Synthesis of Knowledge of Hazardous Fuels Management in Loblolly Pine (*Pinus taeda* L.) Forests

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Products are discussed as examples of previous operations and are not endorsements

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PREFACE

In recent years, the danger of destructive wildfires in many areas of the United States has become a major issue due to an increase in the human population and to decades of fuel accumulation from wildfire suppression and climatic variability. Fencing of livestock has also reduced the frequency of woods burning for livestock grazing. As a result, forests that previously burned regularly have been allowed to build up so much fuel so that when a wildfire does occur, it can be intense and difficult to suppress, endangering both lives and property as well as degrading the forest. A series of major wildfires in the West and in Florida during the late 1990's highlighted the problem and provided the catalyst for new aggressive government strategies for reducing hazardous fuel levels. The Cohesive Fuels Strategy (U.S. Department of the Interior and U.S. Forest Service 2006) and the Healthy Forests Initiative (U.S. Department of the Interior 2006a) have accelerated the rate of hazardous fuel reduction through administrative reform, new legislation, and increased funding. The mandate of the Healthy Forests Initiative was to reduce fuels to the point where a subsequent management of regular low-intensity prescribed burns would be possible, with an emphasis on forests near buildings and roads (the wildland-urban interface). Subsequently, government agencies increased their fuel reduction activities, especially the use of mechanical equipment, to either mulch fuels or remove them from the forest. According to the October 2006 Healthy Forest Report (U.S. Department of the Interior 2006b), Federal agencies have reduced the wildfire hazard on over 18 million acres since 2000. Based on accomplishment reports, the Federal government treated over three million acres of the wildland-urban interface and over one million acres of other land in the South. For both areas, prescribed burning was the most common treatment.

Complementing the work of the Healthy Forest Initiative is the Joint Fire Science Program, which is a collaboration among six Federal agencies to provide scientific information in support of fuel and fire management programs. In 2005, the Program funded research to develop Knowledge Syntheses for hazardous fuel management in forest types that are characterized by:

- A broad geographic coverage
- A significant wildland-urban interface
- A susceptibility to destructive insect outbreaks
- A set of ecosystems with high political and public interest
- A potential for smoke problems and air quality issues
- A potential susceptibility to invasive species

For the South, loblolly pine (*Pinus taeda* L.) meets all of these criteria and this synthesis is intended to serve as a general overview of hazardous fuels in loblolly pine-dominated forests as well as a reference guide on different fuel management treatments. Other types of southern pine forests, including those dominated by slash pine (*Pinus elliottii* Engelm.) and longleaf pine (*Pinus palustris* P. Mill.) will be covered in other syntheses. However, selected examples of fuel management from these forest types will be discussed if the information is relevant to loblolly pine forests. The synthesis is not designed to be a manual on recommended treatments. Rather, information is provided to allow readers to understand which treatment options are feasible, what the approximate expected costs would be, and how treatments may affect fuels and non-fuel factors such as soil, water quality, and wildlife. Readers are given enough information to decide what options should be explored in greater detail through other publications or consultation with professionals.

This synthesis relies heavily on anecdotal information in addition to published works. Southern fuel reduction operations are rarely documented and while some land managers informally exchange information on such operations, many are not familiar with previous operations and what was learned. This lack of documentation and limited information exchange was a major incentive for the development of this and other fuel management syntheses. During the development of this synthesis, various private and public land managers were interviewed about their fuel management techniques and experiences, with an emphasis on finding new or more effective ways of dealing with fuels as well as identifying operational issues that may not be obvious (e.g. contract terms, soils). Therefore, some of the information provided in this synthesis is derived from the scientific literature (and identifiable by literature citations), while other information is noted as being derived from personal communication. In some cases we summarize anecdotal information from our visits with forest managers and operators. The latter is done in an attempt to avoid providing explicit costs, such as contracted prices, from specific operations.

