

Fuels Management in the Hot Continental Division, Southern Appalachian Mountains:

Matthew J. Reilly, Joseph J. O'Brien, and Thomas A. Waldrop

Southern Research Station
Center of Forest Disturbance Science

INTRODUCTION

The Southern Appalachian Mountains, hot continental division-mountains (M220, Cleland et. al, 2007) are a topographically and biologically complex region with over 10 million ha of forested land. As a result of complex environmental gradients there is a great diversity of forest types. Abundant moisture and a long warm growing season result in high levels productivity across the region. Disturbances such as fire, severe windstorms, and outbreaks of pathogens are common and can affect large areas. As a result of interactions among these factors, forest fuels can be dynamic and it is necessary to monitor and update estimates of fuel loading frequently. Fire exclusion since the early 20th Century has allowed fuels to increase across most of the region and resulted in the accumulation of both live and dead fuels. A rapidly expanding wildland-urban interface (WUI) and the potential for wildfires to increase in frequency and severity due to climate change mean that managers will be required to devote more resources to fuel management. Managers require effective methods of fuel management that will reduce the potential for hazardous wildfires and maintain landscape diversity across the region.

FIRE HISTORY OF THE SOUTHERN APPALACHIAN MOUNTAINS

Fire played an integral role in determining historic patterns of forest vegetation across the southern Appalachian Mountain region (Delcourt and Delcourt 1997). Natural ignition by lightning is infrequent today (Barden and Woods 1973, Harmon 1982), but historical accounts suggest that recurrent anthropogenic fire was common in forests of the region from 10,000-12,000 years before present through the arrival of Europeans (DeVivo 1991, Van Lear and Waldrop 1989, Fowler and Konopik 2007). Fowler and Konopik (2007) outline five periods of anthropogenic fire regimes each having different impacts on vegetation as changing cultures, fluctuations in population sizes, and altered land use priorities have all had an impact on fire regimes and forest structure.

During the first period, Native Americans burned valleys near settlements to clear land for agriculture while upper slopes and ridges were selectively burned to promote wildlife habitat and mast production (DeVivo 1991, Delcourt and Delcourt 1997). Fire frequency during this time was likely negatively correlated to distance to settlements (Delcourt and Delcourt 1997). Some estimates suggest that the fire frequency was between 7 and 12 years on ridges and upper slopes at elevations below 1000 m, but less frequently at upper elevations (Frost 1995). Other authors suggest that Native Americans burned as frequently as annually and biannually in some areas (Barden 1997). The pre-settlement landscape was likely a "shifting mosaic of open grasslands, woodlands, and closed forests with widely scattered Indian villages" (Buckner 1989).

The second era of fire use began with the arrival of Europeans in the 16th Century. The new arrivals introduced pandemic diseases and populations of Native Americans plummeted, initially reducing fire frequency and altering forest structure. Shortly after colonization in the 17th Century, the population of Europeans increased and much of the landscape was occupied by settlers who began adopting many of the Native American burning practices.

A third period characterized as the industrial era began in the latter 19th century as railroads made previously isolated parts of the mountains easily reachable and allowed for transportation of large amounts of commodities. Subsequent large scale timber exploitation resulted in heavy fuel loads from slash, and created drier, more open stands resulting in much higher intensity fires than previous eras though similar in frequency to previous eras (Harmon 1982). These high intensity and often stand replacing fires ushered in the fourth era of fire exclusion beginning in the early 20th Century. Complete fire exclusion was the policy of federal and state land management agencies until the fifth era of fire management began in the late 20th Century and continues to the present. Currently, prescribed fires are the dominant form of fire use in the Southern Appalachian Mountains. Suppression is still practiced on wildfires, though some wildland fire use is practiced.

Fire exclusion caused important changes in the structure and function of Southern Appalachian forests (Vose 2000). Stem density has increased in the shrub layer and species composition has changed with a greater dominance of shrubs such as mountain

laurel (*Kalmia latifolia*). High vegetation density has inhibited regeneration of overstory species and decreased diversity of herbaceous communities in the understory (Chastain and Townsend 2008). Fuel loads have also increased for reasons not related to fire exclusion, such as overstory mortality resulting from native and exotic pathogens. Accelerated mortality has increased the quantity of coarse woody debris and other organic matter that have augmented carbon and nutrient pools in the forest floor. The magnitude of these effects varies across the region and among ecosystems but each presents a difficult situation for forest management and restoration. It is critical that managers understand how the interactions of past land use and disturbances have given rise to current stand conditions so that appropriate actions can be taken to mitigate fuel risks.

The recognition of the role of fire in maintaining biodiversity and its usefulness as a forest management tool resulted in the active use of prescribed fire in Southern Appalachian Mountains beginning in the 1980's. Fires today are less frequent and generally much smaller than those of the past (Barden and Woods 1973, Lafon et al. 2005). Despite the usefulness of prescribed fire, its application is often limited by air quality issues and operational complexity due to a rapidly growing wildland urban interface.

Of the approximately 15.2 million ha encompassed by the Southern Appalachian Mountain region, eighty-four percent of the land is privately owned (~13 million ha) (SAMAB 1996). Approximately 2.2 million ha of the Southern Appalachian Mountain

region are under federal ownership as either National Forests or National Parks. Federal lands represent the vast majority of area where fuels are being managed. They include ten National Forests and as well as the Great Smoky Mountains and Shenandoah National Parks. An additional 202,000 ha are owned and managed by state agencies, a little over 40,000 ha by the Departments of Energy and Defense, and about 20,000 ha by the Cherokee Indian Reservation. Approximately 7.7 million ha of forested land in the region are under private ownership, where fuels are usually unmanaged.

FORESTS OF THE SOUTHERN APPALACHIAN MOUNTAIN REGION

Regional Climate, Ecosystem Processes, and Disturbance Regimes

The Southern Appalachian Mountain region lies within the Hot Continental Division and runs from the northeastern region of West Virginia through western Virginia and North Carolina, to the northwestern part South Carolina and northern Georgia, to northeastern Alabama (SAMAB 1996). Elevations generally range from 600 m in major river valleys to over 3000 m on upper ridges and peaks. Local climate differs drastically across the region along latitudinal and elevational gradients. Increases in elevation are associated with decreasing temperature and increasing precipitation, relative humidity, and cloud cover. Summers are usually hot and daytime temperatures frequently reach above 32° C while below freezing temperatures are common throughout the winter. Mean temperature is 19° C in the south and decreases to 8.3° C in the north. Annual precipitation is abundant and decreases from a maximum in the south of approximately

200 cm to just over 75 cm in the north. Most precipitation falls during the spring in the form of rain but winter snows and summer thunder storms are frequent. Region wide droughts occur approximately every decade. See Chapter 3 for additional detail on the physical setting for this division.

The region is well known for its biological diversity and is home to a variety of forest types which are generally distributed along strong elevational and topographic gradients (Whittaker 1956). Other factors, such as precipitation and temperature, also vary along these gradients and affect forest composition and ecosystem processes such as decomposition (Abbott and Crossley 1982), turnover of soil carbon (Garten and Hanson 2006), and aboveground forest productivity (Bolstad et al. 2001). There is some evidence that these ecosystem processes control fuel loading (Iverson et al. 2003, Kolaks et al. 2004, Waldrop et al. 2004), but variation in rates of input across the landscape may be balanced by corresponding rates of decomposition (Waldrop 1996, Kolaks et al. 2003). Evidence from over 1000 study plots at low to mid elevation across the southern extent of the region found little difference in surface fuels across topographic positions (Waldrop et al. 2007). Instead, disturbance history and type were found to play a greater role in determining fuel loads.

