Forest Ecology and Management 291 (2013) 128–135

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effect of long-term understory prescribed burning on standing and down dead woody material in dry upland oak forests

John A. Polo [a], Stephen W. Hallgren [a,*], David M. Leslie Jr. [b]

[a] Oklahoma State University, Department of Natural Resource Ecology and Management, 008C Ag Hall, Stillwater, OK 74078, USA
[b] U.S. Geological Survey, Oklahoma Cooperative Fish and Wildlife Research Unit, Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, USA

ARTICLE INFO

Article history:
Received 24 July 2012
Received in revised form 29 October 2012
Accepted 30 October 2012
Available online 7 January 2013

Keywords:
Coarse woody debris
Fine woody debris
Snags
Quercus stellata
Quercus marilandica

ABSTRACT

Dead woody material, long ignored or viewed as a nuisance for forest management, has gained appreciation for its many roles in the forest including wildlife habitat, nutrient storage and cycling, energy for trophic webs, protection of soil, fuel for fire and carbon storage. The growing interest in managing dead woody material has created strong demand for greater understanding of factors controlling amounts and turnover. Prescribed burning, an important management tool, may have strong effects of dead woody material given fire's capacity to create and consume dead woody material. We determined effects of long-term understory prescribed burning on standing and down woody material in upland oak forests in south-central North America. We hypothesized that as frequency of fire increased in these stands the amount of deadwood would decrease and the fine woody material would decrease more rapidly than coarse woody material. The study was conducted in forests dominated by post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*) in wildlife management areas where understory prescribed burning had been practiced for over 20 years and the range of burn frequencies was 0 (unburned) fires per decade (FPD) to 4.6 FPD. The amount of deadwood was low compared with more productive forests in southeastern North America. The biomass (24.7 Mg ha^{-1}) and carbon stocks (11.7 Mg ha^{-1}) were distributed among standing dead (22%), coarse woody debris (CWD, dia. > 7.5 cm., 12%), fine woody debris (FWD, dia. $\leqslant$ 7.5 cm., 23%), and forest floor (43%). There was no evidence that understory prescribed burning influenced the amount and size distribution of standing and down dead woody material. There were two explanations for the lack of a detectable effect. First, a high incidence of severe weather including ice storms and strong winds that produce large amounts of deadwood intermittently in an irregular pattern across the landscape may preclude detecting a strong effect of understory prescribed burning. Second, fire suppression during the first one-half of the 20th Century may have led to encroachment of woody plants into forest gaps and savannas creating a patchwork of young and old stands that produced deadwood of different sizes and at different rates.

1. Introduction

Dead woody material in forests consists of dead standing and down trees, branches, stumps and roots. It has numerous roles in ecosystem functions including wildlife and plant habitat, energy and mineral nutrient supply for the detritus trophic web, fuel for fire, storage of organic matter and nutrients, and regulation of surface runoff (Brown et al., 2003; Harmon et al., 1986; Harmon, 2002; Loeb, 1996). Prior to the sea change in forest conservation that took place around the middle 20th Century that recognized the importance of all parts of an ecosystem, deadwood was considered a nuisance and removed at earliest convenience (Thomas, 2002). Now, its value is recognized, and it is the focus of expanded research. Increased knowledge about the types, distribution, and turnover of dead woody material is important to understanding its role in the ecosystem and how to manage it while conserving other ecosystem attributes.

Quantity of deadwood depends on the balance between inputs and outputs (Goodburn and Lorimer, 1998; Harmon et al., 1986). Inputs are determined by site productivity, stand age and density, successional stage, and disturbance regime. Outputs are determined by rates of microbial decomposition, fragmentation, leaching and fire regime. Effects of fire are particularly interesting because the fire regime throughout much of North America was strongly altered following Euro-American settlement and fire was completely suppressed in many places (Guyette et al., 2002; Nowacki and Abrams, 2008; Pyne et al., 1996). Prescribed burning has become an important management tool to restore ecosystems to

* Corresponding author. Tel.: +1 405 744 6805; fax: +1 405 744 3530.
E-mail address: steve.hallgren@okstate.edu (S.W. Hallgren).

0378-1127/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2012.10.048

historic conditions (Pyne et al., 1996). Benefits of prescribed burning include control of invasive species, preservation of biological diversity, improved wildlife habitat and management of wildland fuels. Although prescribed fire is often used to reduce the amount of hazardous fine fuel (Mitchell et al., 2009; Stephens and Moghaddas, 2005; Stephens et al., 2009), its effects on the quantity of deadwood are problematic in some ecosystems (Waldrop et al., 2010) because fire has the potential to produce as well as consume deadwood.

Fire has been a major disturbance in the upland oak forests in the ecotone between the eastern deciduous forest and the southern Great Plains of the United States for thousands of years (Albert, 1981; Clark et al., 2007; DeSantis et al., 2010a, 2010b; Stambaugh et al., 2009). Fires were often of anthropogenic origin because Native Americans used fire for many purposes (Guyette et al., 2002; Moore, 1972), and the fire regime was most likely low severity fires every 0–10 years (Brown, 2000). Burning probably increased shortly after Euro-American settlement as the settlers learned to use fire for the same purposes as the Native Americans (Guyette et al., 2002). Eventually the increase in human population resulted in the need for fire suppression to protect life and property including forest timber resources. Fire suppression in oak forests can lead to increased stand density to the detriment of herbaceous vegetation (Burton et al., 2010; Burton et al., 2011), increased mesophytic tree species, reduced oak dominance and increased encroachment of eastern redcedar (DeSantis et al., 2010b). Use of prescribed burning to reverse changes in forest vegetation composition and structure has been increasing, but there is a dearth of background information on effects of prescribed burning on various ecosystem attributes.