INTRODUCTION

The loblolly pine forests of the South and the wildfires that occur within them do not lend themselves to easy ecological classification because of the influence of human land use on the region. The extent of loblolly pine and its importance are largely a result of agricultural abandonment, forest management, wildfire suppression, and the extensive use of prescribed burning. The majority of wildfires in the South are started by humans, and wildfire occurrence will be exacerbated by the rapidly expanding population and the way that new housing is often built adjacent to loblolly pine forests. Thus, southern forest management must take into account the broader landscape context of a particular management unit. Furthermore, changing forestland ownership patterns indicate a growing proportion of small parcels where hazardous fuel management is problematic. To better understand this complex interaction between loblolly pine, humans, and hazardous fuel management, the history of the southern forests and how loblolly pine came to become the dominant pine species will be reviewed. In addition, the population growth in the South and the growing wildland-urban interface will be discussed, as well as evolving land ownership patterns.

HISTORY OF SOUTHERN FORESTS

At the time of European arrival, most major southern vegetation communities were produced by the interaction between species adaptations, natural disturbances, and Native American agricultural and fire practices. While it is known that the Native Americans regularly used fire around their settlements (Stanturf and others 2002), the landscape was a mosaic of savanna-like longleaf (resulting from lightning-ignited fires) interspersed with lowlands, and the ecotone between the two contained substantial amounts of loblolly pine forests. Apart from limited observations by early Spanish explorers, the earliest European and American descriptions of the southern landscape date from the 19th century, by which time the Native American influence had been declining for over a century and the majority of the region had been depopulated by disease and warfare. While travelers wrote of large expanses of longleaf pine-dominated savannas, their travels were limited in scope, and systematic study of the southern landscape would not occur until the early 20th century. Even now, the extent and composition of pre-European forests remains unclear. Utilizing old government and personal accounts to estimate the pre-European range of longleaf pine, Frost (1993) estimated that longleaf-dominated forests and savannas covered 93 million acres in the pre-European South while pine-hardwood and slash pine forests covered another 13 million acres.

While details about the pre-European forests will likely remain unknown, it is known that until the arrival of steam-powered equipment, the majority of post-European forests were unlogged mature pine-dominated stands that were burned regularly by local farmers and herdsmen. Conner and Hartsell (2002) estimated that in 1630 (after the decline of Native American populations and before large-scale clearing), southern pine and hardwood forests covered 354 million acres in vegetation patterns similar to those found in the early 19th century. Starting in the late 19th century, railroad technology freed loggers from a dependence on large rivers for log transport. At the same time, the growing market for lumber as well as the success of cash crops such as tobacco and cotton encouraged large-scale logging and conversion to farms. By 1927, only 12.6

million acres of the original 121 million acres of pre-European pine forests remained (Schultz 1997) (Due to differences in methodologies, the pre-European estimates provided by Schultz (1997) and Frost (1993) do not match). Poor farming practices, the cotton boll weevil (*Anthonomus grandis*), and the Great Depression forced many small farmers off their lands and these areas were left to revegetate on their own. Since loblolly pine is a prolific seeder and was often left in depressions or along property boundaries, it quickly colonized these abandoned areas. In addition, Federal Depression-era work programs, such as the Civilian Conservation Corps, planted large areas with loblolly pine and slash pine seedlings for soil conservation. This revegetation produced the second forest of the South, which would form the foundation of the future southern forestry industry. The disturbance history of pine forests may have changed as well, as certain state laws, such as Georgia's O.C.G.A. § 4-3-3 "Permitting livestock to run at large or stray" (State of Georgia 2006), which was enacted in 1953, encouraged landowners to fence their property, and caused a major reduction in the frequency of woods burning.

THE MODERN SOUTHERN FORESTS

The total forest area of the South has remained fairly stable since 1982. Conner and Hartsell (2002) estimate that there were about 215 million acres of forests in 1999, versus 218 million acres in 1982. Reversing a long-term trend, additions to forestland started to exceed removals by 1987, although when compared to the total forest acreage, the increase is fairly small. Recently, Florida and Louisiana have been losing forest area while Alabama, Arkansas, Mississippi, and Kentucky have been gaining

(Wear and Greis 2002).

Of the 200 million acres of timberland in the South (forests with sufficient wood for potential harvesting) in 1999, 52 percent were hardwood, 25 percent were loblolly pine-shortleaf pine (*Pinus echinata* P. Mill.), 7 percent were longleaf pine-slash pine, and 15 percent were oak-pine (Conner and Hartsell 2002). The uplands of the Coastal Plain and lower Piedmont are dominated by pines while the upper Piedmont, Appalachian Mountains, Cumberland Plateau, and Lower Mississippi Alluvial Valley are dominated by hardwoods. While the hardwoods are largely naturally regenerated, 48 percent of the pine forests were planted. Another important characteristic of the pine forests of the South is the age structure. Most planted stands are harvested by age 30 to 40. Of 30 million acres of planted pine in the South in 1999, 89 percent were less than 28 years old and half were less than 13 years old (Conner and Hartsell 2002).