In addition to fire, other disturbances occur at variable frequencies and severities, with impacts ranging from single tree mortality to large areas of mortality resulting from high wind, hurricanes, floods, pathogen outbreaks, drought, and ice storms. There is considerable evidence that these disturbances may also vary in intensity along

environmental gradients (Harmon et al. 1984, Elliott and Swank 1994, McNab et al. 2004, Reilly et al. 2006, Stueve et al. 2007). The interactions between environmental gradients and disturbance hold implications for fuels management by altering dead and down surface fuels as well as patterns of regenerating live fuels in recently disturbed areas. Waldrop et al. (2007) found litter was lower on sites that had been burned in the last ten years and that one-hour fuel loads were higher on sites recently impacted by southern pine beetles. In areas that had been subjected to beetle attack, fire, and/or wind larger woody fuels were more abundant than on undisturbed sites.

Major Forest Ecosystems of the Southern Appalachian Mountains

The diverse vegetation in the Southern Appalachian Mountains has the potential to create a wide array of fuel management scenarios. We present an ecosystem-based approach using major vegetation and “macro” habitat groups delineated by the Southern Appalachian Assessment (SAMAB 1996). These forest ecosystems correspond well with those that others have described within the region (Whittaker 1956, McLeod 1988, Newell et al. 1999) and provide managers with a useful classification scheme.

Additionally, GIS data on the distribution and occurrence of these ecosystem types across the region are readily and freely available from the Southern Appalachian Assessment Online Database (http://samab.org/data/SAA_data.html).

Bottomland Hardwood Forests

Bottomland hardwood forests are found at the lowest elevations in the major river valleys and constitute approximately 12,500 ha in the region. These forests are dominated by several species including sweetgum (*Liquidambar styraciflua*), yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), river birch (*Betula nigra*), American sycamore (*Platanus occidentalis*), green ash (*Fraxinus pennsylvanica*), American elm (*Ulmus americana*), silver maple (*Acer saccharinum*), and cottonwood (*Populus deltoides*). Bottomland hardwood forests are very productive with rapid decomposition rates due to seasonal flooding and high soil moisture. Floods play a role in the disturbance regime of bottomland hardwood forests and may redistribute coarse woody debris and remove litter, especially after large events.

Invasion of exotic species has potentially altered fuel structure in bottomland hardwood forests. Dense thickets of Chinese privet (*Ligustrum sinense*) and multiflora rose (*Rosa multiflora*) may form large patches of continuous fuels capable of carrying fire under dry conditions. Large patches of kudzu (*Pueraria lobata*) reaching into canopies along forest edges may also occur. The presence of these species may warrant the use of fuels management to reduce localized fire hazards and control further spread of invasive species.

Oak Forests

Oak forests occur across a wide range of middle elevations and vary in topographic moisture. These are the most extensive ecosystems in the region and cover

approximately 7.5 million ha. Xeric oak forests are dominated by chestnut oak (*Quercus prinus*) and scarlet oak (*Quercus coccinea*) with an abundant ericaceous shrub layer. Post oak (*Quercus stellata*), black oak (*Quercus velutina*), southern red oak (*Quercus falcata*), blackjack oak (*Quercus marilandica*) and bear oak (*Quercus ilicifolia*) may be found at lower elevations. Mesic oak forests are dominated by white oak (*Quercus alba*) and northern red oak (*Quercus rubra*). Pignut hickory (*Carya glabra*) may also be present. A thick layer of potentially flammable ericaceous shrubs composed mostly of mountain laurel (*Kalmia latifolia*) with several species of blueberry (*Vaccinium* spp.) and huckleberry (*Gaylussacia* spp.) is often present throughout. Rhododendron (*Rhododendron maximum*) may be present in mesic oak forests. The shrub layer represents a major proportion of hazardous fuels, particularly when composed of mountain laurel, and can frequently pose a serious problem for fuel management.

Fire plays a major role in the disturbance regime of oak forests. It is hypothesized that much of these forests throughout the region developed under a regime of frequent low intensity fires (Abrams 1992). Fires are thought to have encouraged oak regeneration and inhibited encroachment of more fire sensitive mesic species like red maple and blackgum (*Nyssa sylvatica*). Lack of fire in the last century has likely increased the abundance of mountain laurel and other ericaceous shrubs and created hazardous fuel conditions. Wind and logging are also part of the disturbance regime in oak forests. Both of these disturbances have the potential to increase larger woody fuels (Waldrop et al. 2007).

Southern Yellow Pine Forests

Southern yellow pine forests are present on the xeric upper slopes and ridges of low and middle elevations and make up approximately 600,000 ha in the Southern Appalachian Mountain region. Virginia pine (*Pinus virginiana*), pitch pine (*Pinus rigida*), and Table Mountain pine (*Pinus pungens*) are the major constituents of southern yellow pine forests across the region with their respective importance increasing with decreasing topographic moisture and increasing elevation. A dense shrub layer consisting primarily of ericaceous species including blueberry, huckleberry, and mountain laurel is frequently present. Also frequently present in the shrub layer are hardwood species such as oaks, blackgum, and red maple. Piedmont species such as shortleaf pine (*Pinus echinata*) and loblolly pine (*Pinus taeda*) may also occur but are limited to the lowest elevations. Longleaf pine (*Pinus palustris*) has a very limited montane distribution in the southwestern most part of the region on dry ridges up to 600 m.

Many yellow pine stands were established early in the 20th century before the period of fire exclusion (Brose and Waldrop 2006) and are now in a decadent state (Williams et al. 1990). Active programs of prescribed burning are in place to promote regeneration of fire-adapted species, such as Table Mountain pine and pitch pine, by reducing the presence of encroaching shrubs and hardwood species and allowing sunlight to reach the forest floor. Past work has assumed that regeneration of these species required intense stand replacing fires, but more recent work suggests that periodic surface fires of moderate intensity may be sufficient (Waldrop and Brose 1999, Brose and Waldrop 2006).

Southern yellow pine ecosystems represent one of the most challenging issues for fuel managers. Potentially flammable evergreen canopies and abundant vertical fuels like mountain laurel can result in high severity crown fires. In addition, disturbance such as wind, ice storms, and southern pine beetle infestations can increase the abundance of both small diameter and large woody fuels (Waldrop et al. 2007). Periodic surface fires would not only facilitate regeneration but they would also reduce dangerous fuel loads.

Mixed Pine-Hardwood Forests

Mixed pine-hardwood forests are found on lower and middle elevation slopes and ridges across the Southern Appalachian Mountains, comprising approximately 1.6 million ha. Dominant species include the major constituents of both oak and southern yellow pine forests at varying densities. Oak species may include chestnut, scarlet, white, and northern red oak. At lower elevations pine species may include loblolly and shortleaf. Middle to upper elevation mixed pine-hardwood forests may include Virginia, pitch, and Table Mountain pines. Fire susceptible species, such as red maple, blackgum, white pine (*Pinus strobus*), and eastern hemlock (*Tsuga canadensis*) may be present in areas where fire has been excluded. A shrub layer consisting of species of blueberry, huckleberry and mountain laurel is also often present.