We studied effects of prescribed burning on quantities of standing dead trees and down dead woody material in upland oak forests in south-central North America. Research has shown low intensity dormant season burns can significantly reduce understory shrubs and saplings and increase herbaceous vegetation (Burton et al., 2010, 2011) but they have little effect on the trees larger than 5 cm diameter at breast height (DBH). Forest ecologists have speculated frequent low-intensity fires before Euro-American settlement reduced dead woody material because periodic fires consumed down wood and reduced stand density (Spetich et al., 1999). Prescribed burning mesic forests of mixed oak and pine reduced shrubs and saplings and litter but the effect did not last long due to resprouting and new litter inputs. Overstory mortality was minor and replaced by growth of remaining trees (Waldrop et al., 2008, 2010). Most research on effects of fire on dead woody material has been based on short-term study of one or two burns (Graham and McCarthy, 2006; Hubbard et al., 2004; Uzoh and Skinner, 2009; Liljaa et al., 2005; Chiang et al., 2008; Waldrop et al., 2008, 2010; Kolaks et al., 2004); few have studied long-term effects of repeated burning (Neill et al., 2007). We hypothesized long-term understory prescribed burning would reduce dead woody material, especially small material, and the effect would be directly related to the frequency of burning. The study was conducted in three Wildlife Management Areas (WMA) managed by the Oklahoma Department of Wildlife Conservation where dormant season prescribed fire had been used at frequencies ranging from 0 to 5 fires per decade for over 20 years to improve wildlife habitat.

2. Methods

2.1. Study sites

The study was conducted on three WMAs in the upland oak forests of eastern and central Oklahoma: Okmulgee WMA (OWMA), Lexington WMA (LWMA), and Cherokee WMA (CWMA) (Fig. 1). The WMAs were managed by the Oklahoma Division of Wildlife Conservation. The forests were dominated by post oak (*Qurecus stellata*) and blackjack oak (*Quercus marilandica*) (Duck and Fletcher, 1943; Rice and Penfound, 1959; Küchler, 1964) and were relatively free from harvesting and human disturbance due to shallow soils and low productivity (Therrell and Stahle, 1998). The elevation ranged from 180 to 370 m. Soils at OWMA were of the Hector complex: excessively drained stony sandy loam to 15 cm and fine sandy loam 15–33 cm on slopes 5–30%. These soils did not have potential for commercial timber production (Sparwasser et al., 1968). Soils at LWMA were of the Stephenville-Darsil-Newalla and Stephenville-Darsil complexes. The predominant Stephenville soil was well drained, fine sandy loam and loamy fine sand to 25 cm and sandy clay loam 25–70 cm on

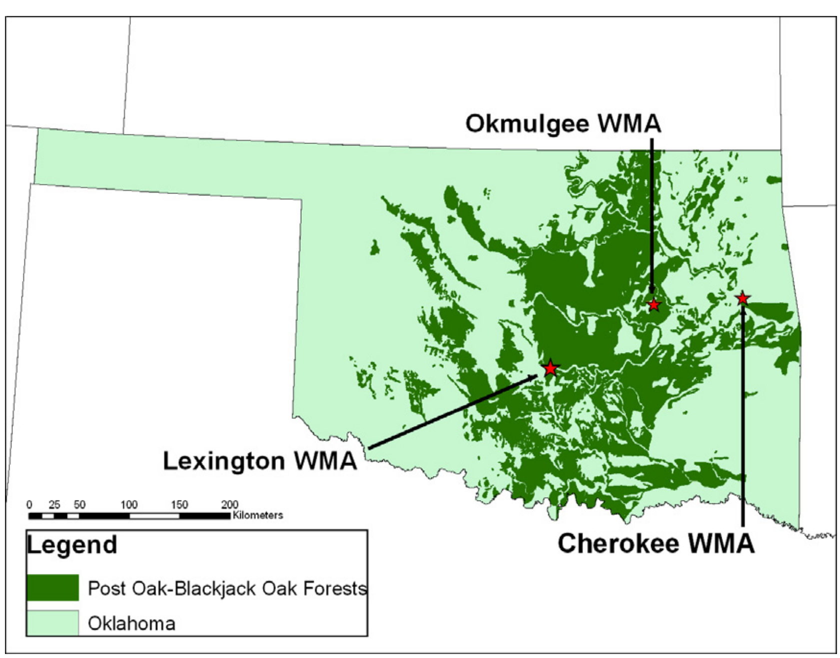

Fig. 1. Locations of the three wildlife management areas (WMA) in the post oak-blackjack oak forests of Oklahoma (Duck and Fletcher, 1943; Küchler, 1964).

slopes 3–8%. The soil supported native woodland suitable for production of firewood and fence posts (Bourlier et al., 1987). Soils at CWMA were of the Hector series: somewhat excessively drained, fine sandy loams with a depth of 40–80 cm on 2–30% slopes. The site index for base age 50 years for oak was 55 on shallow slopes and 35 on steep slopes (Cole, 1970). Mean annual precipitation increased from 102 cm at LWMA to 111 cm at OWMA to 122 cm at CWMA. Year-to-year variation in precipitation was very high: 50–190 cm. The mean annual temperature was 16 °C with average winter temperatures of −3 °C and summer temperatures of 33 °C.

Prescribed burning had been used to manage the vegetation for improved wildlife habitat for at least 22 years at these WMAs, and every fire date and location had been documented. At each site, we sampled eight management units with different fire frequencies. The burn frequencies ranged from 0 to 4.55 fires per decade (FPD) and 0–7 years since fire (YSF). 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 to 50%, temperature < 27 °C, and wind speed < 25 kph. These conditions were considered ideal for achieving the goals of fuel and vegetation management and fire containment (Weir, 2009). Over the 22 years, there was one wildfire at OWMA and two at CWMA that occurred under conditions similar to those used for the prescribed burns.

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 plots when they fell in an unacceptable location such as a clearing. A 50 m randomly oriented transect was started at each random point. Down woody material was estimated by the line-intersect sampling method (Van Wagner, 1968; Woodall and Williams 2005). Intersections with a transect were counted by time-lag fuel classes. These classes were: small, fine woody debris (SFWD, 1-h time-lag fuel class, dia. ⩽ 0.6 cm); medium, fine woody debris (MFWD, 10-h time-lag fuel class, 0.6 cm < dia. ⩽ 2.5 cm); large, fine woody debris (LFWD, 100-h time-lag fuel class, 2.5 cm < dia. ⩽ 7.5 cm); and coarse woody debris (CWD, 1000-h time-lag fuel class, dia. > 7.5 cm). The SFWD tallies were taken in four 2-m segments at 10, 20, 30, and 40 m along the transect. The MFWD and LFWD tallies used the same four segments and an additional 2-m segment at the 48-m mark. Measurements for CWD were taken along the entire 50-m transect. Litter depth was measured to the nearest centimeter every 10 m along the transect starting at 10 m.