THE HISTORY, CURRENT DISTRIBUTION, AND ECONOMIC IMPORTANCE OF LOBLOLLY PINE

The age structure and geographic distribution of southern forests have important implications for understanding loblolly pine and its connection with fuels and wildfire. Loblolly pine is a modern paradox in that even though it is one of the most widespread and important tree species in the South, its widespread dominance and economic significance are actually a fairly recent occurrence. As mentioned earlier, it is believed that during the last few centuries of the pre-European era, most of the Coastal Plain uplands were dominated by longleaf pine and kept in savanna-like conditions by frequent fires set by Indians and lightning, with loblolly pine and slash pine thought to have been confined to the moist zone between the droughty, fire-prone uplands and the hardwood-dominated wet bottomlands (Stanturf and others 2002). Loblolly pine historically also existed as a co-dominant species with longleaf and shortleaf pine on upland sites in the Coastal Plain, and was common in pine and pine-hardwood stands across the Piedmont and to east Texas, beyond the natural range of longleaf pine.

Like most southern pines, loblolly pine is adapted to colonizing recently disturbed areas where the soil has been exposed. Loblolly pine seeds are light, and can travel a long distance. Once seeds germinate, the seedlings can grow rapidly despite harsh conditions. However, while loblolly pine are fire-tolerant once they reach a certain size, seedlings have less resistance to fire, and trees need to reach about 5 to 10 feet tall to survive a fire. That is why loblolly pine was historically restricted to the mesic (wet) margins, even though it grows faster than longleaf pine, which is tolerant of the drier conditions of the more pyric upland areas. In the Piedmont, loblolly pine was confined to wet depressions since it could not outcompete the hardwoods in wet areas or shortleaf pine in the drier areas (Stanturf and others 2002). Given its value as a forestry species and its adaptability to different soils and climates, loblolly pine now extends from Delaware to Florida and east Texas (fig. 1).

It is not possible to associate loblolly pine with any particular soil type, although it is unlikely to be found in excessively well-drained or poorly-drained soils, mainly because of high nutrient demands rather than soil moisture relations. Similarly, loblolly pine is not found exclusively in any particular plant community, although naturally maintained populations do require periodic major disturbances to give seedlings an advantage over hardwoods. The advantages of loblolly pine over slash pine for intensive forestry is in greater fusiform rust (*Cronartium fusiforme*) resistance, higher juvenile growth rates, and better responsiveness to cultural treatments such as fertilizer and competition control. Loblolly pine is also more resistant to ice damage, another reason why it is preferred north of the natural range of slash pine.

Since the 1950's, forestry has been an important part of the southern economy. Abt and others (2002) found that by 1997, the wood products-based sector accounted for about 5.5 percent of southern jobs and 6.0 percent of the gross regional product. Outside of the slash pine-dominated flatwoods of north Florida, loblolly pine is the most important species for southern forestry.

FORESTLAND OWNERSHIP PATTERNS

The bulk of southern forestland has always been in private hands, with many large tracts created during the Great Depression for hunting or forest products. One project of the Civilian Conservation Corps, for example, was planting trees. In 1999, 89 percent of the 200 million acres of timberland in the South were privately owned (Conner and Hartsell 2002). Birch (1997) estimated that there were 4.9 million ownership units. There were 3.13 million acres of loblolly and shortleaf pine in southern National Forests and 2.20 million acres in other public ownership in 2002 (Smith and others 2004). The nature of southern land ownership has important implications for potential fuel management treatments since owners have different objectives and constraints on the management of their land.

Large forested tracts are typically managed for forest products or game species, and are usually pine forests. However, the ownership patterns of these large tracts have been changing over the last few decades. According to Stanturf and others (2003a), 54 percent of southern plantations are owned by corporations and there is a growing trend of land sales from traditional forestry companies to investment fund companies. From 1982 to 1999, investment companies increased their land base by 20 percent to 20 million acres. Another important trend with large tracts is that in certain high population growth areas, forestry companies are selling the land for development, and eliminating prescribed burning as a management practice because of the associated liability. Where intensive management continues today, forest industry does not use prescribed burning because it conflicts with their fertilization practices.