Disturbance regimes and productivity in mixed pine-hardwood forests are similar to those of oak and southern yellow pine forests. The mixed nature of these forests could be due to their mid-successional status. In the absence of fire to promote pine regeneration,

southern yellow pine forests will eventually succeed to oak forests in most cases. This process may be accelerated by other disturbances, particularly southern pine beetle attacks, in stands with older pines. In these areas there may be large amounts of both small diameter and large woody fuels on the ground (Waldrop et al. 2007). A frequent, low intensity fire regime may promote the coexistence of both pine and oaks.

Mixed Mesophytic Hardwood Forests

Mixed mesophytic hardwoods forests are among the most diverse forest communities in the Southern Appalachian Mountains, constituting approximately 334,000 ha. Dominant trees may often include yellow-poplar, white oak, northern red oak, basswood (*Tilia americana*), yellow buckeye (*Aesculus octandra*), white ash (*Fraxinus americana*), eastern hemlock, American beech (*Fagus grandifolia*), and sugar maple (*Acer saccharum*). These forests are typically found on moist east and north facing slopes and sheltered coves above 1200 m.

Fires in these forests were historically infrequent and remain that way today. Their sheltered nature and upper elevational range likely results in higher fuel moistures relative to other ecosystem types. However, periods of prolonged drought can result in overstory mortality which may result in increased surface fuels and higher midstory density where canopy gaps occur (Olano and Palmer 2004).

White Pine-hemlock-hardwood Forests

White Pine–hemlock-hardwood forests are typical of cool, moist ravines over a range of elevations. These forests occupy approximately 293,000 ha. Species composition is dominated by white pine and eastern hemlock with occasional hardwoods such as yellow-poplar, blackgum, black birch (*Betula lenta*), Frasier magnolia (*Magnolia fraseri*) and red maple. Rhododendron is common in the shrub layer. Forest structure is often composed of large diameter trees at low density with a thick layer of rhododendron in the midstory.

The historical disturbance regime of white pine-hemlock-hardwood forests was likely dominated primarily by wind. Although generally long lived, large white pine and eastern hemlock may be susceptible to windthrow which promotes gap phase regeneration of the less shade tolerant deciduous species. It is likely that these forests were sheltered from most fires historically because of their occurrence in ravines with high moisture. However, when fire does occur in these forests, mortality can be high (Reilly et al. 2006). The recent invasion of the hemlock woolly adelgid (*Adelges tsugae*) has resulted in large scale mortality of eastern hemlock. High rates of tree mortality will likely cause a pulse in both small and large surface fuels as branches and snags fall.

Northern Hardwood Forests

Northern hardwood forests are distributed in coves and upper slopes at elevations between 1200 and 1700 m and cover approximately 63,500 ha of the Southern

Appalachian Mountain region. Dominant species include sugar maple, American beech, and yellow birch (*Betula alleghaniensis*). Other species such as pin cherry (*Prunus pensylvanica*) and species found in mixed mesophytic hardwood forests may also be present. Species frequently present in the shrub layer are striped maple (*Acer pensylvanicum*) and American mountain ash (*Sorbus americana*).

Disturbance in northern hardwood forests is primarily by wind; fire was likely infrequent historically. Due to the elevational distribution of these forests fuel moisture is likely higher relative to other ecosystems in the region. The response of northern hardwood forests to droughts is likely similar to that of mixed mesophytic forests where canopy mortality may increase surface fuels and high levels of recruitment results in increased sapling densities. These effects may potentially be more drastic depending on exposure on upper slopes on which the forests occur.

Spruce-Fir Forests

Spruce-fir forests occur at the highest elevations, generally above 1500 m. These forests occupy approximately 36,400 ha. Growing seasons are short; weather is characterized by abundant moisture, high relative humidity, and high cloud cover. Dominant species include red spruce (*Picea rubens*) and Fraser fir (*Abies fraseri*). Species common to northern hardwood forests such as yellow birch, sugar maple, and pin cherry may also be present in spruce-fir forests. Woody species found in the shrub layer may include

rhododendron, Catawba rhododendron (*Rhododendron catawbiense*), mountain maple (*Acer spicatum*) and American mountain ash.

The disturbance regime of spruce-fir forests includes wind and ice storms. Although fire frequency is low, these forests are structurally similar to boreal forests and large high severity fires have occurred during prolonged drought. One fire in Haywood County N.C. burned approximately 10,000 ha in three days in what is now the Shining Rock Wilderness Area in October of 1925. Accounts of this fire reported that up to 30 cm of organic matter was consumed and in some spots up to two meters of soil was eroded (USDA Forest Service). Other local accounts describe a stand replacing fire that occurred near Mt. Mitchell during the early 1900's. More recently, acid precipitation and attacks of the balsam woolly adelgid (*Adelges piceae*) have resulted in large-scale mortality of canopy trees. Areas recently disturbed by ice or the balsam woolly adelgid (Smith and Nicholas 2000) may have abundant coniferous regeneration capable of carrying intense fire.

FUEL MANAGEMENT IN THE SOUTHERN APPALACHIAN MOUNTAINS

Limitations and Goals of Fuels Management in the Southern Appalachian Mountains

Current fuels management in the Southern Appalachian Mountains is performed primarily by public land managers on oak, southern yellow pine, and mixed pine-hardwood forests. The most effective technique employed by land managers is

prescribed fire. However, the use of prescribed fire can be reduced by smoke management requirements, lack of fiscal resources, operational complexity due to the wildland-urban interface, and concern for litigation due to smoke impacts or prescribed fire escapes. Fuels continue to accumulate regardless of the ease in application of prescribed fire making use of alternative treatments necessary. These methods primarily include mechanical or a combination of mechanical and prescribed fire treatments.

Goals of fuel management in the Southern Appalachian Mountains vary but in addition to reducing risk of wildfire, they also include promoting biodiversity, restoring native ecosystems, and improving wildlife habitat. Decreasing wildfire risk involves reducing surface fuels, and increasing the gap between surface fuels to live crown (Agee and Skinner 2005). Promotion of biodiversity and restoration of native ecosystems often focuses on regenerating fire adapted species like Table Mountain and pitch pines. Fuel treatments for restoring native ecosystems also include reducing the density of mountain laurel, rhododendron, and fire-susceptible tree species like red maple (Nowacki and Abrams 2008). These species may substantially reduce regeneration of desirable species such as oak. Fuel treatments such as prescribed fire and thinning which increase surface light levels may also be used to improve wildlife habitat by promoting the growth of new vegetation and promoting flowering (Whitehead 2003), increasing floral visitation of pollinators (Campbell et al. 2007), and fruit production (Blake and Hoppes 1986, Greenberg et al. 2007). To date most studies on fuel treatments have dealt primarily with prescribed fire and its effects on forest structure and live fuels with some emphasis on the forest floor and dead and downed fuels. However, results from the National Fire and Fire

Surrogate Study explicitly address effects of fuel treatments on forest floor as well as dead and downed woody fuels (Waldrop et al. 2008).

