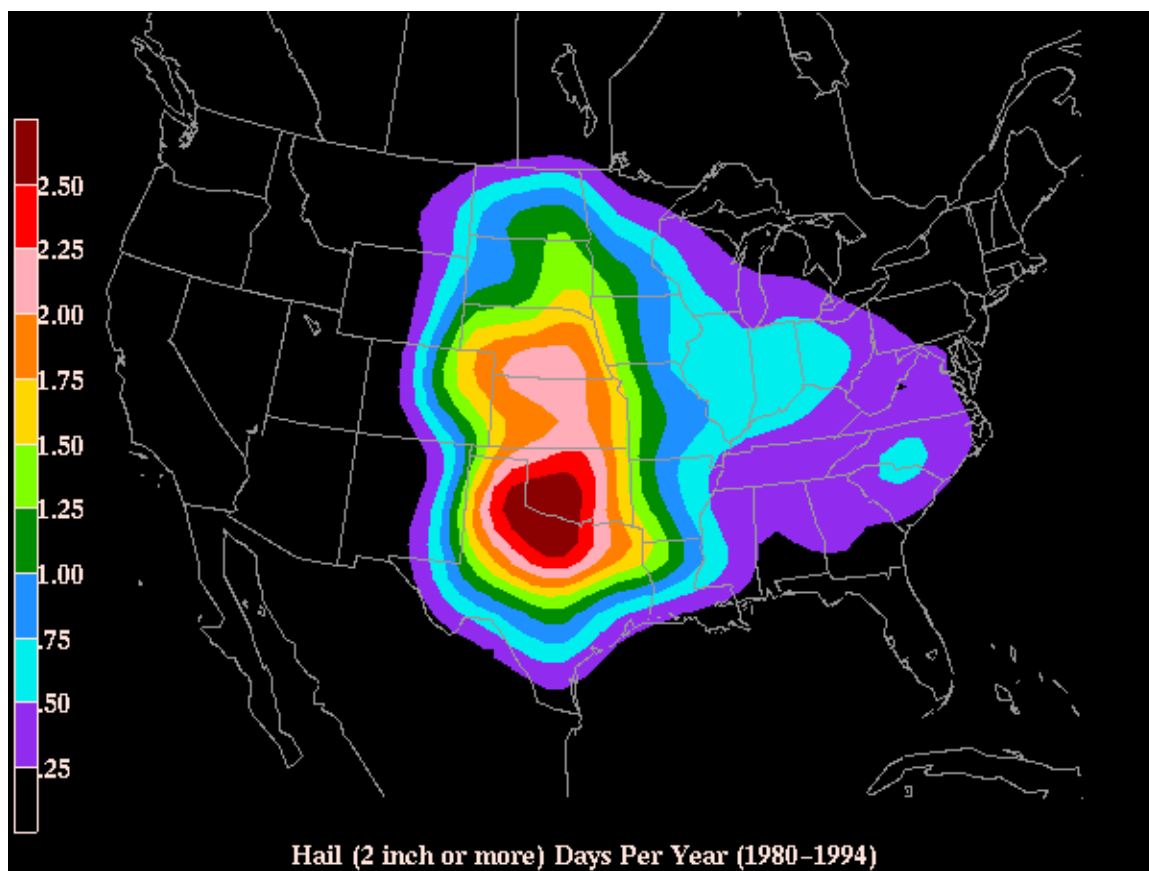
Figure 2. Damaging hail days per year in the continental U.S. Oklahoma was among a small group of states that received the most days of strong wind in the country, from Brooks 2011a

Figure 3. *Corallorhiza wisteriana*, a saprophytic orchid in Pasco County, Florida. The plant is an example of flora that rely on down woody debris for sustenance. Note the decayed log immediately behind the stems.