While the total forest acreage (all owners) does not appear to have changed much since 1982, there have been significant changes in tract sizes. Birch (1997) found that between 1978 and 1994, both the number and acreage of private forestland tracts increased while average tract size decreased. These trends reflect the growing importance of individual landowners buying forestland as an investment, and the desire of people to move further away from urban centers. One of the most important consequences is the increase of small housing tracts adjacent to larger forested tracts in rural areas, an important characteristic of the wildland-urban interface.

THE WILDLAND-URBAN INTERFACE AND FIRE

According to the 2000 Census, the U.S. population increased 13 percent during the previous decade to over 281 million (Perry and Mackun 2001). The West and South grew much faster (20 and 17 percent) than the Midwest and Northeast (8 and 6 percent) and the southern population increased to over 100 million, accounting for 36 percent of the total U.S. population. Accompanying this rise in population was a general increase in housing development in rural areas, especially near major urban centers. From 1982 to 1992, 6.5 million acres in South were converted from rural to urban population densities, with highest rates of conversion in Texas, Georgia, Florida, and North Carolina (Cordell and Macie 2002). This conversion is the basis for the growth in the wildland-urban interface, which now ranges from 5 percent in Texas to 44 percent in North Carolina (Radeloff and others 2005).

For most cases, the wildland-urban interface can be considered a mix of rural features (forests and agriculture) and urban ones (high road and housing densities) where there is an increased risk for wildfire ignition and spread, and an increased risk of damage for features valued by humans. The wildland-urban interface is an important area for fuel management, and its definition is commonly based on housing units per unit area. However, as pointed out by Wimberly and others (2006), it is more realistic to consider the wildland-urban interface as a dynamic group of social, physical, and biotic gradients. For example, a southern wildland-urban interface could range from isolated recreational cabins to dense subdivisions. Thus, in this guide, the wildland-urban interface will be treated as a general concept rather than specific set of conditions.

While the nature of the wildland-urban interface is somewhat vague, its importance in the fuel management discussion is clear. As will be discussed in the next section, the majority of southern wildfires are caused by debris burning and arson. This means that there is a two-way wildfire risk relationship in these areas, where residential areas adjacent to forests are the most likely areas for wildfires to start. At the same time, the density of homes and their proximity to fuel sources suggests that once a wildfire starts, it can quickly spread to the houses and cause a large amount of damage in a small area. Thus, protecting homes from wildfire is considered a priority for both firefighters and foresters.

An important consideration for protecting homes is the size and location of nearby forest tracts. In many areas of the wildland-urban interface, loblolly pine forests are often broken up into small forested tracts intermixed with residential tracts. As a forest tract decreases in size, it becomes more difficult and expensive to manage fuels given the economy of scale for forestry treatments such as thinnings or prescribed burning (Greene and others 1997). In other words, there are certain fixed costs to treatments regardless of the total acreage treated (e.g. move-in costs), thus as tract size decreases, the cost per acre generally increases. Mechanical treatments, for example, may suffer from these economies of scale, but they may be the only option where prescribed burning is precluded for other reasons. However, the renewed interest in forest biofuels may change the economics associated with these treatments.

The increase in the area of wildland-urban interface and changing social values in an urban-dominated society are often cited as major impediments to hazardous fuel management (e.g. Stanturf and others 2003b), particularly where prescribed burning is considered. However, Loomis and others (2001) conducted a phone survey of Florida residents and found that the majority considered prescribed burning acceptable. Most southern state governments have also passed legislation specifically designed to promote prescribed burning, although Haines and others (2001) found that the most important limitations to burning operations were state-level smoke (i.e., air quality) regulations, personnel limitations, and legal liability.

FIRE AND FUEL ISSUES

We will consider loblolly pine forests not as a distinct habitat, but as a gradient of growing conditions and plant species compositions, with loblolly pine as the dominant overstory species. Likewise, the fuel conditions found in these forests vary according to tree and understory species composition, growth and decomposition rates, stage of succession, past management practices, and other factors. Therefore, to effectively deal with fuels and wildfire risk under these varying conditions, managers should treat each forest as unique and be adaptable to different management options.