Fuels Management Techniques

Prescribed Fire

Prescribed fire is by far the most frequently used fuel management technique in the Southern Appalachian Mountain region. Prescribed fire has a relatively short history in the region because of fear that hardwoods and soils may be damaged and the potential difficulty in controlling fire on slopes (Van Lear and Waldrop 1989). In the early 1980's, managers first used prescribed fire for site preparation after clearcutting hardwood stands (Phillips and Abercrombie 1987), while the use of prescribed fire for restoration of native communities began in the 1990's (Waldrop and Brose 1999).

The effects of prescribed fire as a fuel management technique have the potential to vary a great deal depending largely on burning conditions and the ultimate goals of managers. Both of these will inevitably differ largely across ecosystems and result in variation in fire intensity and severity. We summarize the effects of prescribed fire as a fuel management tool from published reports in oak, southern yellow pine, mixed pine-hardwood, mixed-mesophytic, and white pine-hemlock-hardwood forest ecosystems. Managers must be cautious when considering the results summarized below since they

are derived from a limited number of observations and likely do not capture the full range of effects under a wide variety of burning conditions.

Prescribed Fire in Oak Ecosystems

Prescribed fires in oak ecosystems are generally low to moderate severity surface fires (Elliott et al. 1999, Vose et al. 1999, Waldrop et al. 2008) due to the characteristics of the broad-leaved surface fuels and resilience of most oak species to fire damage. However, areas of higher intensity fire can occur where there is a thick layer of ericaceous shrubs. In one study, fire intensity in an oak forest ranged from 9.9 to 53.6 kW/m with flame lengths range from 0.3 to 0.5 m and rate of spread between 0.3 to 1.4 m/min (Phillips et al. 2006). Temperatures one to two meters above the ground ranged from less than 52 to 160°C. In another study, a mean temperature of 59°C was measured 16.8 mm in the soil and as deep as 52 mm (Vose et al. 1999).

Prescribed fires in oak ecosystems generally have only minor effects on forest structure (Table 1) (Elliott et al. 1999, Waldrop et al. 2007). Although there is little effect on stand basal area, density of saplings initially decreases after treatment. However, due to vigorous sprouting of both hardwoods and ericaceous shrubs, sapling density can reach or exceed pre-fire density levels two to three years after application of two prescribed fires (Waldrop et al. 2007). Effects on surface fuels are mostly limited to consumption of about half the mass of small wood and litter, while effects on the humus layer and coarse

woody debris are minor (Vose et al. 1999). Due to the high productivity of most sites, surface fuels rapidly attain pretreatment loadings.

Prescribed Fire in Southern Yellow Pine Ecosystems

Prescribed fires in southern yellow pine ecosystems, particularly those dominated by Table Mountain and pitch pine, are likely to offer managers some of the greatest challenges due to the potential for high severity fires. Mountain laurel can act as a vertical fuel where it is abundant, allowing flames to reach into pine canopies. Observed flame temperatures have reached greater than 800°C and with a 59°C heat pulse penetrating 24 mm into the forest floor (Vose et al. 1999). Reported flame lengths can vary a great deal and range from 1 to 3 m to 12 to 46 m (Welch et al. 2000). Elliott et al. (1999) also reported ignition of crowns on upper slopes and ridges.

Prescribed fires in southern yellow pine ecosystems can have major effects on forest structure (Table 2). Studies have found reductions in basal area of 20 to 35% and reduction in stem density of overstory trees from 40 to 75% (Elliott et al. 1999, Vose et al. 1999, Welch et al. 2000). Despite large initial reduction of density in the sapling layer, shrubs and hardwoods sprout even after these higher severity fires and densities can actually increase in years following fire (Welch et al. 2000). Effects on surface fuels are mainly limited to consumption of between 60 and 70% of the mass of small wood and litter, while effects on the humus layer and coarse woody debris are minor (Vose et al. 1999).

Prescribed Fire in Mixed Pine-hardwood Ecosystems

Studies on prescribed fire in mixed pine-hardwood ecosystems have shown the potential for large variation in fire intensity and severity from site to site (Waldrop and Brose 1999). This variation is likely driven by variable densities of mountain laurel along with heterogenous canopy structure with mixtures of more flammable pine crowns and less flammable deciduous crowns. Hubbard et al. (2004) reported flame lengths from 0.3 to 1.52 m. Temperature sensitive paints on ceramic tiles estimated a maximum temperature of 135°C at 30 cm above the ground and a temperature of 59°C at 1.0 cm the forest floor. In another study, Waldrop and Brose (1999) report high fire intensity with crowning occurring on upper ridges.

Prescribed fires in mixed pine-hardwood forest ecosystems can also have a highly variable effects on forest structure and soils (Table 3). Waldrop and Brose (1999) document the effects of this variation on stand structure, regeneration, and components of the forest floor. Sites burning at low intensity had an average reduction in basal area of approximately 20% among trees over 5 cm dbh while plots burning at high intensity had an average reduction in basal area of 96%. Decreases in the density of trees 2.5 to 4.9 cm dbh ranged from 40% in low intensity plots to 99% in high intensity plots. All stems less than 2.5 cm dbh were killed but abundant regeneration of hardwoods occurred in all sites regardless of intensity. Pine regeneration varied among fires and was greatest at medium-low intensity and lowest at medium-high and high intensity. Regardless of

intensity, effects on the forest floor were limited to consumption of litter with little consumption of humus and exposure of mineral soil. Other studies in mixed pine-hardwood ecosystems have found similar results of low intensity prescribed fire on forest structure and the forest floor (Hubbard et al. 2004, Elliott and Vose 2005).

Prescribed Fire in Mixed Mesophytic Hardwood Ecosystems

Mixed mesophytic hardwood ecosystems commonly occupy sheltered sites with high moisture and thus tend to burn at lower intensity during prescribed fires. Although mountain laurel may be present, rhododendron and saplings of mesic hardwoods are generally the most abundant live fuels. Due to lower fire risk compared to other ecosystems of the Southern Appalachian Mountains, fuel treatments in mixed mesophytic hardwood ecosystems may be of low priority. As a result, studies and observations on prescribed fire in this type are limited. Available observations report that intensity is substantially lower than in other ecosystems as temperatures between one and two meters above the ground were consistently below 52°C and a temperature of 49°C penetrated only 0.5 mm on average into the ground (Vose et al. 1999).

Low intensity prescribed fires in mixed mesophytic hardwood ecosystems have little effect on live fuels in the overstory and midstory (Table 4). Elliott et al. (1999) found no overstory mortality after a prescribed fire and although stems in the midstory were killed their presence was maintained after the fire by vigorous sprouting. After the same fire there was also little effect on surface fuels (Vose et al. 1999). There was little change in

the mass of coarse woody debris, small wood, or litter, but mass of the humus layer increased.

Prescribed Fire in White Pine-hemlock-hardwood Ecosystems

Although white pine-hemlock-hardwood forest ecosystems generally occur on moist sites, observations on three prescribed fires suggest that fires of moderate intensity can occur, particularly in areas with thick layers of ericaceous shrubs. Clinton et al. (1998) found that flame lengths range from 0.3 to 1.5 m for backing fires and from 1.2 to 4.5 m in head fires. Rates of spread varied from 1.8 to 3.0 m per minute for head fires to 0.3 m per minute for backing fires. Maximum flame temperatures ranged from 260 to 704°C. Although information from these fires on live fuels was not available, results on the effects on surface fuels found that on average about 50% of the mass of small wood (<8 cm) and litter was lost, while about 20% of the humus layer was lost. Burning can be overly damaging to white pine because the species has thin bark and crowns low to the ground, particularly when young.