DWD Inputs				Snags		DWD Exit	
Stand Factors	Environmental Factors			&			
	Abiotic	Biotic		DWD		Abiotic	Biotic
Density	Drought	Insects	→		→	Fragmentation	Detritivore
Age	Fire	Disease				Leaching	
Productivity	Ice					Fire	
Size	Wind						
	Hail						
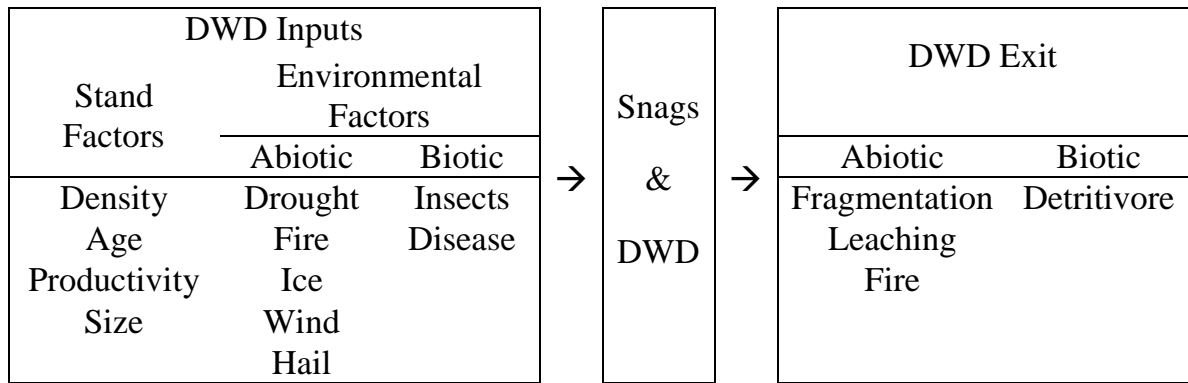
Figure 4. Model of dead wood input and exit from a forest. Starting on the left side, forest characteristics influence the quantity of potential dead wood. Environmental factors are the mortality inducing events that lead to creation of dead wood. Decomposition processes appear to the right of the model
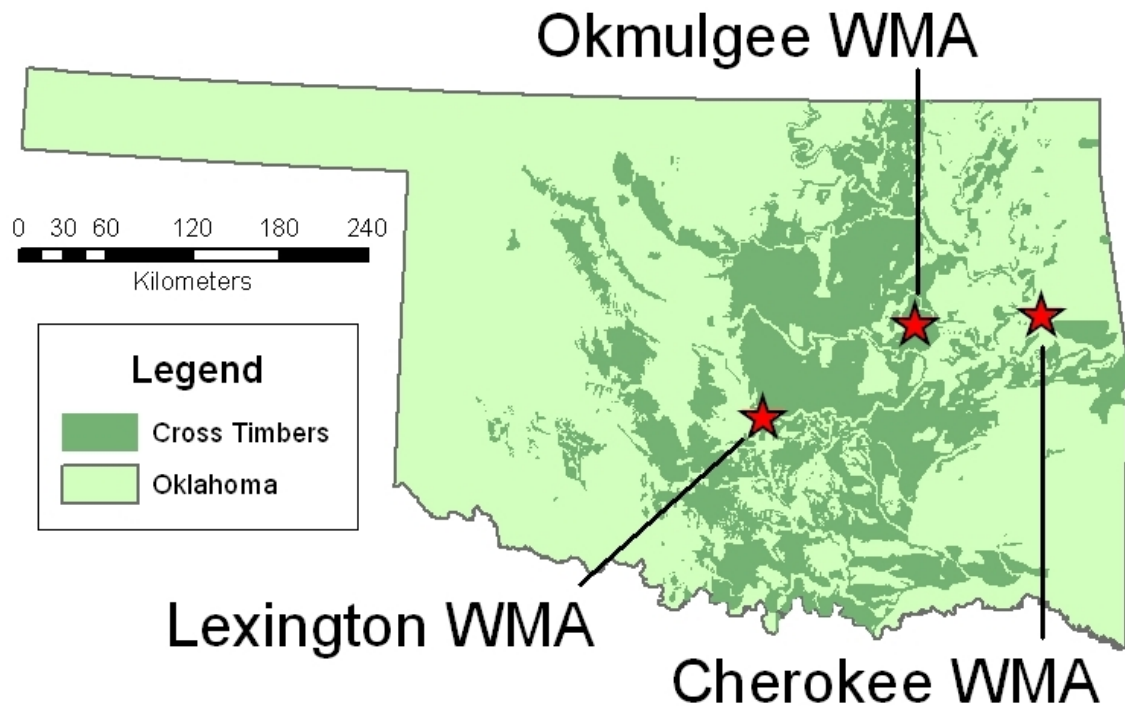
Figure 5. The locations of the three study sites in Oklahoma. Sites were wildlife management areas located in central and eastern Oklahoma, throughout the range of the Cross Timbers
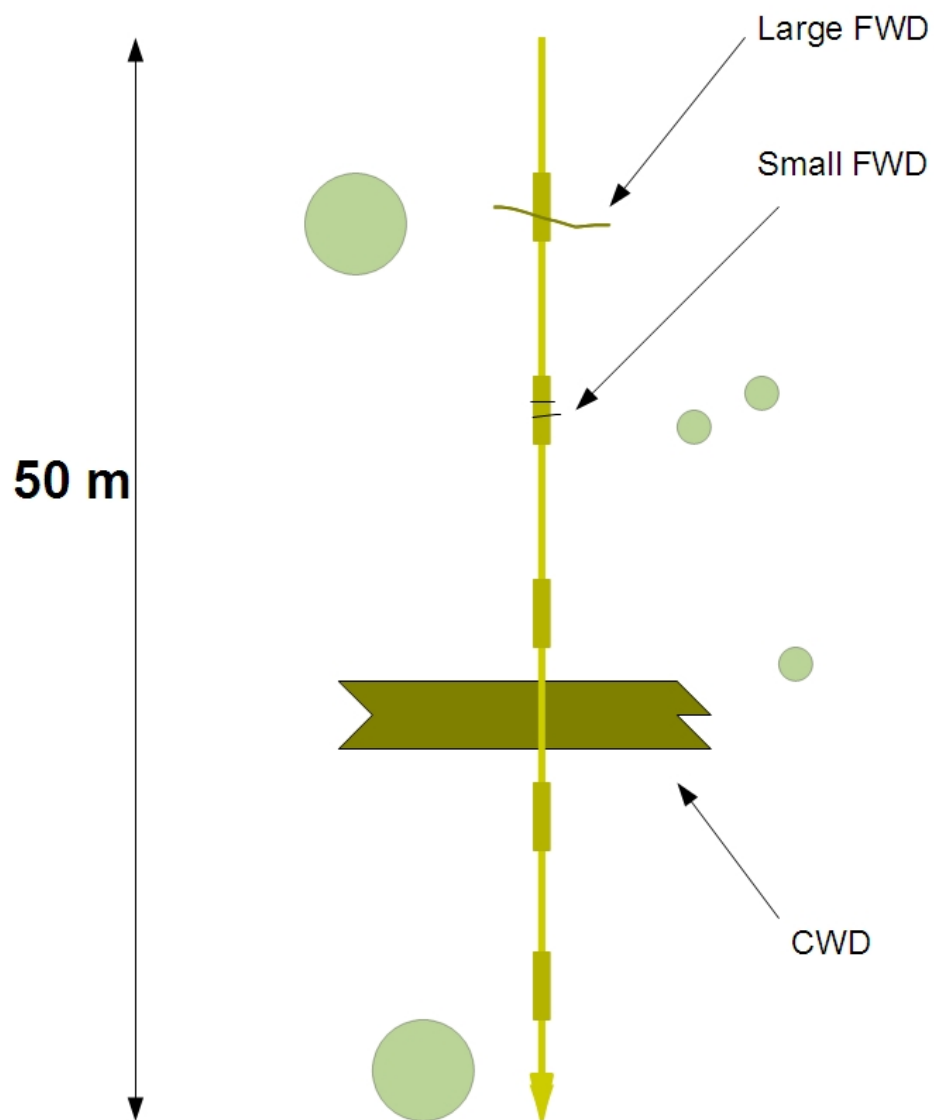
Figure 6. Diagram of a DWD transect. Thicker sections approximate the subsections used for sampling small, medium, and large FWD. CWD was sampled along the whole length of the transect.
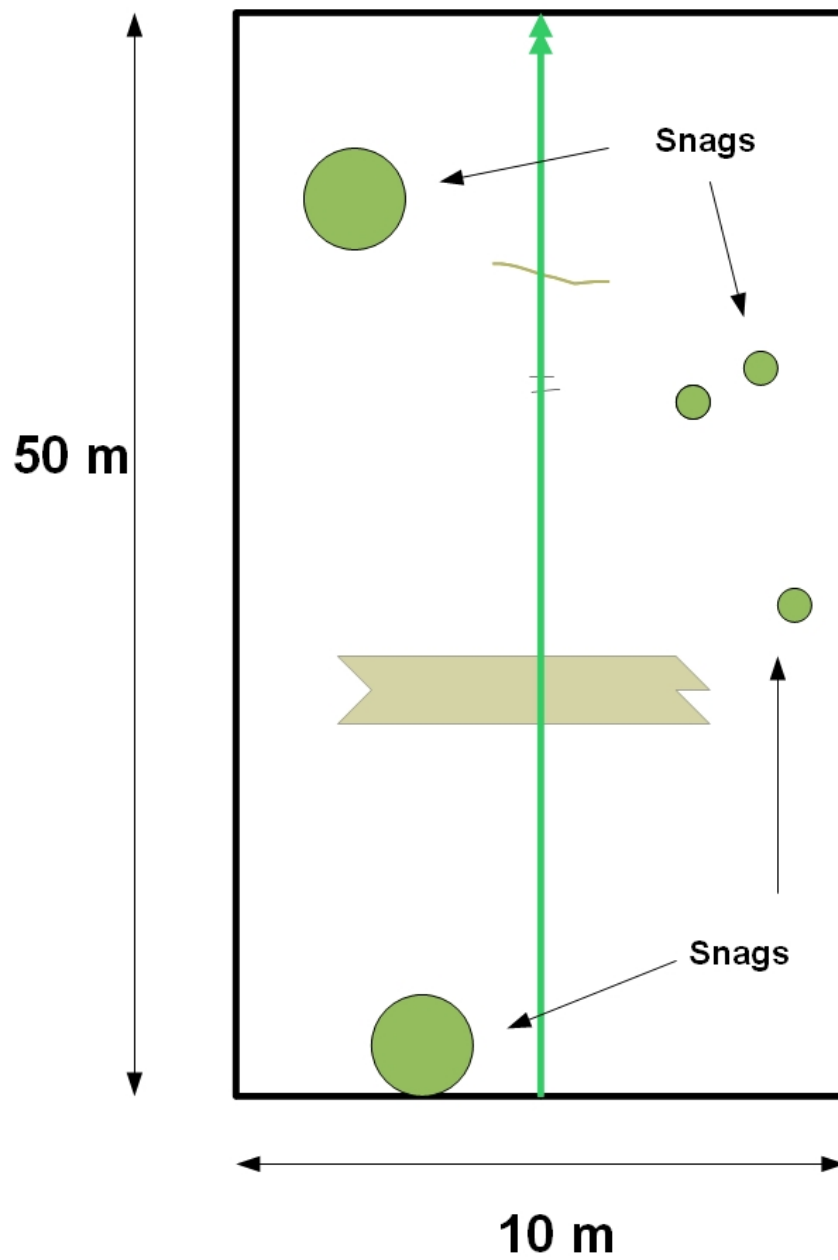
Figure 7. A diagram of a snag plot. At the end of the midline (the starting point of the DWD transect line), the BAF 10 prism plot was measured.
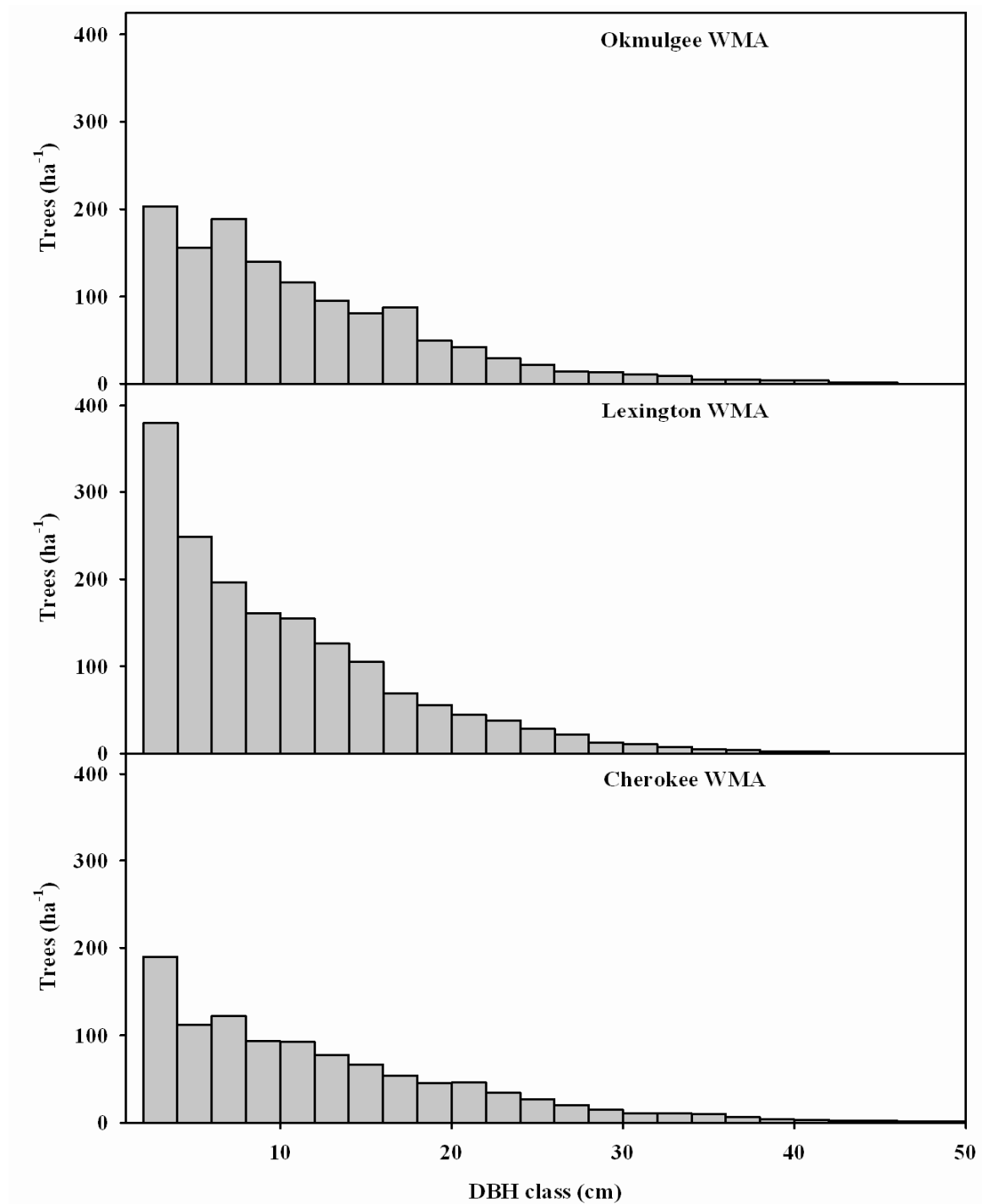
Figure 8. The diameter distribution in terms of trees ha^{-1} by 2 cm dbh class across all management units in three wildlife management areas (WMA). The shape of the distribution is a reverse-J, which means that the stands were approaching an old-growth stage of size structure.
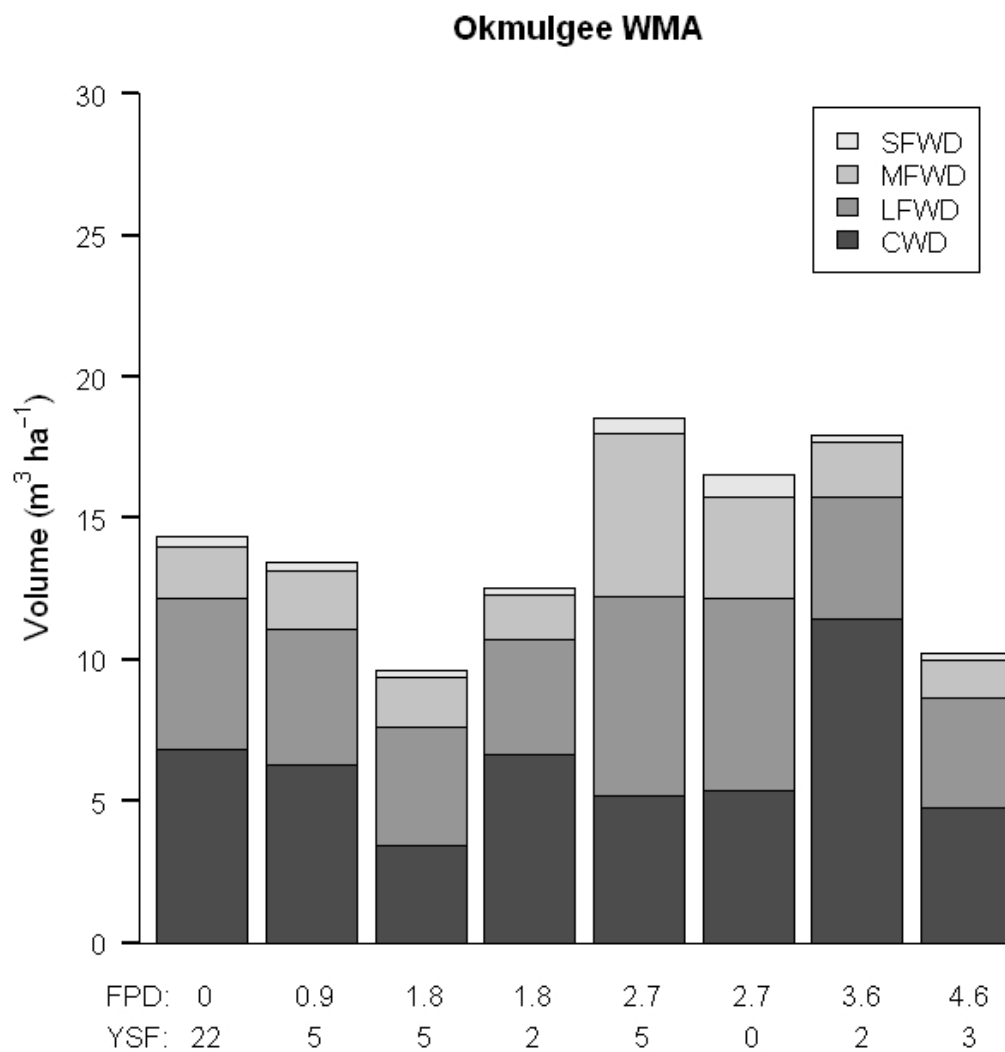
Okmulgee WMA