WILDFIRE IN THE SOUTH

Occurrence—While the yearly occurrence of wildfires in western forests is well known due to their severity and difficulty to suppress, the 13 southern states actually have far more wildfires than the 15 western states, according to the National Interagency Fire Center (2006a). The vast majority of southern wildfires and burned acreage are generally caused by humans.

Although the South has more wildfires than other regions of the country, they are mostly smaller in size due to fragmentation and easy access, which results in effective initial attack. For example, in Georgia, while there are about 8,700 wildfires annually, they average less than five acres (Georgia Forestry Commission 2006). Similarly, the average Arkansas wildfire is about 14 acres (Personal communication. 2005. M. Cagle and L. Nance, Staff Forester and Deputy State Forester, Arkansas Forestry Commission, 3821 West Roosevelt Rd., Little Rock, AR 72204). From 1997 to 2005, there were 43 U.S. wildfires of at least 100,000 acres but only one (the 1998 Volusia complex wildfire in North Florida) was in the South (National Interagency Fire Center 2006b). However in 2007, the largest wildfire in the U.S. occurred in and around the Okefenokee Swamp in southern Georgia and northern Florida (for administrative purposes this complex was managed as three separate fires, the Sweat Farm Road, Big Turnaround, and Bugaboo). Nevertheless, the annual probability of a southern forest having a wildfire appears to be very low. Zhai and others (2003) analyzed data from 17,534 south-central permanent inventory plots that were measured from 1988 to 1992 and found that within the previous two years of measurement, 0.2 percent of the plots had been burned by wildfire, 3.3 percent had been prescribed burned, and 0.9 percent had been burned by unidentified factors. Thus, a conservative estimate for wildfire probability for the south-central U.S. could be 0.5 percent per year.

Causes of wildfire—Wildfire data collected by state forestry agencies indicates that the majority of wildfires in the South are caused by debris burning (e.g. yard wastes) and arson. For example, in Georgia, debris burning is responsible for 51 percent of the wildfires while arson was responsible for an additional 18 percent (Georgia Forestry Commission 2006). Similarly, 43 percent of Arkansas wildfires were due to arson while 30 percent were from debris burning (Arkansas Forestry Commission 2006). However, Florida is an important exception to this trend. While arson accounts for 25 percent of wildfires and debris burning accounts for another 19 percent, lightning causes 19 percent (Florida Division of Forestry 2004). Furthermore, Florida has a pronounced lightning season (May-October) during which lightning becomes the dominant ignition source.

Types of wildfire—In the South, wildfires can move slowly through the organic layers of soils (duff-related fires), near the surface of the ground, or in the crowns of trees. In coastal parts of the Carolinas, thick organic soils can be a major issue for duff-related fires during dry conditions. While organic soils do not burn intensely, they can burn for many days and produce large amounts of smoke. Heavy accumulations of duff may pose a serious threat to some southern pine forests, in terms of mop-up effort required, potential smoke production, and danger associated with re-ignition. Forest fragmentation and a longer frequency between fires only serve to increase the threat. During droughty years, the risk of damaging the roots of trees may be increased with duff fires.

Surface fires are common types of wildfire, where the mid- and understory vegetation are consumed, and the overstory canopy (crown) does not burn except under unusual wind and drought conditions.

Crown fires are relatively rare, even during severe wildfire seasons. While crown fires are uncommon, overstory trees can still be harmed by the heat generated by surface fires, through scorching or thermal girdling. For example, the 1998 wildfire season in North Florida was unusually intense and destructive due to an extended drought and a string of arson attacks and lightning strikes. Outcalt and Wade (2004) examined burned slash pine stands in Osceola National Forest and found that even though the wildfires had killed about 30 to 50 percent of trees, crown fire had been relatively rare. For most stands, only 10 to 20 percent of the plots had at least 75 percent crown scorch (where the heat from a fire singes the leaves and needles in the top branches of trees), which included some cases of crown fire (where fire has spread to the top branches of the trees). Crown fires were not common in stands that had been regularly prescribed burned, yet were fairly common in stands that had not been prescribed burned.

WHAT ARE HAZARDOUS FUELS?