Mechanical Treatment

Although the use of mechanical fuel reduction treatments is currently limited, they may be useful alternatives in areas where the risks associated with prescribed fires are unacceptable. Mechanical treatments may lack many of the ecological effects of fire and are typically more expensive to apply. In the western United States, mechanical fuel

treatments usually include some degree of thinning followed by various methods of yarding and treatment of residual slash, possibly with prescribed fire (Youngblood et al. 2007). As a result of its limited use there is little available research on the effects of mechanical treatments on Appalachian forest fuels. Results from one site of the National Fire and Fire Surrogate explicitly address effectiveness of mechanical fuel treatments (Waldrop et al. 2007) provided a detailed look at the effects of two fuel-reduction treatments on forest structure in western North Carolina. A mechanical treatment involved chainsaw felling of all stems > 1.8 m tall and <10.2 cm dbh, as well as all mountain laurel and rhododendron stems regardless of size. In addition, two prescribed fires, both with and without the mechanical treatment, were conducted at a 3-year interval. After five years the mechanical treatment alone had no effect on basal area and structure of overstory trees. Density of hardwood saplings after the mechanical treatment decreased initially but slowly returned to levels similar to pretreatment levels by year 5 as a result of vigorous sprouting. Cover of shrubs initially decreased by a great deal after mechanical treatment and had recovered to only less than half the pretreatment abundance by year five. Cover of both mountain laurel and rhododendron, which constituted most of the shrub abundance, followed an identical trend.

The combination of mechanical treatment followed by two prescribed fires reduced basal area from 23.8 to 16.6 m² /ha after five years. Density of hardwood saplings decreased initially but was more than double pretreatment levels three years after treatment.

Application of a second prescribed fire reduced hardwood sapling density to just slightly higher than pretreatment levels by year five. Cover of all shrubs initially decreased to

near zero after the mechanical and burn treatment and remained at very low levels to year five. Cover of both mountain laurel and rhododendron followed this trend.

Chemical Treatment

Herbicides have been studied in the Southern Appalachian Mountains for competition control to favor pines and oaks (Neary et al. 1984, Loftis, 1985, Lorimer et al. 1994, Kass and Boyette, 1998) and for habitat of some wildlife species including small mammals (McComb and Rumsey 1982) and herpetofauna (Harpole and Haas 1999). However, no study has examined herbicide use for fuel reduction in the region. This treatment may be viable in the Southern Appalachian Mountains where fire or mechanical treatments are impractical, such as along the wildland-urban interface or on steep inaccessible slopes, but its impacts are unknown. Studies in the pine flatwoods of Florida (Brose and Wade 2002) and in Gulf Coast longleaf pine (Haywood 2009) show short-term increases in fuel loading which led to increases in fire intensity and damage. These results could occur in the Southern Appalachian Mountains although differences in species composition make the impacts difficult to predict. Waldrop et al. (2010) showed increased fire intensity for 5 years after chainsaw felling shrubs and small trees in the Southern Appalachians.

Although untested, a similar pattern would likely occur if herbicides were used.

A Comparison of the Effectiveness of Fuel Treatments

Despite the absence of a large body of information from different ecosystems on the effects of non-fire fuel treatments, the existing literature offers some evidence of

differences in the effectiveness of treatment options. Results from the National Fire and Fire Surrogate study (Youngblood et al. 2007) in oak ecosystems strongly suggest that a combination of felling shrubs and small trees and prescribed fire is the most effective means of controlling mountain laurel and other ericaceous shrubs, a fuel of concern in the region. Studies from different ecosystems on prescribed fire are consistent on the ability of mountain laurel and other ericaceous shrubs to rapidly increase in the years following treatment. The issue of how these fuels respond to mechanical and burn treatments in other ecosystem types is unknown. The ubiquity of mountain laurel and other ericaceous shrubs across the landscape suggest that it is possible that the response of different ecosystems could be similar. However, interactions with variables that may differ among ecosystems, such as moisture patterns and disturbance regimes could also result in different responses. Results from future studies in other ecosystems could shed light on whether the effectiveness of mechanical and burn treatments are limited to oak forests, or if they would be useful across the landscape.

The feasibility of widespread application of a mechanical plus burning treatment is questionable. The expense and amount of time required to treat areas may make it difficult to apply across large areas. In addition, in order for mechanical treatments to be effective the use of prescribed fire will still be required. Although there is no one solution, the use of mechanical treatment may be most useful in areas with immediate hazardous fuels treatment needs such as the wildland urban interface. Also, mechanical treatments can be very effective in preparing long unburned sites for prescribed burning. Clearly a manager must be resilient and open to cautiously experimenting with different

combinations of techniques, drawing experience and observation until more experimental data are available.

Prioritizing areas for treatment is critical to allocate resources most effectively. Fuel treatment prioritization hinges on managers making decisions that will not result in a decrease of acreage in acceptable condition while protecting vital assets. For example, a best management practice would be to focus efforts on maintaining areas that currently have low fuel loads and are simple to burn and only then allocating resources to problem areas when these activities will not cause an increase in untreated acreage. A burn prioritization model can streamline treatment programs and be useful for mapping current conditions and designating treatment priorities in a spatial context (Hiers et al. 2003).

The diversity and productivity of ecosystems in the Southern Appalachian Mountains coupled with a complex disturbance regime makes fuels management a challenge. Understanding this relationship will better enable managers to understand the dynamic interactions between disturbances which can alter fuel loads over short periods of time. Although rates of decomposition across the region are rapid, increases in dead and downed fuels following disturbance may create pulses in the abundance of hazardous fuels. In this case, understanding the temporal variation in the distribution of fuels may be as important as understanding the spatial variation. This is especially pertinent in the context of climate change scenarios where more frequent droughts and warmer temperatures could exacerbate the effects of disturbances such as native and exotic pathogens. These effects could be especially large in long unburned mature stands with

older decadent individuals and well developed shrub layers. Effective mitigation of these threats depends on effective fuels monitoring at large scales and adaptive management techniques to meet future challenges.

Research Needs

Prescribed burning is a relatively new tool in the Southern Appalachian Mountains. As a result, less is known about fuel reduction treatment impacts for the region than in other areas of the United States. Critical research needs include the impacts of mechanical and chemical treatments, comparisons of season and frequency of prescribed burning, and cumulative effects of repeated fuel reduction treatments over many years. With each of these treatments more information is needed to understand the impacts to most components of the ecosystem, biotic and abiotic, and the probability of introducing new and possibly unwanted components such as non-native invasive plants and animals. Research on smoke prediction is just underway in this region and is extremely difficult because of the complex topography and weather patterns that must be considered.