Figure 9. Effect of fires per decade (FPD) and years since fire (YSF) on volume of small, fine woody debris (SFWD); medium, fine woody debris (MFWD); large, fine woody debris (LFWD); and coarse woody debris (CWD) at Okmulgee WMA.
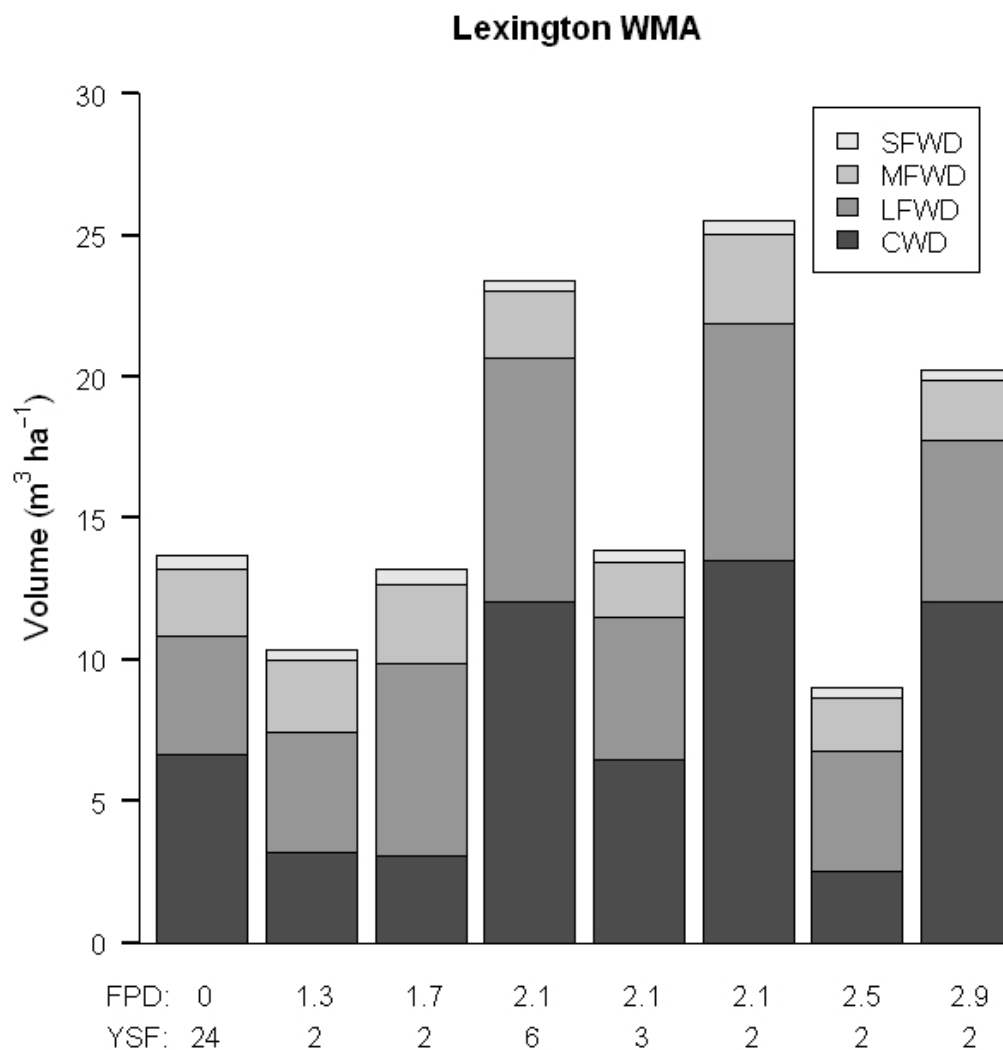
Figure 10. Effect of fires per decade (FPD) and years since fire (YSF) on volume of small, fine woody debris (SFWD); medium, fine woody debris (MFWD); large, fine woody debris (LFWD); and coarse woody debris (CWD) at Lexington WMA.
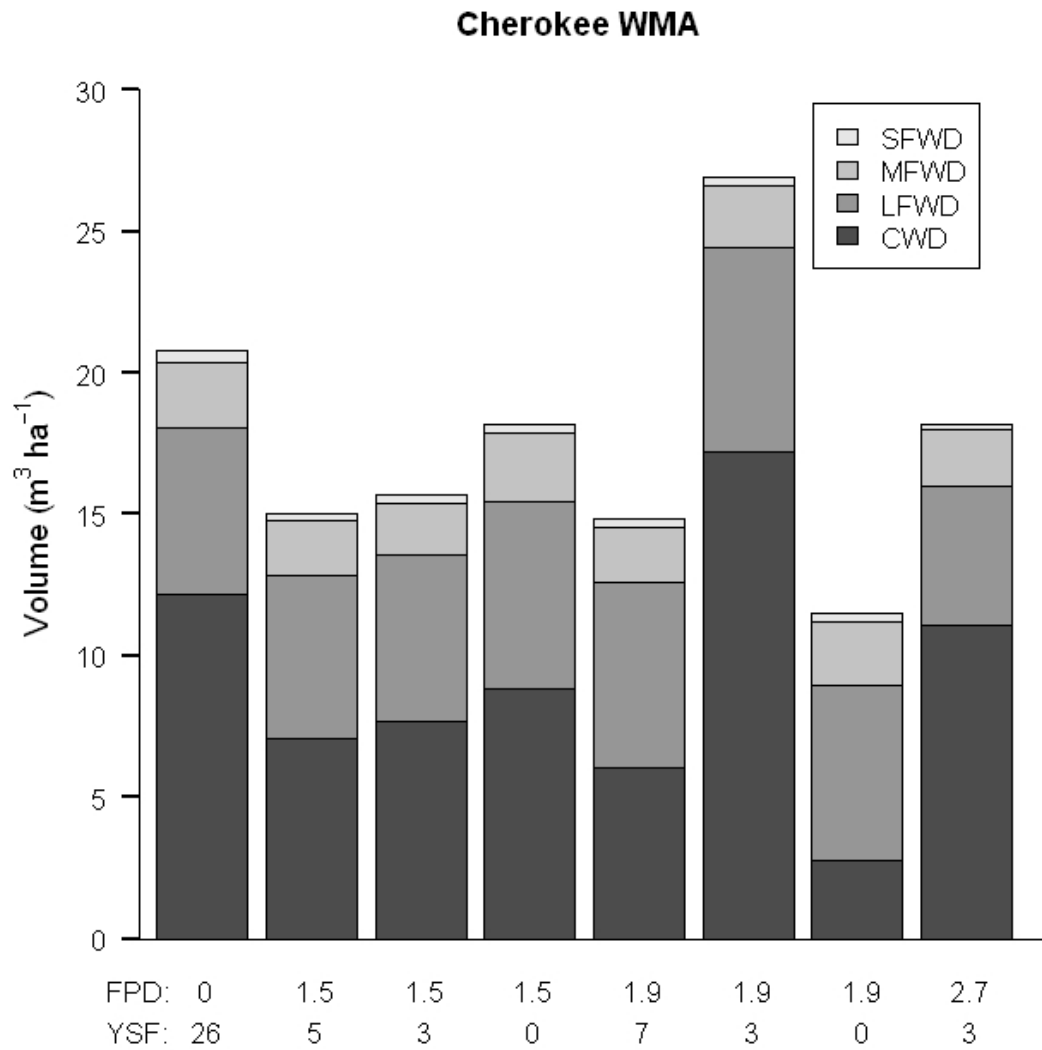
Figure 11. Effect of fires per decade (FPD) and years since fire (YSF) on volume of small, fine woody debris (SFWD); medium, fine woody debris (MFWD); large, fine woody debris (LFWD); and coarse woody debris (CWD) at Cherokee WMA.