Wildfires in the South are often situated near buildings and roads and can cause large amounts of property damage and injury in a small area. In addition, since the wildland-urban interface is rapidly expanding, wildfire danger has to be considered for both existing homes and infrastructure as well from expected future development.

Furthermore, different land managers have different protection priorities, varying from endangered species to water quality to recreational visitors. Hence, the concept of what is considered hazardous fuels is a matter of interpretation and objectives and does not easily lend itself to definition. A background on forest fuel concepts as they relate to fire behavior and intensity is provided in Appendix A.

Fuel management objectives will vary by location, protection priorities, budgetary resources, and the long-term management goals of each landowner. The most common objective related to fuel management is to manipulate forest vegetation in order to reduce the potential for severe wildfires. Another common objective is to manipulate forest vegetation in order to form a protective barrier around a stand or resource. The main idea behind a fuel management treatment in a loblolly pine forests is either to reduce the density of some targeted species of vegetation, or to effectively change the structural condition of the forest. A number of techniques can be employed to accomplish this, including thermal (prescribed burning), mechanical, chemical, and biological methods.

FUEL TREATMENT TECHNIQUES

PRESCRIBED BURNING

Overview—Prescribed burning is the most common tool for managing fuels in the South due to the relatively low cost per acre and the ability to reduce fuel levels rather than rearrange them. There are four general firing techniques for prescribed burning, the choice of which to use should be made based on the objectives of the burn, the fuels present, the topography of the area, and the weather conditions. Wade and Lunsford (1989) provide land managers a guide for using prescribed burning in southern forests; therefore coverage of firing techniques is limited here. The basic firing techniques described in the prescribed burning guide include: (1) back fires, which are slow moving and result in minimum residual tree scorch; (2) head fires, which are fast moving and result in good smoke dispersal; (3) flank fires, which are relatively moderate in speed and useful for securing the edges of a burned area, and (4) spot fires, which can have characteristics of the other three techniques depending on the density of the grid, the topography, and weather conditions.

If a stand has an open canopy, prescribed burning every 2 to 3 years encourages early-successional herbaceous species at the expense of woody ones. However, prescribed burning is also an imprecise practice that can quickly turn from beneficial to destructive with unexpected weather changes or fuel conditions. Furthermore, off-site smoke can lead to automobile accidents as well as air quality problems. The legal liabilities from these off-site problems and the logistical difficulties of burning near roads and buildings are major concerns. Consequently, the long-term use of prescribed burning in some areas of the South is becoming questionable due to restrictions on burning near dense housing and roads, and it is likely that some current burning programs will become too costly or infeasible within the next 20 years, regardless of the intent of the landowner. However, in many parts of the South, social and economic conditions still allow the regular use of prescribed burning and probably will continue to do so for the next few decades.

Until the last few decades, the South was predominately a rural region where the burning of fields and forests was an accepted cultural practice. Prescribed burning is still used in loblolly pine forests to prevent fuel accumulation and encourage forage for game species. However, relative to the total area of forests, prescribed burning is not common in most southern states outside of the coastal plain pine forests. For example, an average of approximately 900,000 acres are prescribed burned every year in Alabama (Alabama Forestry Commission 2005), which represents 4 percent of the total forest area of about 23 million acres. In Arkansas, about 300,000 acres are treated each year (Personal communication. 2005. M. Cagle and L. Nance, Staff Forester and Deputy State Forester, Arkansas Forestry Commission, 3821 W. Roosevelt Rd, Little Rock, Arkansas 72204), or 2 percent of the 18.8 million acres of forestland. In contrast, an average of two million acres are prescribed burned in Florida every year (Florida Division of Forestry 2006), or 14 percent of the total 14.7 million acres of forestland, while an average 300,000 acres are burned by wildfires. For Florida, these numbers reflect the presence of fire-prone flatwoods, the importance of lightning and humans as ignition sources, and aggressive prescribed burning programs by private and public land managers.