LITERATURE CITED

- Abbott, D.T. and D.A. Crossley Jr. 1982. Woody litter decomposition following clearcutting. *Ecology* 63: 35-42.
- Abrams, M. D.. 1992. Fire and the development of oak forests. *BioScience*. 42: 346-353.
- Agee, J.K. and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211: 83-96.
- Barden, L.S. and F.W. Woods. 1973. Characteristics of lightning fires in southern Appalachian forests. *Proceeding of the Annual Tall Timbers Fire Ecology Conference* 13: 345-361.
- Barden, L.S. 1997. Historic prairies in the piedmont of North and South Carolina, USA. *Natural Areas Journal*. 17: 149-152.
- Blake, J. G., and W. G. Hoppes. 1986. Influence of resource abundance on use of tree-fall gaps by birds in an isolated woodlot. *Auk* 103: 328–340.
- Bolstad, P.V., Vose, J.M. and S.G. McNulty. 2001. Forest productivity, leaf area, and terrain in southern Appalachian deciduous forests. *Forest Science* 47: 419-427.
- Brose, P.H. and D. Wade. 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. *For. Ecol. Manage.* 163(2002): 71-84
- Brose, P.H. and Waldrop, T.A. 2006. Fire and the origin of Table Mountain pine-pitch pine communities in the southern Appalachian mountains, USA. *Canadian Journal of Forest Research* 36: 710-718.
- Buckner, E.R. 1989. Evolution of forest types in the Southeast. In: Waldrop, T.A. *Proceedings of Pine-Hardwood Mixtures: A Symposium on Management and Ecology of the Type*. Pp. 27-33. Asheville, N.C. USDA, Forest Service, Southeastern Forest Experiment Station.
- Campbell, J.W., Hanula, J.L., and T.A. Waldrop. 2007. Effects of prescribed fire and fire surrogates on floral visiting insects of the blue ridge province in North Carolina. *Biological Conservation* 134: 393-404.
- Chastain, R.A. and Townsend, P.A. 2008. Role of evergreen understory shrub layer in the forests of the central Appalachian Highlands. *Journal of the Torrey Botanical Society* 135(2), 2008, pp. 208–223.
- Clinton, B.D., J.M. Vose, W.T. Swank, E.C. Berg, and D.L. Loftis. 1998. Fuel consumption and fire characteristics during understory burning in a mixed white pine-

hardwood stand in the southern Appalachians. Research Paper SRS-12. USDA, Forest Service, Southern Research Station, Asheville, N.C.

- Delcourt, H.R. and P.A. Delcourt. 1997. Pre-Columbian Native American use of fire on Southern Appalachian landscapes. *Conservation Biology*. 11: 1010-1014.
- DeVivo, M.S.. 1991. Indian use of fire and land clearance in the southern Appalachians. In: Nodvin, S.C. and T.A. Waldrop. *Fire and the environment: ecological and cultural perspectives*. Gen. Tech. Rep.. SE-69. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 306-312.
- Elliott, K.J. and W.T. Swank. 1994. Impacts of drought on tree mortality and growth in a mixed hardwood forest. *Journal of Vegetation Science* 5: 229-236.
- Elliott, K.J., R.H. Hendrick, A.E. Major, J.M. Vose, and W.T. Swank. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. *Forest Ecology and Management* 114: 199-213.
- Elliott, K.J. and J.M. Vose. 2005. Effects of understory prescribed burning on shortleaf pine (*Pinus echinata* Mill.)/mixed-hardwood forests. *Journal of the Torrey Botanical Society*. 132: 236-251.
- Fowler, C. and E. Konopik. 2007. The history of fire in the southern United States. *Human Ecology Review* 14: 165-176.
- Frost, C. C. 1995. Presettlement fire regimes in southeastern marshes, peatlands, and swamps. In: S. I. Cerulean and R. T. Engstrom, eds. *Fire in wetlands: a management perspective*. Proceedings of the Tall Timbers Fire Ecology Conference, No. 19. Tallahassee, FL: Tall Timbers Research Station: 39-60.
- Garten Jr., C.T. and P.J. Hanson. 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. *Geoderma* 136: 342-352.
- Greenberg, C. H., D. J. Levey, and D. L. Loftis. 2007. Fruit production in mature and recently regenerated upland and cove hardwood forests of the southern Appalachians. *Journal of Wildlife Management* 71: 321-335.
- Harmon, M.E. 1982. Fire history of the westernmost portion of the Great Smoky Mountains National Park. *Bulletin of the Torrey Botanical Society* 109: 74-79.
- Harmon, M.E., S.P. Bratton, and P.S. White. 1984. Disturbance and vegetation response along environmental gradients in the Great Smoky Mountains. *Plant Ecology* 55: 129-139.
- Harpole, D.N. and C.A. Haas. 1999. Effects of seven silvicultural treatments on terrestrial salamanders. *For. Ecol. Manage.* 114(1999):349-356.

- Haywood, J.D. 2009. Eight years of seasonal burning and herbicidal brush control influence sapling longleaf pine growth, understory vegetation, and the outcome of an ensuing wildfire. *For. Ecol. Manage.* 258(2009):295-305.
- Hiers, J.K., S.C. Laine, J.J. Bachant, J.H. Furman, W.W. Green, and V. Compton. 2003. Simple spatial modeling tool for prioritizing prescribed burning activities at the landscape scale. *Conservation Biology* 17: 1571-1578.
- Hubbard, R.M., J.M. Vose, B.D. Clinton, K.J. Elliott, and J.D. Knoepp. 2004. Stand restoration burning in oak-pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling. *Forest Ecology and Management* 190: 311-321.
- Iverson, L.R., D.A. Yaussy, J. Rebbeck, T.F. Hutchinson, R.P. Long, B.C. McCarthy, and C.L. Riccardi. 2003. Spatial and temporal distribution of fire temperatures from prescribed fires in the mixed oak forests of southern Ohio. In *Proceedings of the 13th Central Hardwood Forest Conference, 1-3 April 2002, Urbana, Ill.* Edited by J.W. Van Sambeek, J.W. Dawson, J.O. Ponder, E.F. Loewenstein Jr., and J.S. Fralish. USDA For. Serv. Gen. Tech. Rep. NC-234. PP. 293-294.
- Kass, DJ. And W.G. Boyette. 1998. Preharvest herbicide method to develop competitive oak reproduction in upland oaks stands in the mountains and Piedmont of North Carolina: 7-year results. In: Waldrop, T.A. (ed.), *Proceedings of the Ninth Biennial Southern Silvicultural Research Conference.* U.S. Department of Agriculture, Forest Service, Southern Research Station, General Technical Report SRS-20, 253-257.
- Kolaks, J., B.E. Cutter, E.F. Lowenstein, K.W. Grabner, G. Hartman, and J.M. Kabrick. Fuel loading in the central hardwoods. 2003. Paper 1A-3. In *Proceedings of the 2nd International Wildland Fire Ecology and Fire Management Congress, 16-20 Nov. 2003, Orlando, Fla.* [CD-ROM]. American Meteorology Society, Boston, Mass.
- Kolaks, J., B.E. Cutter, E.F. Lowenstein, K.W. Grabner, G. Hartman, and J.M. Kabrick. 2004. The effect of thinning and prescribed fire on fuel loading in the central hardwood region of Missouri. In *Proceedings of the 14th Central Hardwood Forest Conference.* 16-19 Mar. 2004, Wooster, Ohio. Edited by D.A. Yaussy, D.M. Hix, R.P. Long, and P.C. Goebel. USDA For. Serv. Gen. Tech. Rep NE-316. pp. 168-178.
- Lafon, C.W., J.A. Hoss, and H.D. Grissino-Mayer. 2005. The contemporary fire regime of the central Appalachian Mountains and its relation to climate. *Physical Geography* 26: 126-146.
- Loftis, D.L. 1985. Preharvest herbicide treatment improves regeneration in Southern Appalachian hardwoods. *S. J. Appl. For.* 9(1985):177-180.