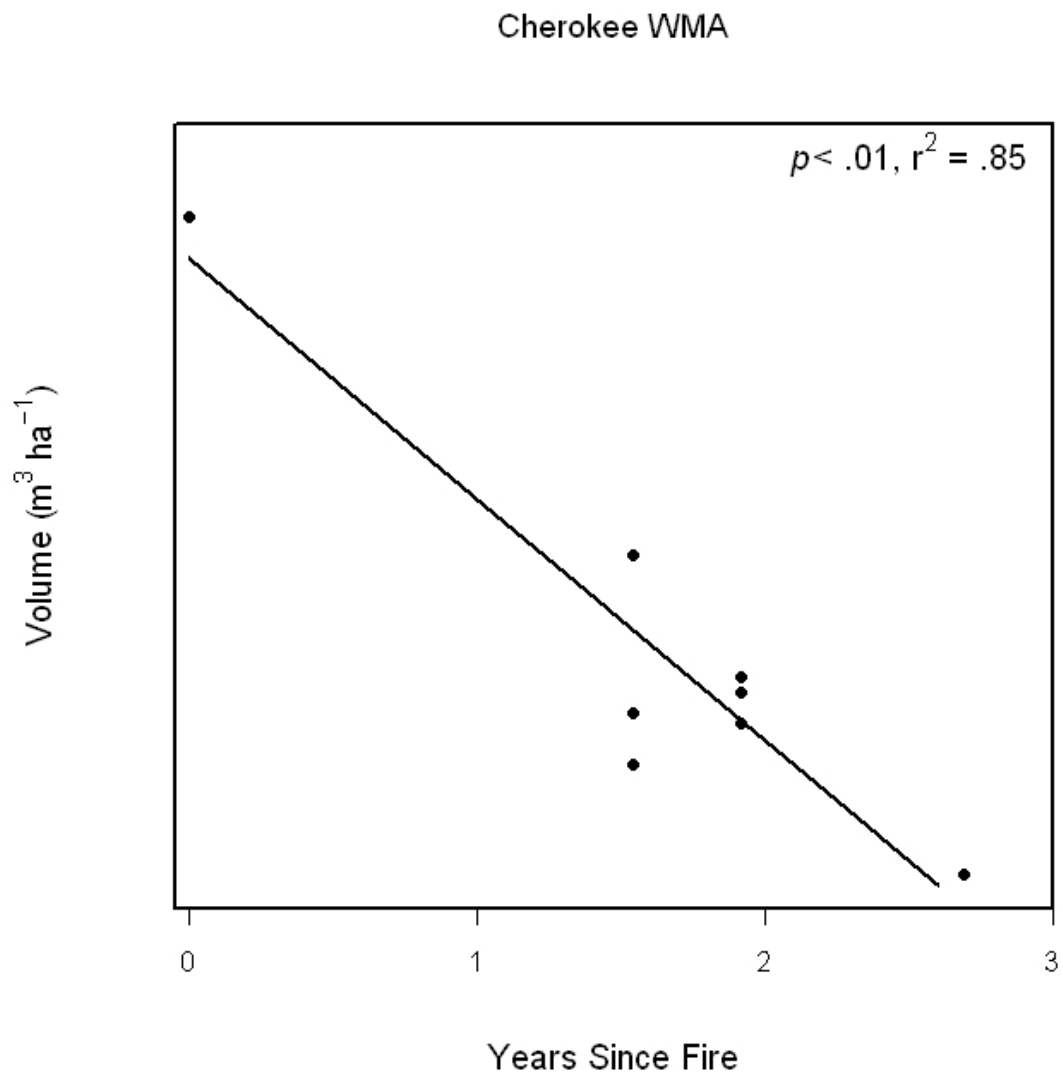
Figure 12. Plot of the regression of fires per decade and *Q. marilandica* CWD volume in Cherokee WMA. A negative relationship resulted; when the fire frequency increased, the volume declined.
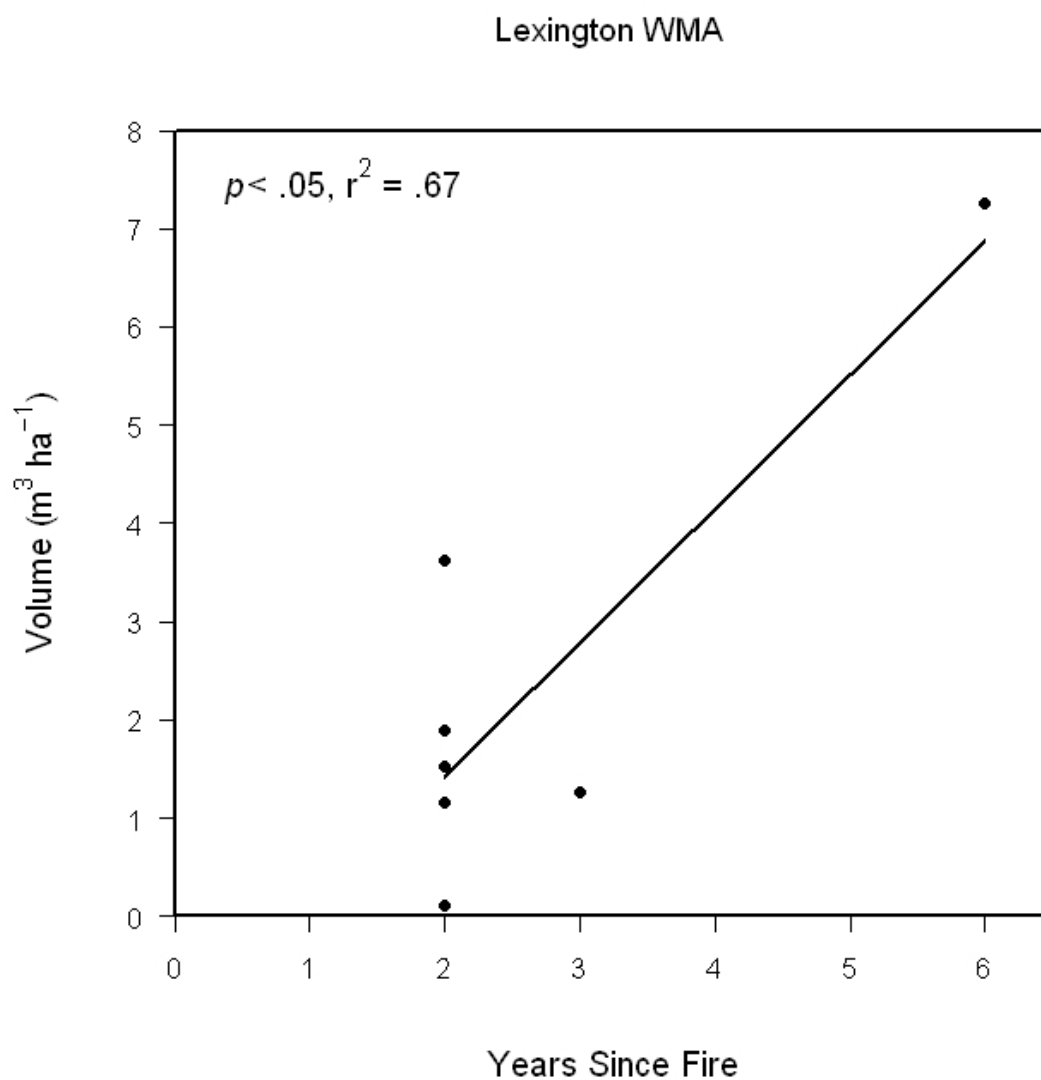
Figure 13. Regression plot of years since fire and *Q. stellata* CWD volume Lexington WMA. The volume of *Q. stellata* CWD built up as the time since the last fire increased.
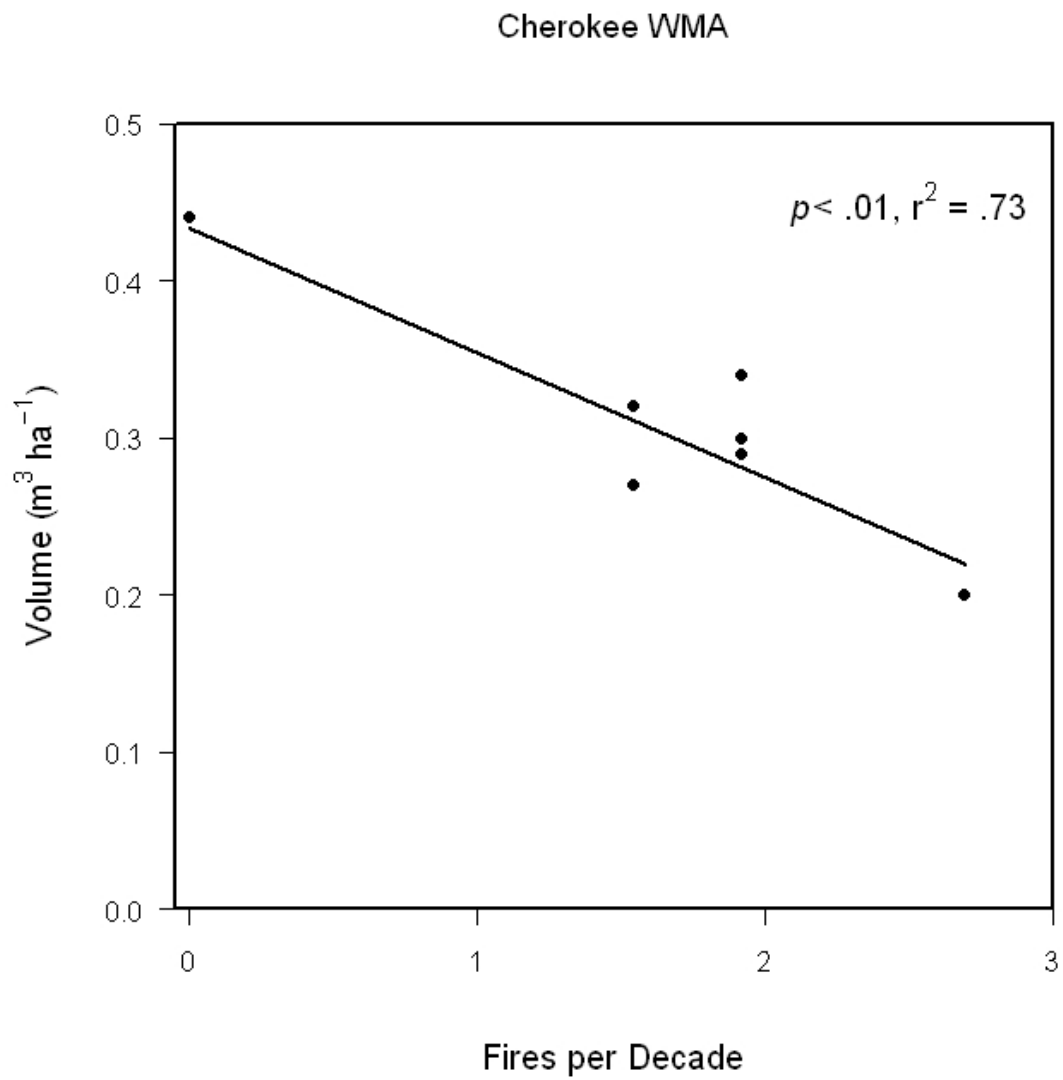
Figure 14. Regression plot fires per decade and small, fine woody debris in Cherokee WMA. The volume decreased as fire became more frequent.
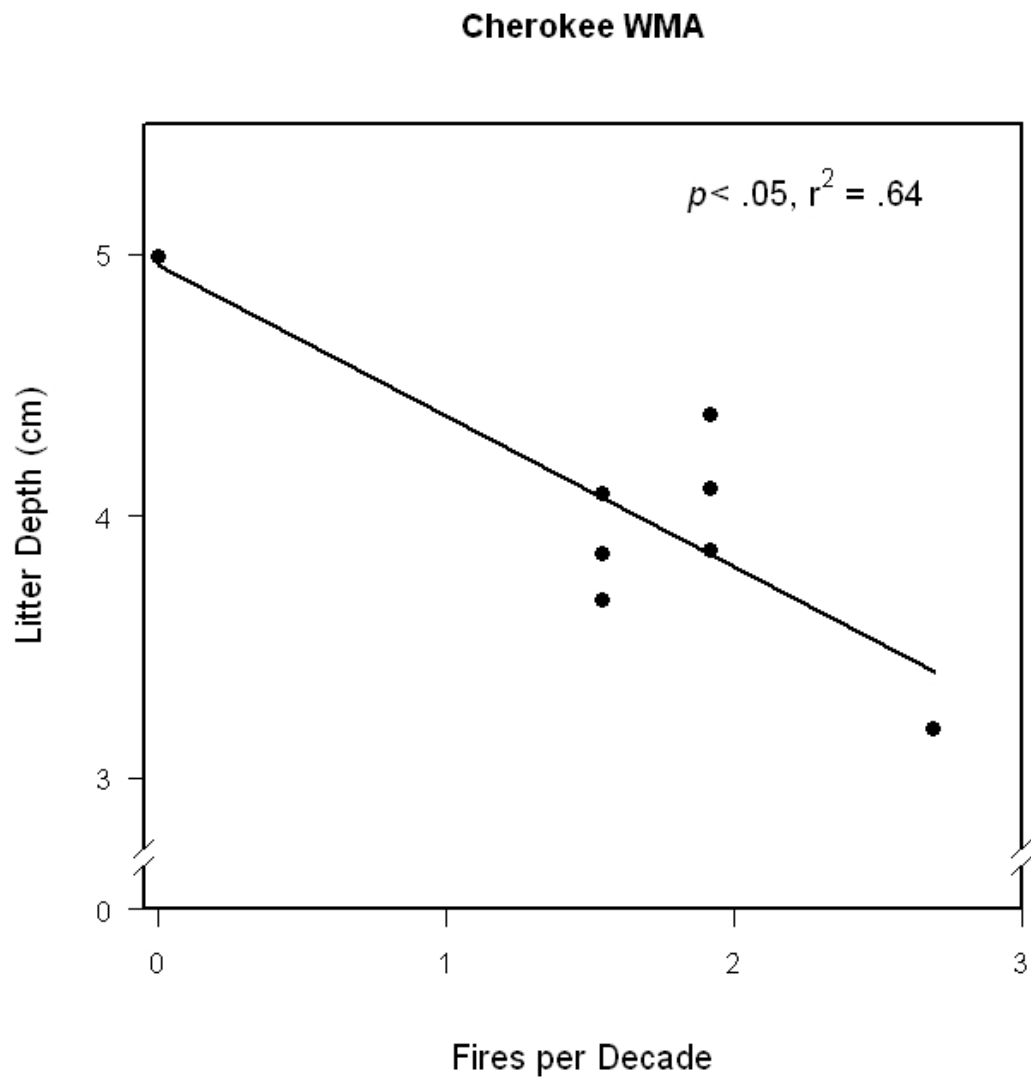
Cherokee WMA