Minimum dimensions for CWD were >7.5 cm diameter at intersection and 50 cm length. Measurements taken for CWD were diameter at intersection and condition of the bark and wood. Condition classes were integers from one to five, one being least decayed to almost dust for five (Table 1). Pieces had to be >45° from vertical and detached at the base.

Standing dead trees were sampled on a 50 m by 10 m plot measured along the 50-m transect. All standing dead trees at least 1.4 m tall, attached at the base to the roots, and less than 45° from vertical were measured. For each snag, we recorded: species, DBH, height, bark condition (Table 1), 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. The basal area of live trees >2 cm DBH was measured with a basal area factor (BAF) 10 prism. 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

Volume of down woody material was calculated on a per hectare basis for three FWD classes and one CWD class for each transect. FWD volume ($m^3\,ha^{-1}$) was calculated as (Woodall and Williams, 2005):

$$\mathrm{FWD}_i = (kc/L)nd_i^2$$

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 midpoint diameter in meters of class i (fine, medium and large). The correction for slope only was included when the slope was >20% (Woodall and Williams, 2005).

CWD volume on an area basis ($m^3\,ha^{-1}$) was calculated for each transect as (Van Wagner, 1968):

$$\mathrm{CWD} = \pi^2 \sum d_i^2/8L$$

where d was the intersection diameter in meters of the ith CWD piece in a transect, and L was the length of the transect ($L = 50$ m).

The basal area (BA, $m^2\,ha^{-1}$) of snags was calculated as:

$$\mathrm{BA} = (d/2)^2\pi$$

where d was the DBH in meters. The diameter at the top of the stem was determined by taper values that came from CWD measurements of logs on the ground. Snag volume was determined with Smalian's formula (Woodall and Williams, 2005). Basal area for live trees in $m^2\,ha^{-1}$ was calculated as 2.30 times the tree count with the BAF 10 prism. DBH of the counted trees was used to calculate tree frequency by DBH class.

Deadwood mass was calculated using published estimates of density: standing dead trees = 0.52 g cm^{-3}, CWD = 0.45 g cm^{-3} and FWD = 0.63 g cm^{-3} (Harmon et al., 2008; MacMillan, 1981). Carbon content of all deadwood was estimated as 0.50 times mass (Harmon et al., 2008). Litter volume was multiplied by 0.03 g cm^{-3} to calculated litter mass, which was multiplied by 0.46 to estimate the mass of carbon (Chojnacky et al., 2009).

Univariate linear regression analysis was used to test the significance of effects of FPD and YSF on deadwood and its components separately for each WMA. In addition, multiple regression analyses were conducted with data combined across WMAs to test whether BA and WMA were significant in the regression model of effects of FPD and YSF (Crawley, 2005). All regression analyses were conducted using individual management unit means within a WMA. Control plots were not used in any regression with YSF as an explanatory factor because the date of last burn was not known; fire-free period was known to be at least 22–26 years. Seven years since fire was the longest time without fire in the burned plots. All

Table 1
Decay class descriptions for bark and wood for coarse woody debris and snags. Wood integrity was tested by probing with a screw driver.

Dead wood	Decay class				
	1	2	3	4	5
Bark cover	>90%	89–50%	49–26%	<25%	Hollow
Wood integrity	Solid sapwood	Soft sapwood	Chunks missing	Decayed throughout	Collapsed, powdery

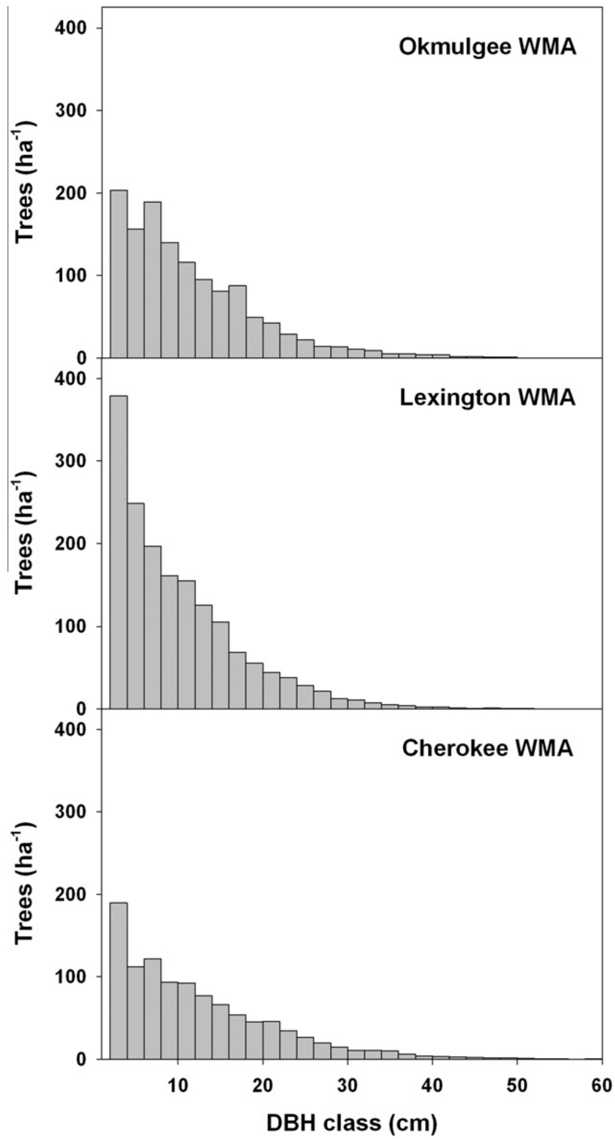

Fig. 2. DBH distribution in terms of trees ha^{-1} by 2 cm DBH class across all management units in three wildlife management areas (WMAs).

regressions were completed with the *R* statistics package (R Development Core Team, 2010). All regression analyses were tested for significance at $P \leqslant 0.05$.