- Lorimer, C.G., J.W. Chapman, and W.D. Lambert. 1994. Tall understory vegetation development as a factor in the poor development of oak seedlings beneath mature stands. *J. Ecology*. 82(1994): 227-237.
- McComb, W.C. and Rumsey, R.L., 1982. Response of small mammals to forest clearings created by herbicides in the central Appalachians. *Brimleyana* 8, pp. 121–134.
- McLeod, D. E.. 1988. Vegetation patterns, floristics, and environmental relationships in the Black and Craggy Mountains. Chapel Hill, NC: University of North Carolina. Ph.D.
- McNab, W.H., C.H. Greenberg, and E.C. Berg. 2004. Landscape distribution and characteristics of large hurricane-related canopy gaps in a southern Appalachian watershed. *Forest Ecology and Management* 196: 435-447.
- Neary, D.G., J.E. Douglass, J.L. Ruehle, and W. Fox. 1984. Converting rhododendron-laurel thickets to white pine with Picloram and Mycorrhizae-innoculated seedlings. *South. J. Appl. For.* 8(3):163-168.
- Newell, CL., R.K. Peet, CJ. Ulrey, T.R. Wentworth, K.D. Patterson, and D.E. McLeod. 1999. Geographic variation in forest distribution across five landscapes in the Southern Appalachian Mountains of North and South Carolina. In: Eckerlin, R.P.(ed.). *Proceedings of the Appalachian Biogeography Symposium Virginia. Museum of Natural History, Special Publications.* 7: 19-34.
- Nowacki, G. J. and M. D. Abrams. 2008. Demise of fire and mesophication of eastern U.S. forests. *BioScience* 58: 123-138.
- Olano, J.M. and M.W. Palmer. 2003. Stand dynamics of an Appalachian old-growth forest during a severe drought episode. *Forest Ecology and Management* 174: 139-148.
- Phillips, D.R. and J.A. Abercrombie. 1987. Pine-hardwood mixtures-a new concept in regeneration. *Southern Journal of Applied Forestry* 11: 192-197.
- Phillips, R.J., Waldrop, T.A., and D.M. Simon. 2006. Assessment of the FARSITE model for predicting fire behavior in the southern Appalachian mountains. In *Proceedings of the 13th Biennial Southern Silvicultural Research Conference, 1-3 March 2005, Memphis, TN.* Edited by K.F. Connor. *USDA Forest Service Gen. Tech. Rep. SRS-92.* pp. 521-525.
- Smith, G.F. and N.S. Nicholas. 2000. Size- and age-class distributions of Fraser fir following balsam woolly adelgid infestation. *Canadian Journal of Forest Research* 30:948-957.

- Stueve, K.M., C.W. Lafon, and R.E. Isaacs. 2007. Spatial patterns of ice storm disturbance on a forested landscape in the Appalachian Mountains, Virginia. *Area* 39: 20-30.
- Reilly, M.J., M.C. Wimberly, and C. Newell. 2006. Effects of a wildfire on beta diversity and species turnover in a forested landscape. *Journal of Vegetation Science* 17: 447-454.
- Southern Appalachian Man and Biosphere Program. 1996. The Southern Appalachian Assessment. Chapter 2 Wildlife and Plant Species. Southern Appalachian Man and Biosphere Program. Knoxville, TN
- Van Lear, D.H. and T.A. Waldrop. 1989. History, use and effect of fire in the southern Appalachians. USDA Forest Service, Southeastern Forest Experiment Station, Gen. Tech. Rep. SE 54.
- Vose, J.M., W.T. Swank, B.D. Clinton, J.D. Knoepp, and L.W. Swift. 1999. Using stand replacement fires to restore southern Appalachian pine-hardwood ecosystems: effects on mass, carbon, and nutrient pools. *Forest Ecology and Management* 114: 215-226.
- Vose, J.M.. 2000. Perspectives on using prescribed fire to achieve desired ecosystem conditions. In *Tall Timbers Fire Ecology Conference Proceedings*, No. 21. Tall Timbers Research Station: pages 12-17.
- Waldrop, T.A. 1996. Dynamics of coarse woody debris- a simulation study for two southeastern forest ecosystems. In *Proceedings of Coarse Woody Debris in the South-Implications to Management and Biodiversity*, 18-20 Oct. 1993, Athens, Ga. Edited by D.A. Crossely Jr., and J.A. McMinn. USDA Forest Service, Southern Research Station, Asheville, N.C. PP. 18-24.
- Waldrop, T.A. and P.H. Brose. 1999. A comparison of fire intensity levels for stand replacement of Table Mountain pine (*Pinus pungens* Lamb.). *Forest Ecology and Management* 113: 155-166.
- Waldrop, T.A., D.W. Glass, S. Rideout, V.B. Shelbourne, H.H. Mohr, and R.J. Phillips. 2004. An evaluation of fuel reduction treatments across a landscape gradient in Piedmont forests: preliminary results of the National Fire and Fire Surrogate Study. In *Proceedings of the 12th Biennial Southern Silvicultural Research Conference*, 24-28 Feb. 2003, Biloxi, Miss. Edited by K.F. Conner. USDA For. Serv. Gen. Tech. Rep. SRS-71. pp. 54-57.
- Waldrop, T.A., L. Brudnak, S. Rideout-Hanzak. 2007. Fuels on disturbed and undisturbed sites in the southern Appalachian mountains. *Forest Ecology and Management* 37: 1134-1141.

- Waldrop, T.A., D.A. Yaussey, R.J. Phillips, T.A. Hutchinson, L. Brudnak, and R.E.J. Boerner. 2008. Fuel reduction treatments affect stand structure of hardwood forests in Western North Carolina and Southern Ohio, USA. *Forest Ecology and Management* 255: 3117-3129.
- Waldrop, T., R.J. Phillips, and D.A. Simon. 2010. Fuels and predicted fire behavior in the southern Appalachian Mountains following fire and fire surrogate treatments. *For. Sci.* 56(1) 2010: 32-45.
- Welch, N.T., T.A. Waldrop, and E.R. Buckner. 2000. Response of southern Appalachian Table Mountain pine (*Pinus pungens* Lamb.) and pitch pine (*P. rigida*) stands to prescribed burning. *Forest Ecology and Management* 136: 185-197.
- Whitehead, M. A. 2003. Seasonal variation in food resource availability and avian communities in 4 habitat types in the southern Appalachian mountains. Dissertation, Clemson University, Clemson, South Carolina, USA.
- Whittaker, R.H. 1956. Vegetation of the Great Smoky Mountains. *Ecological Monographs* 26: 1-80.
- Williams, C. E., W. Johnson, and W. Carter. 1990. Age structure and the maintenance of *Pinus pungens* in pine-oak forests of southwestern Virginia. *The American Midland Naturalist*. 124: 130-141.
- Youngblood, Andrew; Metlen, Kerry; Knapp, Eric E.; Outcalt, Kenneth W.; Stephens, Scott L.; Waldrop, Thomas A.; Yaussy, Daniel. 2007. Implementation of the fire and fire surrogate study – a national research effort to evaluate the consequences of fuel reduction treatments. pp. 315-321. In: Peterson, Charles E.; Maguire, Douglas A., eds. 2005. Balancing ecosystem values: innovative experiments for sustainable forestry. Proceedings of a conference. Gen. Tech. Rep. PNW-GTR-635. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 389p.