Figure 15. Plot of the regression of fires per decade and leaf litter depth in Cherokee WMA. When fire frequency increased, depth of the litter got smaller.
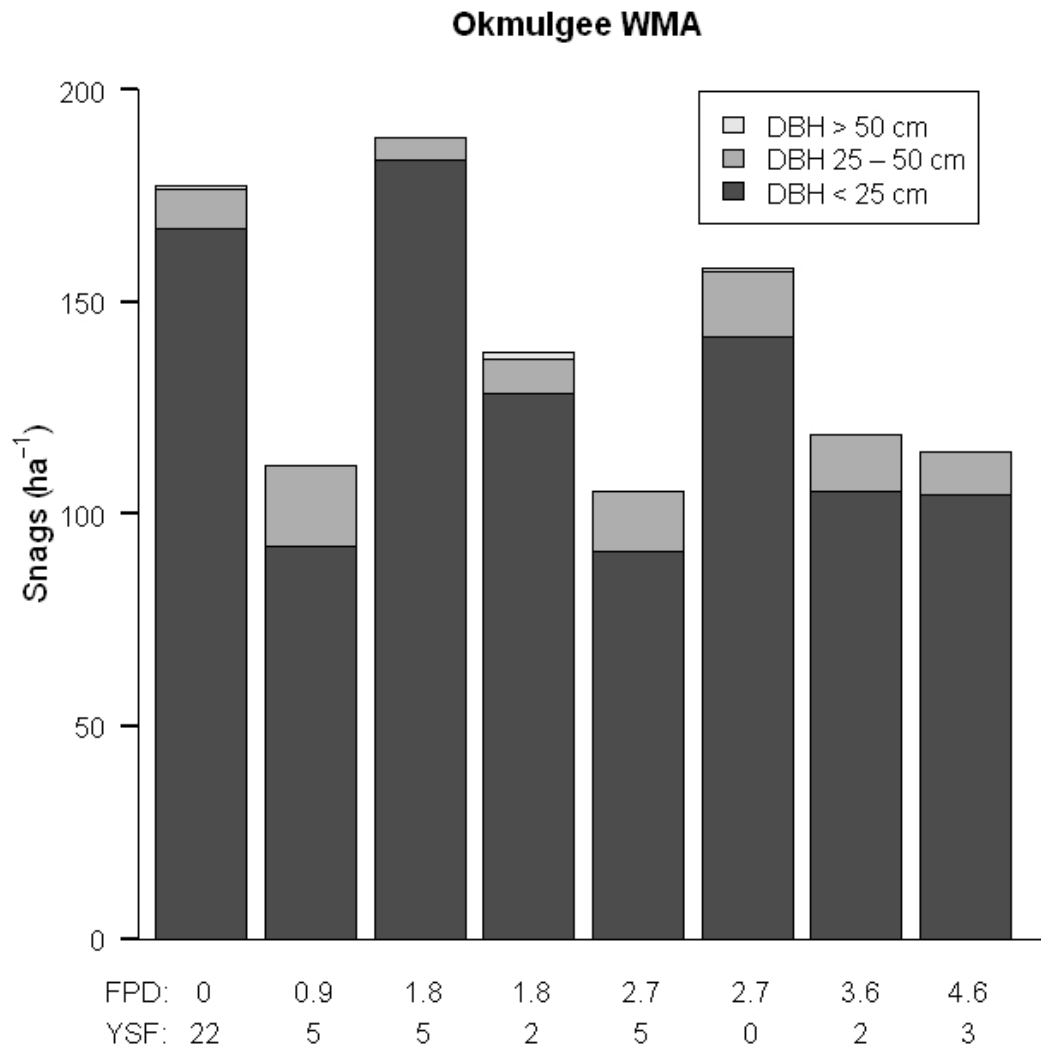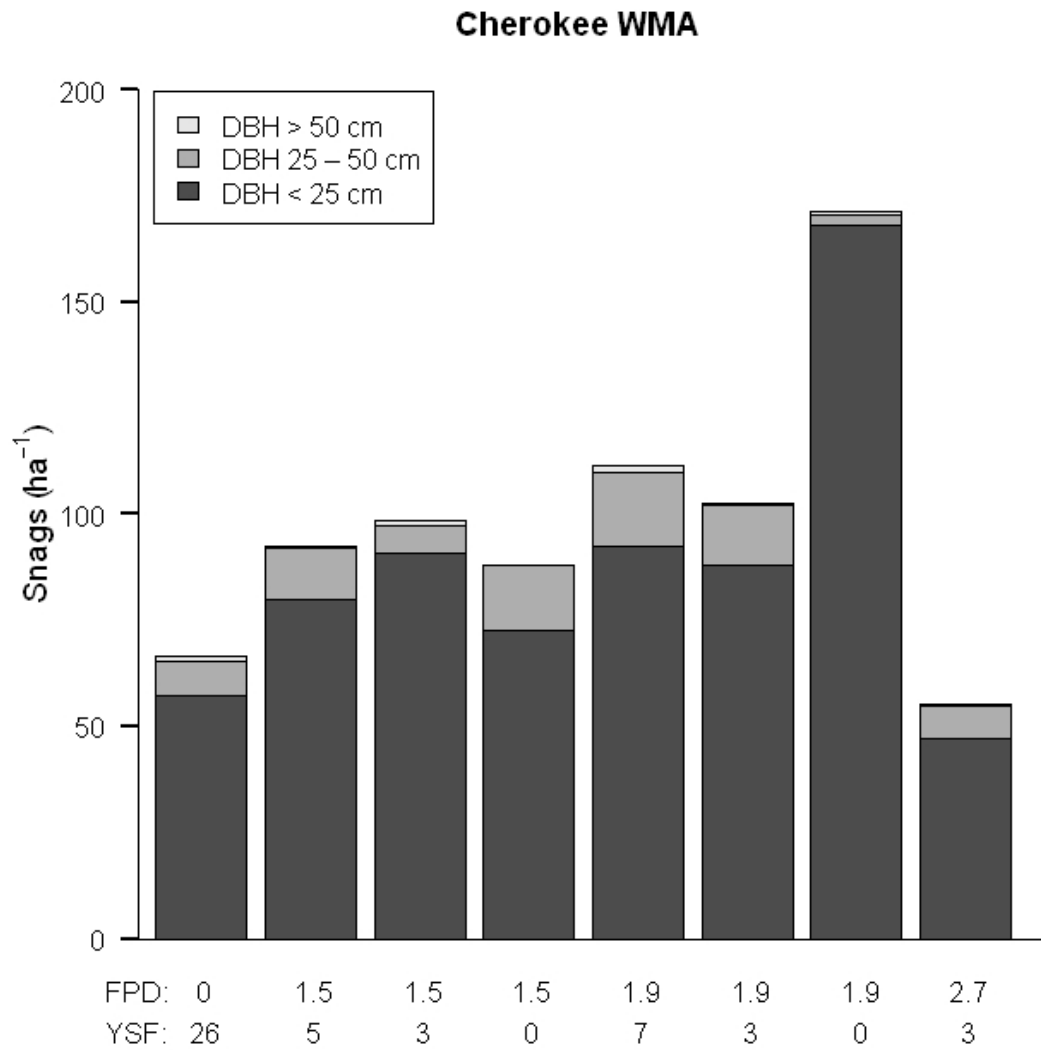
Figure 16. The effect of fires per decade (FPD) and years since fire (YSF) on the snag density in different diameter classes across all the units in Okmulgee WMA.
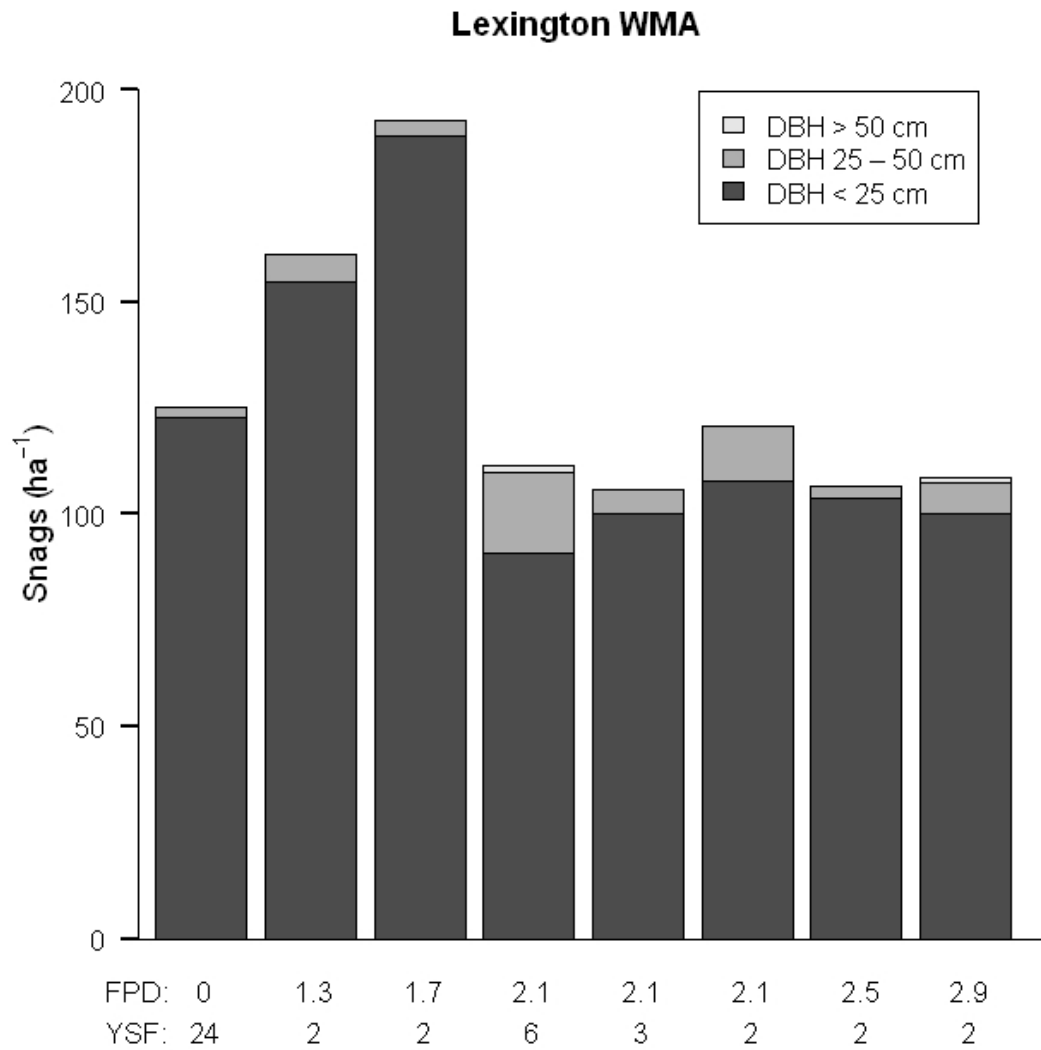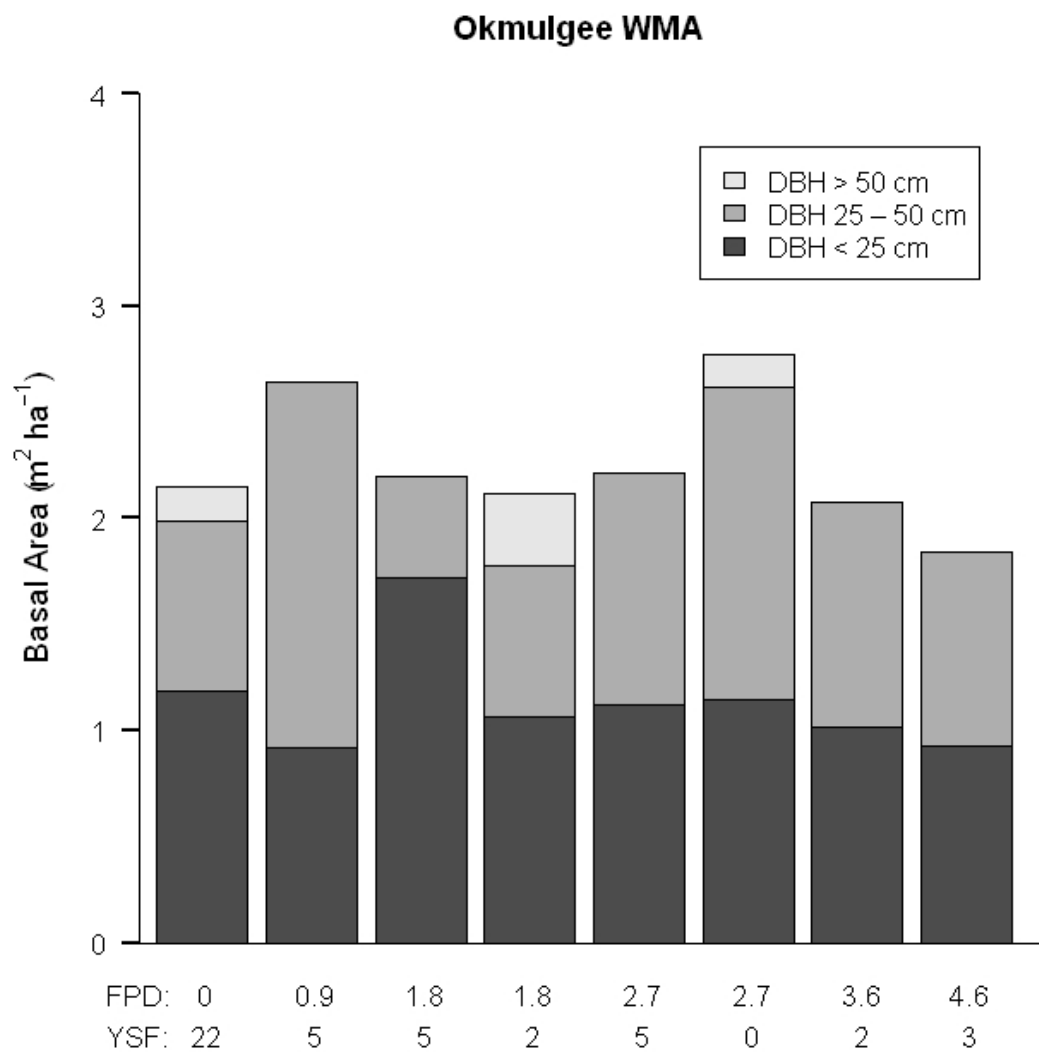
Figure 17. The effect of fires per decade (FPD) and years since fire (YSF) on the snag density in different diameter classes across all the units in Lexington WMA.