3. Results

Neither FPD nor YSF showed an effect ($P \leqslant 0.05$) on basal area of live trees regardless of whether the data were analyzed separately within each WMA or pooled across WMAs. Mean basal area averaged across prescribed burning treatments was 19.3 m^2 ha^{-1} in OWMA, 21.4 m^2 ha^{-1} in LWMA, and 20.3 m^2 ha^{-1} in CWMA, and was not different among WMAs ($P \leqslant 0.05$). DBH distributions of the live trees in terms of trees per ha by DBH class at each site were close to a reverse-J shape curve (Fig. 2) characteristic of all-aged stands in equilibrium.

3.1. Down woody debris and litter

Neither FPD nor YSF showed an effect ($P \leqslant 0.05$) on volume, mass and carbon stocks of any size class of down woody material regardless of whether the data were analyzed separately by WMA or pooled across WMAs. Mean values for WMAs (Table 2) were not different ($P \leqslant 0.05$). Overall size distribution across treatments and WMAs was 41% CWD, 40% large FWD, 17% medium FWD and 2% small FWD (Fig. 3). 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. None of the FWD could be identified to species. Most of the CWD pieces were covered by less than 50% of bark, and the mean condition class (Table 1) was 2.21 at OWMA, 1.56 at LWMA and 1.94 at CWMA. There were a few cases where regressions for down woody material for separate species at specific WMAs were significant. For example, volume of *Q. marilandica* CWD at CWMA decreased as the fire frequency increased ($P < 0.01$, $R^2 = 0.85$). At LWMA, volume of *Q. stellata* CWD increased when the years since fire increased ($P < 0.05$, $R^2 = 0.67$). Volume of small FWD declined with increasing fire frequency in CWMA ($P < 0.01$, $R^2 = 0.73$). Multiple regression analyses did not detect any significant relationship ($P \leqslant 0.05$) of down woody material and its components with basal area of live trees. WMA was not significant ($P \leqslant 0.05$) in any of the multiple regression analyses.

Litter depth was 3.8 cm in OWMA, 3.5 cm in LWMA and 4.0 cm in CWMA, and was not different among WMAs ($P \leqslant 0.05$). In general litter depth did not show a response to FPD and YSF regardless of whether the analysis was done by WMA or pooled across WMAs. The one exception was that litter depth at CWMA decrease by 30% as fire frequency increased from 0 to 2.5 FPD ($P < 0.05$, $R^2 = 0.74$).

Table 2
Mean (±se) volume, biomass and carbon mass for snags, coarse woody debris (CWD), fine woody debris (FWD) and litter at Okmulgee Wildlife Management Area (OWMA), Lexington Wildlife Management Area (LWMA) and Cherokee Wildlife Management Area (CWMA) averaged across prescribed burning treatments. Mean values were not different at $P \leqslant 0.05$.

Units	Component	Wildlife management area		
		OWMA	LWMA	CWMA
Volume (m^3 ha^{-1})	Snags	10.24 ± 2.29	7.84 ± 5.01	12.50 ± 4.26
	CWD	4.95 ± 1.71	6.42 ± 3.71	7.01 ± 3.40
	FWD	7.92 ± 2.83	8.72 ± 2.16	8.54 ± 0.83
	Litter	381.0 ± 104.0	349.0 ± 56.0	402.0 ± 53.0
Biomass (Mg ha^{-1})	Snags	5.32 ± 1.19	4.08 ± 2.61	6.50 ± 2.22
	CWD	2.23 ± 0.77	2.89 ± 1.67	3.15 ± 1.53
	FWD	4.99 ± 1.78	5.49 ± 1.36	5.38 ± 0.52
	Litter	11.40 ± 3.12	10.50 ± 1.68	12.10 ± 1.59
	Total	23.9	23.0	27.1
C (Mg ha^{-1})	Snags	2.66 ± 0.6	2.04 ± 1.3	3.25 ± 1.1
	CWD	1.11 ± 0.4	1.44 ± 0.8	1.58 ± 0.8
	FWD	2.49 ± 0.9	2.75 ± 0.7	2.69 ± 0.3
	Litter	5.00 ± 1.4	4.60 ± 0.7	5.40 ± 0.7
	Total	11.2	10.8	12.9

3.2. Snags

Neither FPD nor YSF had an effect ($P \leqslant 0.05$) on snag density, volume, mass and carbon stocks. Mean total snag density was 99–139 ha^{-1} and not different among WMAs ($P \leqslant 0.05$) (Table 3). There were only 8–12 medium snags >25 cm DBH ha^{-1}. Mean bark coverage for snags was >50% and they all lacked branches <7.5 cm in diameter. Mean wood decay classes (Table 1) were 1.21 in OWMA, 1.45 in LWMA, and 1.49 in CWMA, indicating that wood in snags was firm but could be penetrated with a probe.

The overall ratio of standing dead to live trees (dead/live ratio) across treatments was over 0.129 ± 0.076 across all three WMAs. The dead/live ratio was close to 0.01 for trees 10 cm DBH, and as DBH increased the ratio declined to 0.06 at 20 cm DBH where it began increasing (Fig. 4). At 35–40 cm DBH, the dead/live ratio was