Table 1. Summary of the effects of prescribed fires on live and surface fuels in oak forest ecosystems in the Southern Appalachian Mountains. Values for each fuel type correspond to reported values in each respective study unless fuel type is denoted with a *. In this case exact values were not reported and were estimated for this summary based on tables. Units for each fuel type are as follows: basal area (m²/ha), density (stems/ha), all surface fuels including litter and humus mass and small wood and coarse woody debris (CWD) (kg/ha).

Author	Date	Site	Elevation	Fuel Attribute	Pre	Post	Post + 3 years	Post + 5 years
Waldrop et al. 2008	Jan-02 /Jan-06	Green River Game Land, NC	366 to 793 m	Basal Area	26.5	26.3	26.1	25.9
Waldrop et al. 2008	Jan-02 /Jan-06	Green River Game Land, NC	366 to 793 m	Density <10 cm	*1500	*750	*1500	*875
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Basal Area ≥ 5 cm	28.69	28.42	-	-
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density ≥ 5 cm	1448	1365	-	-
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density ≥ 1 and < 5 cm	8987	1556	-	-
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Litter Mass	3775	2825	-	-
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Humus Mass	14780	13849	-	-
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Small Wood >7.5cm	4234	2465	-	-
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	CWD ≤7.5 cm	8096	7308	-	-

Table 2. Summary of the effects of prescribed fires on live and surface fuels in southern yellow pine forest ecosystems in the Southern Appalachian Mountains. Values for each fuel type correspond to reported values in each respective study. Units for each fuel type are as follows: basal area (m²/ha), density (stems/ha), all surface fuels including litter and humus mass and small wood and coarse woody debris (CWD) (kg/ha).

Author	Date	Site	Elevation	Response Variable	Pre	Post	Post + 1 Year
Welch et al. 2000	Oct-95	George Washington and Jefferson National Forests, VA	-	Basal Area \geq 2.5 cm	23.3	16.6	-
Welch et al. 2000	May-96	George Washington and Jefferson National Forests, VA	-	Basal Area \geq 2.5 cm	28.5	19.2	-
Welch et al. 2000	May-96	Pisgah National Forest, NC	-	Basal Area \geq 2.5 cm	32	25.9	-
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Basal Area \geq 5 cm	26.84	18.86	-
Welch et al. 2000	Oct-95	George Washington and Jefferson National Forests, VA	-	Density < 2.5 cm	1112.7	2912.7	-
Welch et al. 2000	May-96	George Washington and Jefferson National Forests, VA	-	Density < 2.5 cm	1787.7	3250.3	-
Welch et al. 2000	May-96	Pisgah National Forest, NC	-	Density < 2.5 cm	1712.7	2294.5	-
Welch et al. 2000	Oct-95	George Washington and Jefferson National Forests, VA	-	Density \geq 2.5 cm	1525	625	-
Welch et al. 2000	May-96	George Washington and Jefferson National Forests, VA	-	Density \geq 2.5 cm	1594	431	-
Welch et al. 2000	May-96	Pisgah National Forest, NC	-	Density \geq 2.5 cm	1900	887.5	-
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density \geq 5 cm	1545	913	-
Elliott et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density 1 to 4.9 cm	12178	409	5692
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	CWD	8776	7726	
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Humus Mass	30609	28449	
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Litter Mass	5362	1873	
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Small Wood < 7.5 cm	6933	1369	

Table 3. Summary of the effects of prescribed fires on live and surface fuels in mixed pine-hardwood forest ecosystems in the Southern Appalachian Mountains. Values for each fuel type correspond to reported values in each respective study unless fuel type is denoted with a *. In this case exact values were not reported and were estimated for this summary based on tables. Between the first and second year after burning, several sites in Elliott and Vose 2005 and Hubbard et al. 2004 were impacted by southern pine beetle so changes are not wholly attributable to fire. Units for each fuel type are as follows: basal area (m²/ha), density (stems/ha), all surface fuels including litter and humus mass and small wood and coarse woody debris (CWD) (kg/ha).

Author	Date	Site	Elevation	Response Variable	Severity	Pre	Post	Post+1 year
Elliott and Vose 2005	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Basal Area \geq 5 cm	Low	31.1	28.8	23.9
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Basal Area \geq 2.5 cm	Low	28.3	22.7	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Basal Area \geq 2.5 cm	Medium Low	34.5	11.1	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Basal Area \geq 2.5 cm	Medium High	23.4	1.6	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Basal Area \geq 2.5 cm	High	27	1	-
Elliott and Vose 2005	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Density < 0.5 m tall	Low	68,480	138,120	113,740
Elliott and Vose 2005	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Density \geq 5 cm	Low	1485	1362	1150
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density \geq 5 cm	Low	*716	*430	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density \geq 5 cm	Medium Low	*847	*177	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density \geq 5 cm	Medium High	*775	*45	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density \geq 5 cm	High	*776	*6	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density 2.5 to 4.9 cm	Low	*95	*0	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density 2.5 to 4.9 cm	Medium Low	*200	*0	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density 2.5 to 4.9 cm	Medium High	*105	*0	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Density 2.5 to 4.9 cm	High	*110	*0	-
Elliott and Vose 2005	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Density < 5 cm dbh, \geq 0.5 m tall	Low	9100	5900	9525
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Regeneration	Low	-	Pine=13,852 Hardwood=3 2,150	

Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Regeneration	Medium Low	-	Pine=22551 Hardwood=37371	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Regeneration	Medium High	-	Pine=9015 Hardwood=26,590	-
Waldrop and Brose 1999	Apr-97	Chattahoochie National Forest, GA	885 to 1100 m	Regeneration	High	-	Pine=3448 Hardwood=31,537	-
Hubbard et al. 2004	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Humus Mass	Low	11435	10837	-
Hubbard et al. 2004	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Litter Mass	Low	6028	1833	-
Hubbard et al. 2004	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	Small Wood < 5 cm	Low	6906	4425	-
Hubbard et al. 2004	Mar-01	Chattahoochie National Forest, GA / Cherokee National Forest, TN	260 to 415 m	CWD \geq 5 cm	Low	7611	6696	-

Table 4. Summary of the effects of prescribed fires on live and surface fuels in mixed mesophytic hardwood forest ecosystems in the Southern Appalachian Mountains. Units for each fuel type are as follows: basal area (m²/ha), density (stems/ha), all surface fuels including litter and humus mass and small wood and coarse woody debris (CWD) (kg/ha).

Author	Date	Site	Elevation	Fuel Response Variable	Pre	Post
Elliott et al.1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Basal Area \geq 5 cm	27.72	27.82
Elliott et al.1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density \geq 5 cm	1167	1117
Elliott et al.1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Density 1 to 4.9 cm	2153	2652
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Humus Mass	11038	13410
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Litter Mass	4151	4028
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Small Wood \leq 7.5cm	3560	3231
Vose et al. 1999	Apr-95	Nantahala National Forest, NC	1500 to 1700 m	Coarse Woody Debris \geq 7.5cm	15720	15596