Figure 18. The effect of fires per decade (FPD) and years since fire (YSF) on the snag density in different diameter classes across all the units in Cherokee WMA.

Figure 19. Snag basal area response of different diameter classes to fires per decade (FPD) and years since fire (YSF) across all the units in Okmulgee WMA.
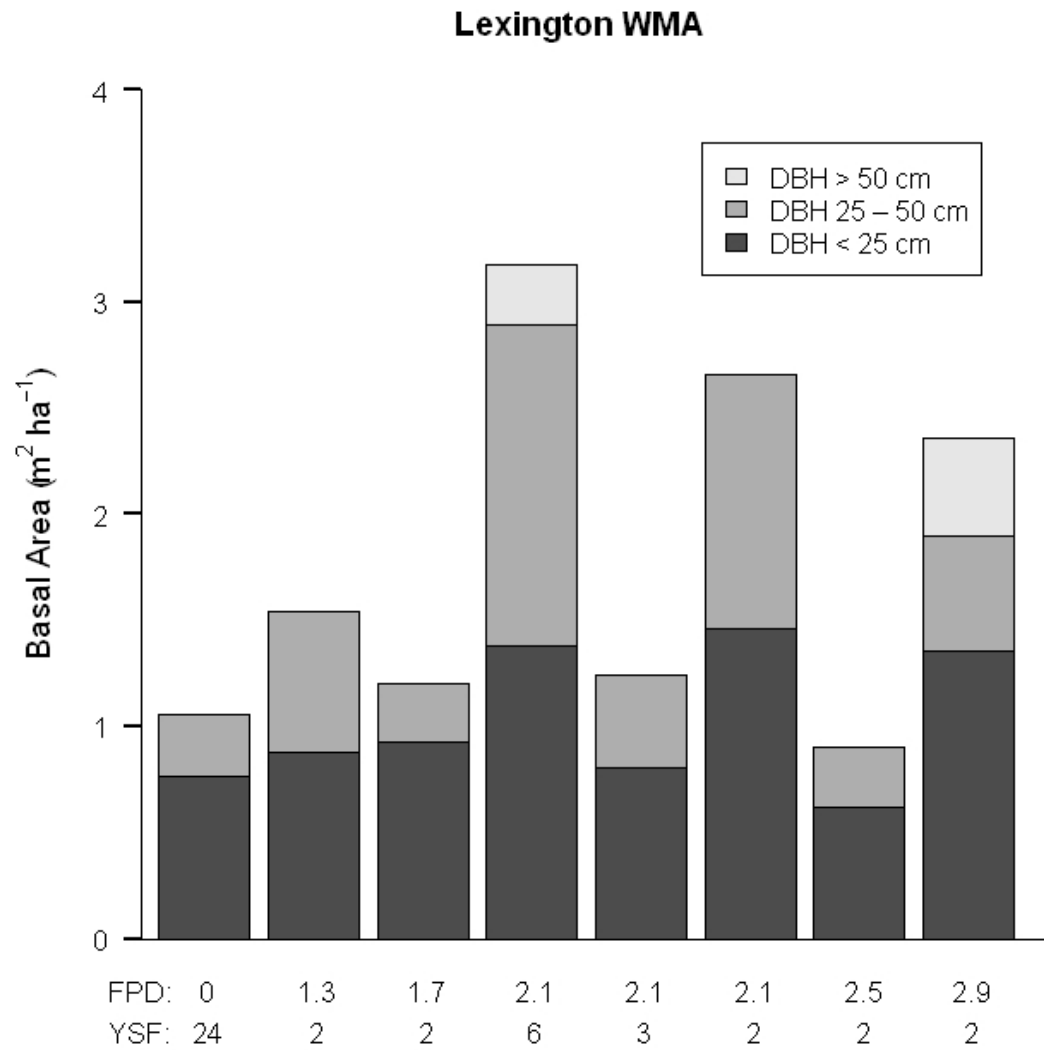
Figure 20. Snag basal area response of different diameter classes to fires per decade (FPD) and years since fire (YSF) across all the units in Lexington WMA.
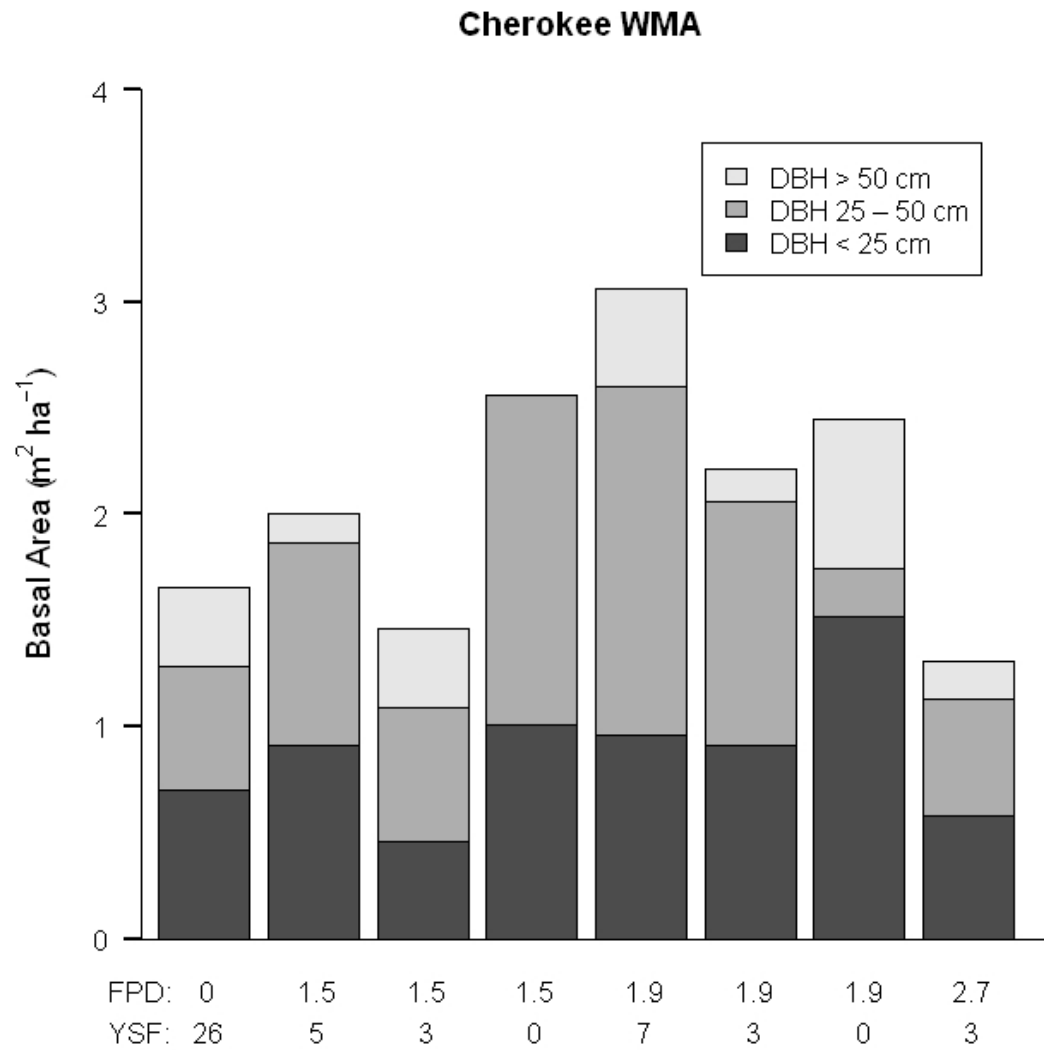
Figure 21. Snag basal area response of different diameter classes to fires per decade (FPD) and years since fire (YSF) across all the units in Cherokee WMA.
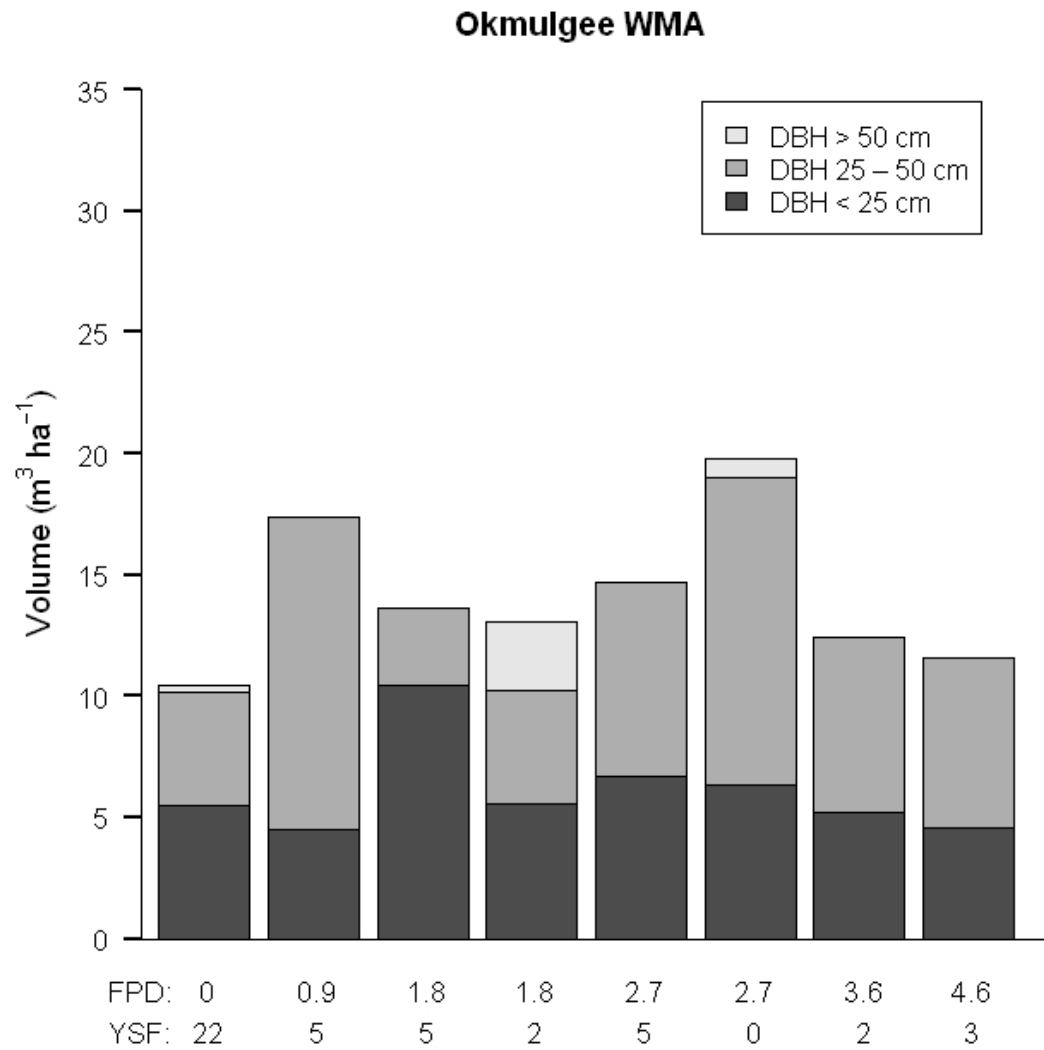
Figure 22. Change in snag volumes of different diameter classes in response to fires per decade (FPD) and years since fire (YSF) in all the unit of Okmulgee WMA.
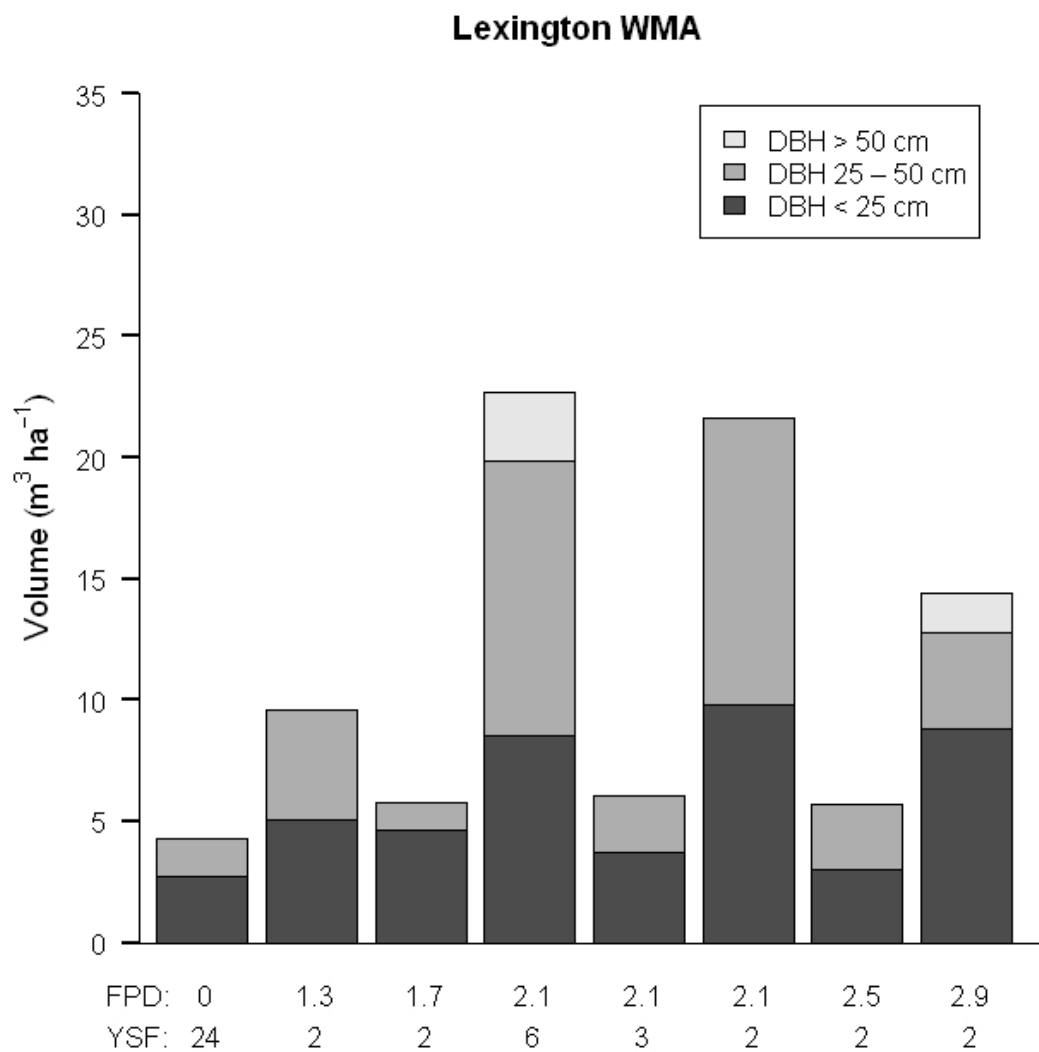
Figure 23. Change in snag volumes of different diameter classes in response to fires per decade (FPD) and years since fire (YSF) in all the unit of Lexington WMA.
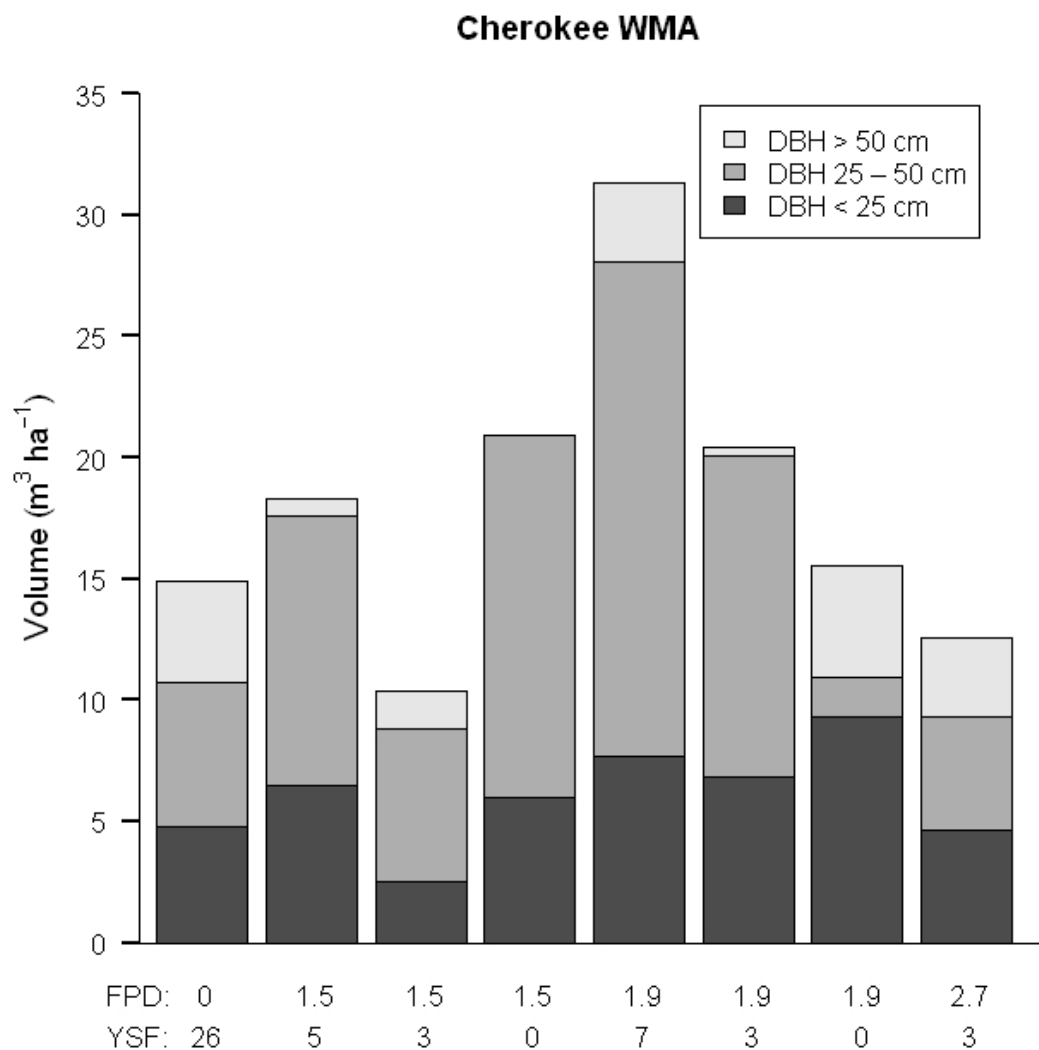
Figure 24. Change in snag volumes of different diameter classes in response to fires per decade (FPD) and years since fire (YSF) in all the unit of Cherokee WMA.
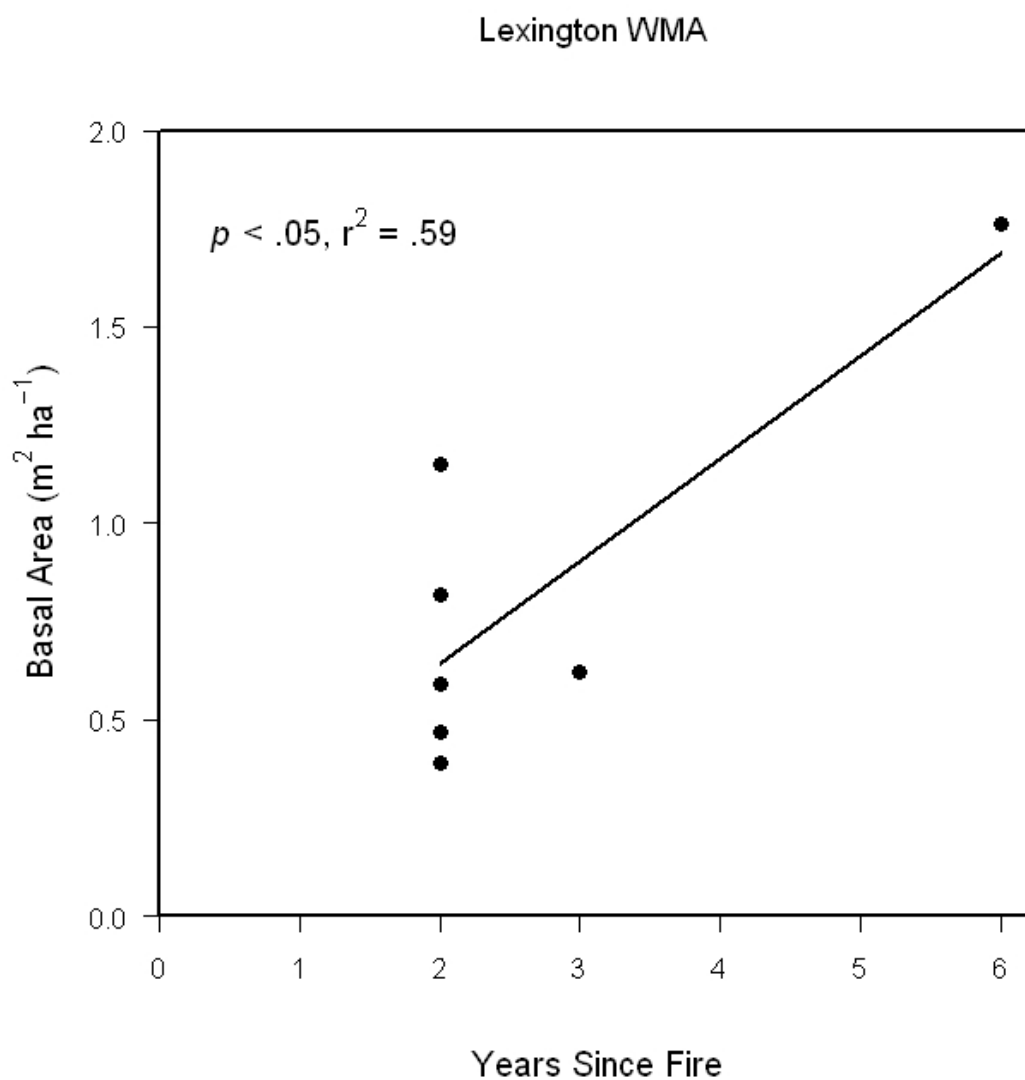
Lexington WMA