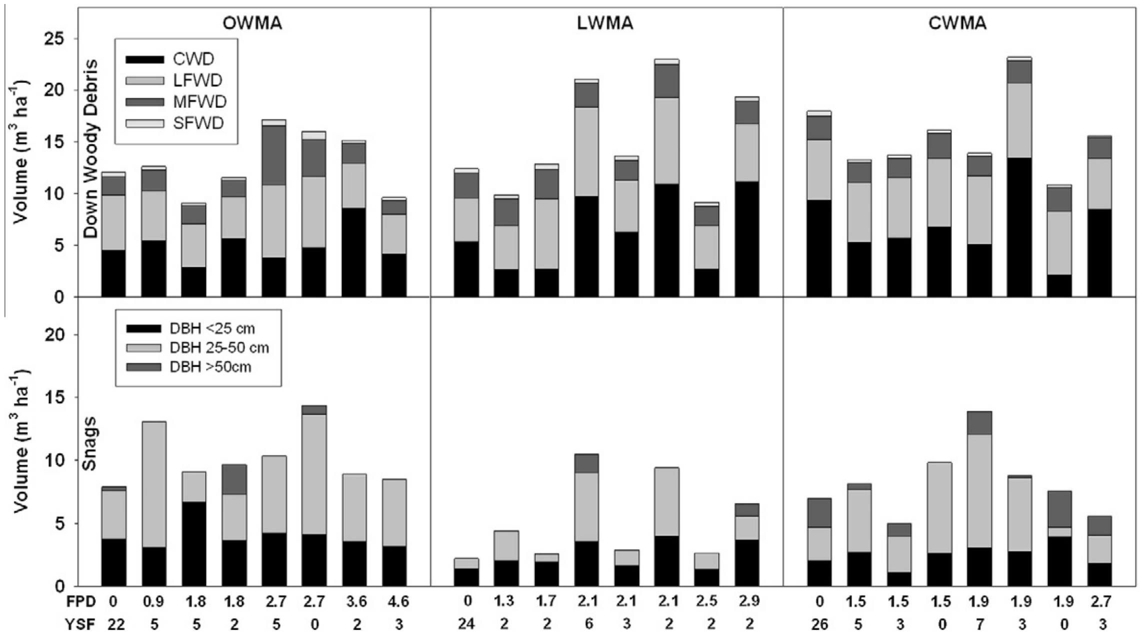

Fig. 3. Effect of fires per decade (FPD) and years since fire (YSF) at Okmulgee Wildlife Management Area (OWMA), Lexington Wildlife Management Area (LWMA), and Cherokee Wildlife Management Area (CWMA) on volume of down deadwood by size class (small, fine woody debris (SFWD); medium, fine woody debris (MFWD); large, fine woody debris (LFWD); and coarse woody debris (CWD)) and on volume of snags by DBH size class.

Table 3
Mean (±se) snag density by size class at Okmulgee Wildlife Management Area (OWMA), Lexington Wildlife Management Area (LWMA) and Cherokee Wildlife Management Area (CWMA) averaged across burning treatments. Mean values were not different at $P \leqslant 0.05$.

Category	Snags (ha^{-1})		
	OWMA	LWMA	CWMA
Total	139 ± 32	129 ± 31	99 ± 37
Dia. 25–50 cm	12 ± 4	8 ± 6	10 ± 5
Dia. > 50 cm	0 ± 1	0	1 ± 1

0.12–0.14. At larger diameters the dead/live ratio increased sharply and was erratic, perhaps due to the small sample size. The pattern of change in dead/live ration was similar across all three WMAs.

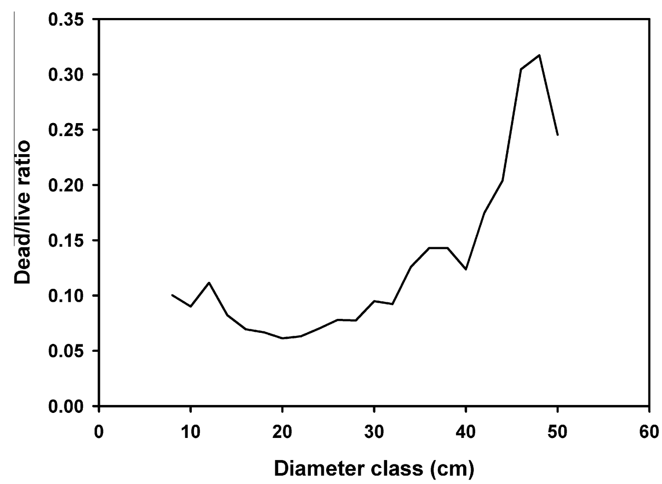

Fig. 4. Dead:live ratio by DBH class for three wildlife management areas all data combined across management units and wildlife management areas.

4. Discussion

We found no evidence to support the hypotheses that long-term prescribed burning of the understory reduced the amount or changed the size distribution of dead woody debris in upland oak forests of south-central North America. Although earlier work showed burning at 5 FPD reduced the density of shrubs and saplings (Burton et al., 2010), this level of burning did not decrease dead woody material. Our findings do not support the contention that fire suppression following Euro-American settlement has led to increased deadwood in forests (Spetich et al., 1999). The tremendous variation and lack of any pattern in both standing and down deadwood across the range of frequencies of prescribed burning (Fig. 3) suggested other factors such as severe weather disturbances and stand history may have been more important than prescribed burning in determining the amount of deadwood. The lack of a prescribed fire effect on CWD and FWD may reflect the high decomposition rates and the irregular rates of CWD input due to periodic disturbances (Woodall and Liknes, 2008). Latitudinal gradients of CWD and FWD across the United States suggested decomposition rates in southern forests were so high that FWD accumulation was not much greater than annual input. CWD accumulation could likewise be very small in some cases due to the irregular periodic inputs (Woodall and Liknes, 2008) not keeping up with decomposition.

Lack of effect from prescribed fire can be partially attributed to resistance of the dominant tree species to low-intensity dormant season burns (Burton et al., 2010). Without severe fires to kill the trees, deadwood input would depend on other disturbances. Severe weather including ice (Lafon and Speer, 2002), wind and hail storms characteristic of south-central North America (Fig. 5) are capable of severe damage to trees including breaking branches and felling trees. Damage to trees from wind and ice is local and highly variable across the landscape (Rebertus et al., 1997), and by comparison effects of prescribed burning may be too small to detect.

Another factor that could have influenced the amount of deadwood was variation in stand structure across the landscape due to changes in fire regime following Euro-American settlement. Prior to the 20th Century, Native Americans burned the forests every

0–10 years by low intensity surface fires (Brown, 2000). Shortly after Euro-American settlement in the early 1900s burning stopped and fire suppression over the past century led to widespread woody encroachment of grasslands and savannas (DeSantis et al., 2010b, 2011; Nowacki and Abrams, 2008; Pyne et al., 1996). This means current stands may be a patchwork of young stands subject to density-dependent thinning of relatively small trees and old-growth stands subject to density-independent mortality of much larger trees. The overall dead/live ratio of 0.129 ± 0.076 was indicative of old-growth stands in North American hardwood forests dominated by oak (Spetich et al., 1999). This finding along with the reverse-J shaped frequency distribution of tree density by diameter class (Fig. 2) suggested the stands were at equilibrium for recruitment and mortality. This meant they were at maximum production of snags and deadwood. In contrast, across the range of DBH classes 15–30 cm the dead/live ratio fell within the range 0.05–0.10 (Fig. 4) characteristic of second-growth stands (Spetich et al., 1999). The high dead/live ratio with smaller DBH trees indicated increased density-dependent mortality of dense young stands. High variability in stand structure among sampled stands within a treatment may have made it impossible to detect effects of prescribed burning.