Figure 25. Regression plot of the effect of years since fire on *Q. stellata* basal in Lexington WMA. The basal area increased when the time since the last fire increased.
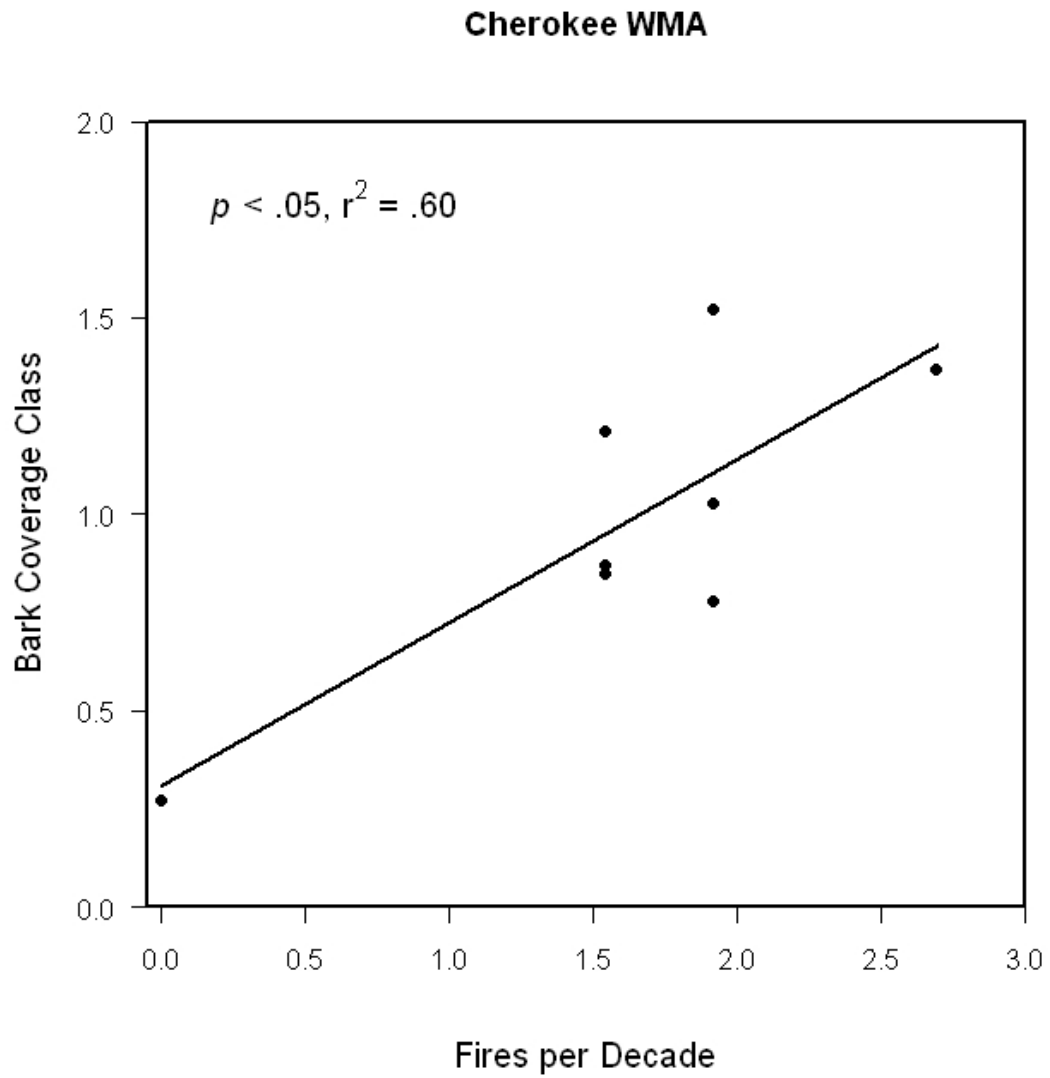
Cherokee WMA