The down deadwood in upland oak forests of south-central North America was low compared with more mesic hardwood forests of eastern North America. We found 13–16 $m^3\ ha^{-1}$ (Table 2) compared to 20 $m^3\ ha^{-1}$ in mature second-growth stands and 60 $m^3\ ha^{-1}$ in old-growth stands in the central hardwood region (Spetich et al., 1999). Post oak-backjack oak forest type in more mesic regions had down deadwood biomass of 9 Mg ha^{-1} (Woodall et al., 2007) compared to 7–9 Mg ha^{-1} in the current study. On the other hand, our findings suggested upland oak forests of south-central North America accumulated an excess of deadwood, 22

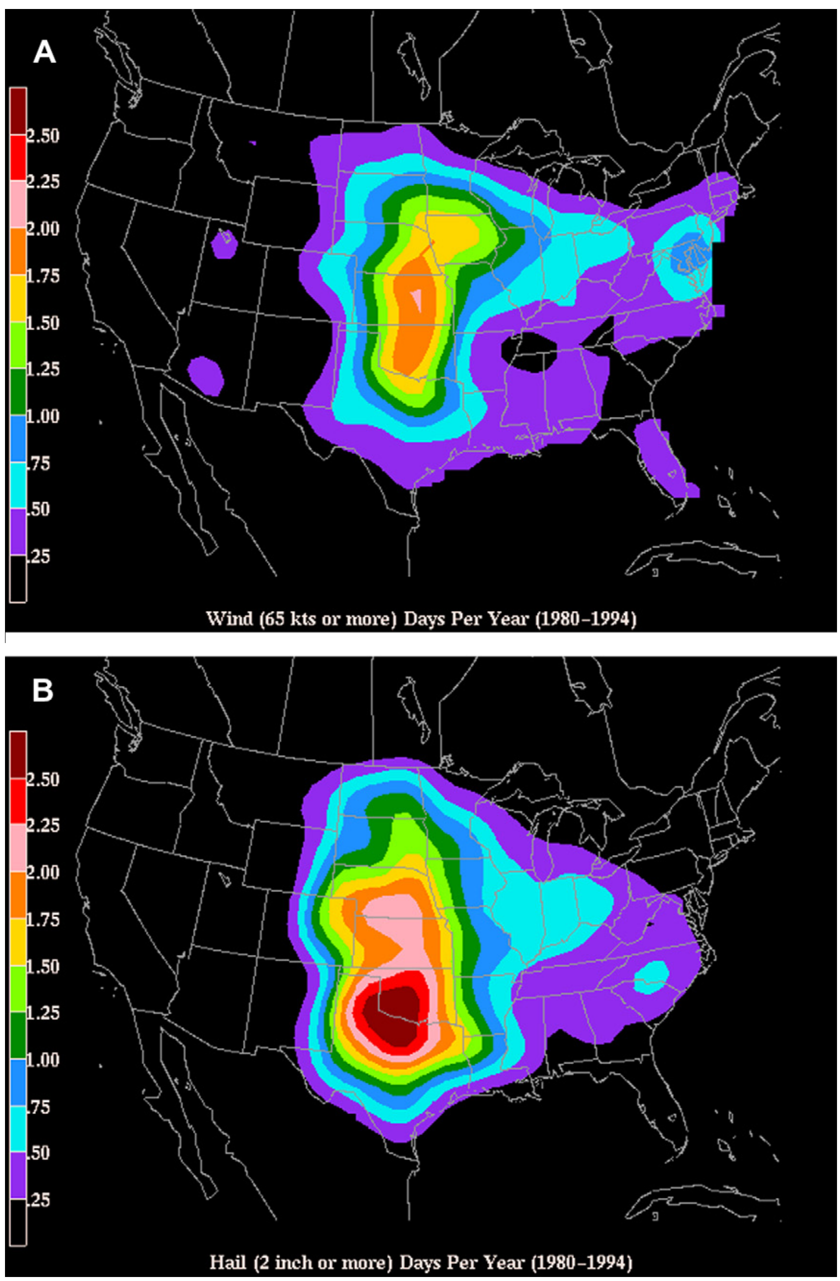

Fig. 5. Strong wind days (A) and damaging hail days (B) per year in the continental US (National Severe Storms Laboratory and Atmospheric Administration, 2012).

times annual growth compared to 17 times annual growth in the central hardwood region (Rosson, 1994; Spetich et al., 1999). This may reflect greater damage from storms and slower decomposition due to frequent drought. Our carbon estimate for above ground deadwood and litter of 11.7 Mg ha^{-1} was about one-half of the amount reported for similar eastern forests reflecting low productivity of the upland oak forests in this region (Woodall et al., 2008).

While prescribed fire may address several management goals in these upland oak forests, there was no indication that it could be used to manage deadwood. The high local variability of dead wood across the landscape due to the high incidence of local disturbances such as ice storms and strong winds combined with variable stand structure in these forests may mask any effects of prescribed burning. Our findings do not support the belief that fire suppression following Euro-American settlement led to increased dead woody material (Spetich et al., 1999).

Acknowledgements

Elizabeth Nguyen and Rodolfo Mota made it possible to finish the field work in a timely fashion. This project was funded by the Federal Aid, Pittman-Robertson Wildlife Restoration Act under Project W-160-R of the Oklahoma Department of Wildlife Conservation and Oklahoma State University. The project was administered through the Oklahoma Cooperative Fish and Wildlife Research Unit (Oklahoma Department of Wildlife Conservation, Oklahoma State University, United States Geological Survey, United States Fish and Wildlife Service, and Wildlife Management Institute cooperating). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Albert, L.E., 1981. Ferndale Bog and Natural Lake: Five Thousand Years of Environmental Change in Southeastern Oklahoma. Studies in Oklahoma's Past 7. University of Oklahoma Archaeological Survey, Norman, OK.

Bourlier, B.G., Sample, G.A., Swafford, B.G., Douthit, G., 1987. Soil Survey of Cleveland County, Oklahoma. U.S. Government Printing Office, Washington D.C.

Brown, J.K., 2000. Introduction to fire regimes. In: Brown, J.K., Smith, J.K. (Eds.), Wildland Fire in Ecosystems: Effects of Fire on Flora, vol. 2. USDA Forest Service GTR-42, Rocky Mountain Research Station, Ogden, UT, pp. 1–7.

Brown, J.K., Reinhardt, E.D., Kramer, K.A., 2003. Coarse Woody Debris: Managing Benefits and Fire Hazard in the Recovering Forest. Gen. Tech. Rep. RMRS-GTR-105. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, p. 16.

Burton, J.A., Hallgren, S.W., Palmer, M.W., 2010. Fire frequency affects structure and composition of xeric forests of eastern Oklahoma. Nat. Area J. 30, 370–379.

Burton, J.A., Hallgren, S.W., Fuhlendorf, S.D., Leslie Jr., D.M., 2011. Understory response to varying fire frequencies after 20 years of prescribed burning in upland oak forest. Plant Ecol. 212, 1513–1525.

Chiang, J.-M., McEwan, R.W., Yaussy, D.A., Brown, K.J., 2008. The effects of prescribed fire and silvicultural thinning on the aboveground carbon stocks and net primary production of overstory trees in an oak-hickory ecosystem in southern Ohio. Forest Ecol. Manage. 255, 1584–1594.

Chojnacky, D., Amacher, M., Gavazzi, M., 2009. Separating duff and litter for improved mass and carbon estimates. South J. Appl. For. 33, 29–34.

Clark, S.L., Hallgren, S.W., Engle, D.M., Stahle, D.W., 2007. The historic fire regime on the edge of the prairie: a case study from the cross timbers of Oklahoma. In: Masters, R.E., Galley, K.E.M. (Eds.), Proceedings of the Tall Timbers 23rd Fire Ecology Conference. Tall Timbers Research Station, Tallahassee, Fla, pp. 40–49.

Cole, E.L., 1970. Soil Survey of Cherokee and Delaware Counties, Oklahoma. U.S. Government Printing Office, Washington D.C.

Crawley, M.J., 2005. Statistics: An Introduction Using R. John Wiley & Sons, West Sussex, England.

DeSantis, R.D., Hallgren, S.W., Stahle, D.W., 2010a. Historic fire regime of an upland oak forest in south-central North America. Fire Ecol. 6, 45–61.

DeSantis, R.D., Hallgren, S.W., Lynch, T.B., Burton, J.A., Palmer, M.W., 2010b. Long-term directional changes in upland *Quercus* forests throughout Oklahoma. USA J. Veg. Sci. 21, 606–618.

DeSantis, R.D., Hallgren, S.W., Stahle, D.W., 2011. Drought and fire suppression lead to rapid forest composition change in a forest-prairie ecotone. Forest Ecol. Manage. 261, 1833–1840.

Duck, L.G., Fletcher, J.B., 1943. A survey of the Game and Fur Bearing Animals of Oklahoma. Bulletin No. 3. Oklahoma Game and Fish Commission, Oklahoma City, OK.

ESRI., 2007. ArcView 9.2. Environmental Systems Research Institute, Redlands, CA.

Goodburn, J.M., Lorimer, C.G., 1998. Cavity trees and coarse woody debris in old-growth and managed hardwood forests in Wisconsin and Michigan. Can. J. For. Res. 28, 427–438.

Graham, J.B., McCarthy, B.C., 2006. Forest floor fuel dynamics in mixed-oak forests of south-eastern Ohio. Int. J. Wildland Fire 15, 479–488.

Guyette, R.P., Muzika, R.M., Dey, D.C., 2002. Dynamics of an anthropogenic fire regime. Ecosystems 5, 472–486.

Harmon, M.E., 2002. Moving towards a new paradigm for woody detitrus management. In: Laudenslayer Jr., W.F., Shea, P.J., Valentine, B.E., Weatherspoon, C.P., Lisle, T.E. (Eds.), Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests Reno, NV. USDA Forest Service, General Technical Report PSW-GTR-181. Pacific Southwest Research Station, Albany, CA, pp. 929–944.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkamper, G.W., Cromack Jr., K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.

Harmon, M.E., Woodal, C.W., Fasth, B., Sexton, J., 2008. Woody Detritus Density and Density Reduction Factors for Tree Species in the United States: A synthesis. Gen. Tech. Rep. NRS-29. U.S. Department of Agriculture, Forest Service, Northern Research Station. Newtown Square, PA p.84.

Hubbard, R.M., Vose, J.M., Clinton, B.D., Elliot, K.J., Knoepp, J.D., 2004. Stand restoration burning in oak-pine forests in the southern Appalachians: effects of aboveground biomass and carbon and nitrogen cycling. Forest Ecol. Manage. 190, 311–321.

Kolaks, J.J., Cutter, B.E., Loewenstein, E.F., Grabner, K.W., Hartman, J.W., Kabrick, J.M., 2004. The effect of thinning and prescribed fire on fuel loading in the central hardwood region of Missouri. In: Yaussy, D.A., Hix, D.M., Long, R.P., Goebel, P.C. (Eds.), Proceedings. 14th Central Hardwood Forest Conference, Wooster, OH. U.S. Department of Agriculture. Forest Service. Gen. Tech. Rep. NE-316. Northeastern Research Station. Newtown Square, PA, pp. 168–178.

Küchler, A.W., 1964. Potential Natural Vegetation of the Coterminous United States. Special Publication No. 36. American Geographical Society, New York.

Lafon, C.W., Speer, J.H., 2002. Using dendrochronology to identify major ice storm events in oak forests of southwestern West Virginia. Clim. Res. 20, 41–54.

Liljaa, S., De Chantala, M., Kuuluvainena, T., Vanha-Majamaab, I., Puttonena, P., 2005. Restoring natural characteristics in managed Norway spruce [*Picea abies* (L.) Karst.] stands with partial cutting, dead wood creation and fire: immediate treatment effects. Scand. J. For. Res. 20, 68–78.