Figure 26. Regression plot of fires per decade and bark coverage category (increasing category means less bark coverage) in Cherokee WMA. As the fire frequency increased, the amount of bark coverage on the snags decreased.
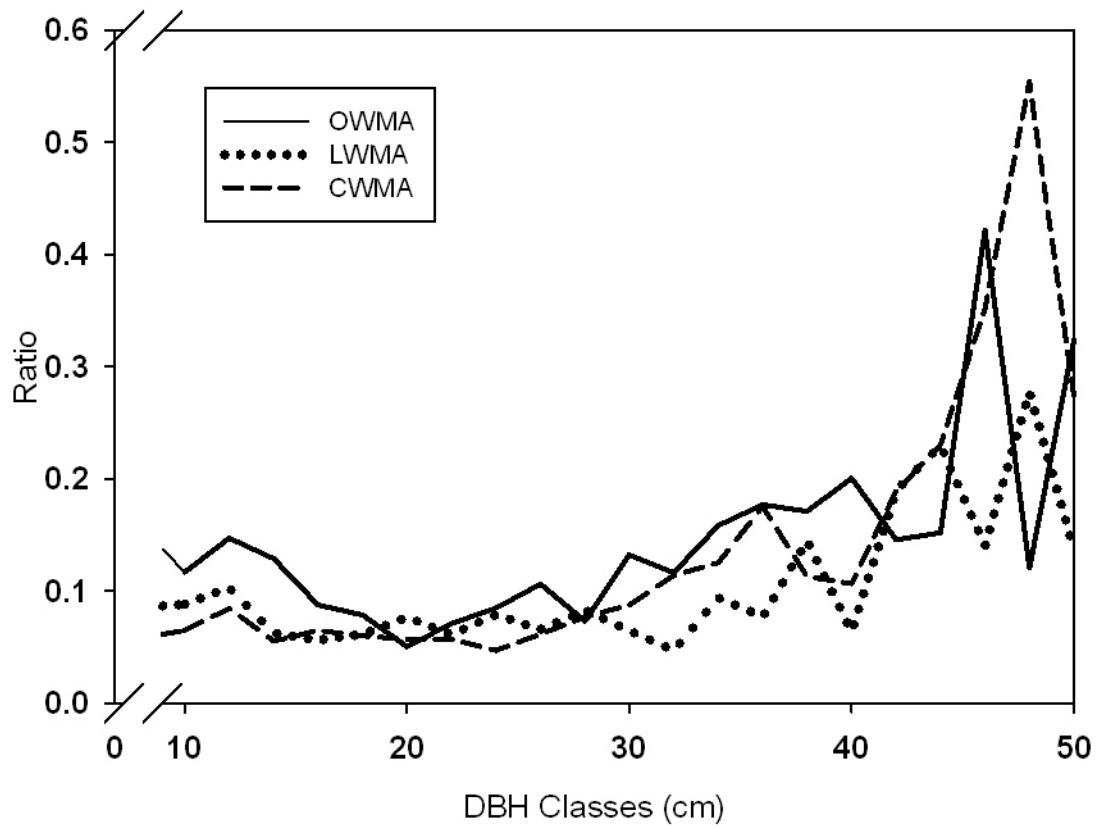
Figure 27. Ratio of dead:live tree stems broken into diameter classes for Okmulgee WMA
(OWMA), Lexington WMA (LWMA), and Cherokee WMA (CWMA). The ratio generally
increases from smaller to larger diameter stems.

Figure 28. Example of an ash silhouette left after a log was burned up in a prescribed fire. The photograph was taken two weeks after the burn in Okmulgee WMA. The silhouette indicated that the log was large enough to be counted as coarse woody debris.

Figure 29. Example of an ash silhouette that remained after a log was partially combusted in a prescribed fire. The photograph was taken two weeks after the burn in Okmulgee WMA. This photograph shows the patchy effect of fire on dead wood.

VITA

John Aquinas Polo

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF PRESCRIBED FIRE ON DEAD WOODY MATERIAL IN

UPLAND, XERIC OAK FORESTS OF OKLAHOMA

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ADVISER'S APPROVAL: Stephen Hallgren

Name: John Aquinas Polo   Date of Degree: July, 2011

Institution: Oklahoma State University   Location: Stillwater, Oklahoma

Title of Study: EFFECTS OF PRESCRIBED FIRE ON DEAD WOODY MATERIAL

IN UPLAND XERIC OAK FORESTS OF OKLAHOMA

Pages in Study: 79   Candidate for the Degree of Master of Science

Major Field: Natural Resource Ecology and Management

Scope and Method of Study: The purpose of this study was to determine the relationship of dead wood components in xeric oak forests to prescribed fire. I sampled in three wildlife management areas in central and eastern Oklahoma's Cross Timbers. Each of the management areas had eight treatment units that provided a range of fire frequencies from 0 to 4.6 fires per decade. I used 30 transects in each treatment unit for planar intersect to measure down woody debris quantities and dimensions and to measure litter depth. Then I set up 500 m^2 plots over the transects and measured snag density, size, and species. Finally, a BAF 10 prism was used for live tree measurements. I performed linear regression on the response data with fires per decade and years since fire as explanatory variables and multiple regression that added live tree basal area and sites as explanatory variables.

Findings and Conclusions: The volumes of down dead wood and snags were highly variable. Down wood volume was between 2.2 and 17.2 m^3 ha^{-1} among the treatments in all sites. Snag volume was approximately half of the total dead wood volume in each treatment and varied between 5.8 and 22.7 m^3 ha^{-1}. The density of wildlife trees >50 cm dbh was 1 ha^{-1}, far less than the recommended density. Litter volume averaged between 349 and 402 m^3 ha^{-1} in the three sites. Live tree basal area was similar in all three sites. Very few of the dead wood measurements had a significant relationship with fire frequency. There were no significant multiple regressions. The lack of effect by fire on dead wood volumes indicated that other disturbances such as ice, windstorms, or disease were probably affecting the dynamics of dead wood. Dead to live tree ratios signaled that these forests were old-growth or approaching such a state. A mixed successional stage could have influenced the quantities of dead wood. To address the shortage of wildlife trees, large, live trees could be girdled and left standing after they die.

ADVISER'S APPROVAL: Stephen Hallgren