Loeb, S.C., 1996. The role of coarse woody debris in the ecology of southeastern mammals. In: McMinn, J.W., Crossley, Jr., D.A. (Eds.), Biodiversity and Coarse Woody Debris in Southern Forests, Proceedings of the Workshop on Coarse Woody Debris in Southern Forests: Effects on Biodiversity. United States Department of Agriculture, Forest Service, General Technical Report, SE-94. Asheville, North Carolina, pp. 108–118.

MacMillan, P.C., 1981. Log decomposition in Donaldson's Wood, Spring Mill State Park. Indiana. Am. Midl. Nat. 106, 335–344.

Mitchell, S.R., Harmon, M.E., O'Connell, K.E.B., 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol. Appl. 19, 643–655.

Moore, C.T., 1972. Man and Fire in the Central North American Grassland 1535–1890: A documentary Historical Geography. PhD dissertation. University of California, Los Angeles, Los Angles, CA. p. 155.

National Severe Storms Laboratory, National Oceanic and Atmospheric Administration, 2012. Severe Thunderstorm Climatology. <http://www.nssl.noaa.gov/hazard/totalthreat.html> (accessed 19.07.12).

Neill, C., Patterson III, W.A., Crary Jr., D.W., 2007. Responses of soil carbon, nitrogen and cations to the frequency and seasonality of prescribed burning in a Cape Cod oak-pine forest. Forest Ecol. Manage. 250, 234–243.

Nowacki, G.J., Abrams, M.D., 2008. The demise of fire and "mesophication" of forests in the eastern United States. Bioscience 58, 123–138.

Pyne, S.J., Andrews, P.L., Laven, R.D., 1996. Introduction to Wildland Fire. John Wiley & Sons, New York.

R Development Core Team, 2010. R: A language and environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. <http://www.R-project.org> (19.07.12.).

Rebertus, A.J., Shifley, S.R., Richards, R.H., Roovers, L.M., 1997. Ice storm damage to an old-growth oak-hickory forest in Missouri. Am. Midl. Nat. 137, 48–61.

Rice, E.L., Penfound, W.T., 1959. The upland forests of Oklahoma. Ecology 40, 593–608.

Rosson Jr., J.F., 1994. *Quercus stellata* growth and stand characteristics in the *Quercus stellata–Quercus marilandica* forest type in the Cross Timbers region of central Oklahoma. In: Fralish, J.H., Anderson, R. (Eds.), Proceedings of the North American Conference on Savannas and Barrens: Living on the Edge. Environmental Protection Agency, Great Lakes National Program Office, Chicago, pp. 329–333.

Sparwasser, W.A., Bogard, V.A., Henson, O.G., 1968. Soil Survey of Okmulgee County, Oklahoma. U.S. Government Printing Office, Washington D.C.

Spetich, M.A., Shiffley, S.R., Parker, G.R., 1999. Regional distribution and dynamics of coarse woody debris in midwestern old-growth forests. Forest Sci. 45, 302–313.

Stambaugh, M.C., Guyette, R.P., Godfrey, R., McMurry, E.R., Marshall, J.M., 2009. Fire, drought, and human history near the western terminus of the Cross Timbers, Wichita Mountains, Oklahoma. USA. Fire Ecol. 5, 51–65.
Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. Forest Ecol. Manage. 215, 21–36.
Stephens, S.L., Moghaddas, J.J., Edminster, C., Fiedler, C.E., Haase, S., Harrington, M., Keeley, J.E., Knapp, E.E., Mciver, J.D., Metlen, K., Skinner, C.N., Youngblood, A., 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forest. Ecol. Appl. 19, 305–320.
Therrell, M.D., Stahle, D.W., 1998. A predictive model to locate ancient forests in the Cross Timbers of Osage County. Oklahoma. J. Biogeogr. 25, 847–854.
Thomas, J.W., 2002. Dead wood: from forester's bane to environmental boon. In: Laudenslayer Jr., W.F., Shea, P.J., Valentine, B.E., Weatherspoon, C.P., Lisle, T.E. (Eds.), Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests Reno, NV. USDA Forest Service, Pacific Southwest Research Station, Gen. Tech. Rep. PSW-GTR-181. Albany, CA. pp. 3–9.
Uzoh, F.C.C., Skinner, C.N., 2009. Effects of creating two forest structures and using prescribed fire on coarse woody debris in northeastern California, USA. Fire Ecol. 5, 1–13.
Van Wagner, C.E., 1968. The line intersect method in forest fuel sampling. Forest Sci. 14, 20–26.
Waldrop, T., Yassy, D.A., Phillips, R.J., Hutchinson, T.A., Brudnack, L., 2008. Fuel reduction treatments affect stand structure of hardwood forests in Western North Carolina and Southern Ohio. USA Forest Ecol. Manage. 255, 3117–3129.
Waldrop, T., Phillips, R.A., Simon, D.A., 2010. Fuels and predicted fire behavior in the southern Appalachian mountains after fire and fire surrogate treatments. For. Sci. 56, 32–45.
Weir, J.R., 2009. Conducting Prescribed Fires: a Comprehensive Manual. Texas A&M University Press, College Station.
Woodall, C.W., Liknes, G.C., 2008. Relationships between forest fine and coarse woody debris carbon stocks across latitudinal gradients in the United States as an indicator of climate change effects. Ecol. Indic. 8, 686–690.
Woodall, C.W., Williams, M.S., 2005. Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NC-256. U.S. Department of Agriculture, Forest Service, North Central Research Station. St. Paul, MN. p. 47.
Woodall, C.W., Oswalt, S.N., Morin, R.S., 2007. Attributes of down woody material in hardwood forests of the eastern United States. In: Buckley, D.S., Clatterbuck, W.K. (Eds.), Procceding of the 15th Central Hardwood Forest Conference. USDA Forest Service, Southern Research Station, e-Gen. Tech. Rep. SRS–101. Asheville, NC., pp. 144–153 [CD-ROM].
Woodall, C.W., Heath, L.S., Smith, J.E., 2008. National inventories of down and dead woody material forest carbon stocks in the United States: challenges and opportunities. Forest Ecol. Manage. 256, 221–228.