Feasibility—There are many factors to be considered when deciding if prescribed burning should be used for fuel reduction. While most constraints will not automatically preclude the practice, some problems may be major enough to make it infeasible. Issues such as forest management objectives, the long-term accumulated costs of regular treatments, and the expected future development of the surrounding lands must be taken into account. Even if prescribed burning is desired and fuel conditions are favorable, constraints from outside the property can effectively preclude the practice. Another important issue to be considered is legal liability. Many southern states have established legal protection for prescribed burning with regard to damage outside the property, but the protection is not absolute and there is always some potential for legal action. This increased protection is often based on having state-certified professionals in charge of the burning and generally does not apply to non-certified burners. Finally, prescribed burning may be incompatible with fertilization programs, as recent pre-burn applications of nitrogen treatments can be wasted through volatilization.

Roads—Major roads and intersections must be protected from excessive smoke, which means a specific set of weather conditions are required. The presence of major roads does not automatically preclude prescribed burning, but it does introduce additional restrictions that may ultimately make prescribed burning impractical. If there are only one or two stretches of roads to be considered, then it may be possible to burn in a way that keeps smoke away from the roads. However, as the extent of roads to be avoided increases, it becomes more and more unlikely that the necessary weather conditions will occur often enough to make regular burning a practical management option. Conversely, a lack of access roads may make prescribed burning dangerous if there is limited ability to move people and equipment to trouble spots.

Firebreaks—Related to the issue of access roads is the presence of firebreaks. The construction of fire breaks can represent a major investment, although some state agencies will build them for private landowners at a reduced cost. Once constructed, the fire breaks will need regular upkeep, and thus to be effective will require a periodic investment.

Housing and other sensitive areas—Like the surrounding road system, housing and other sensitive areas represent a potential limitation. While some neighbors may be willing to tolerate smoke if given prior warning, others may be less accommodating. Another important issue is the danger created by the landscaping activities of neighboring landowners, such as homes that are surrounded by trees or other flammable material. It is the responsibility of the person performing the burn to protect neighboring property from escaped prescribed burns, regardless of how much flammable material the neighbor may allow to accumulate near their homes or other improvements such as utility poles, telephone pedestals, and gas lines.

Another important issue is the presence of smoke-critical areas such schools, airports, or homes with elderly people (fig. 2), where any level of smoke is unacceptable. Like roads, these critical areas can be avoided under certain weather conditions. If the surrounding area near some forest of interest is being developed, then the long-term prospect of being able to maintain a prescribed burning program in that area is likely to be questionable.

Topography—Areas where topography can trap smoke can create serious public relations problems. These include drainages that funnel ground-level smoke as well as hills or mountains that trap rising smoke. River bottoms with bridges are an especially important danger area. These types of topography do not automatically preclude the use of prescribed burning, but suggest that certain weather conditions are necessary.

Concurrent burning operations—The presence of other burning regimes in the area can present both possible limitations and benefits. While it may not seem obvious, prescribed burning programs could compete with each other for the opportunity to burn. In Georgia, the Forestry Commission essentially acts as the unofficial prescribed burning coordinator, but in the other southern states, it may be the individual controlled burn managers who make sure that there are not too many prescribed burns in one area. Of course, if surrounding lands are being burned, coordination and sharing of resources and fire barriers can be seen as a benefit.

Legal issues—A major limitation to the use of prescribed burning is the concern about legal liability. While most southern states have laws designed to encourage the practice, many of these laws are unclear as far as what is legally required and when a burner is legally protected. While many state forestry agencies have the prescribed burning laws posted on their Internet sites, there is little, if any, interpretation of the laws and landowners must decipher the legal complexities on their own. General reviews of state laws on prescribed burning have been performed by Haines and Cleaves (1999) and Sun (2006). However, liability varies based on on-site and off-site factors, the amount of fire and smoke damage, the presence or absence of a state-certified prescribed burn manager, and the preventative measures that were taken. If a landowner has little experience with prescribed burning and the associated legal environment, it is recommended that they contact the appropriate state agency for guidance.

Air quality—For prescribed burning, the most important air quality standards are for (a) air-borne particles that are small enough to enter the lungs and cause health problems, and (b) smoke conditions that reduce driving condition visibility. The issue for prescribed burners is to determine what burning restrictions have been implemented in their particular county. While the Environmental Protection Agency (EPA) does not apply burn bans nor does it regulate prescribed burning (the states do), it monitors both fine (< 2.5 micrometers) and coarse (between 2.5 and 10 micrometers) particles. The EPA maintains an online database of air quality levels (www.epa.gov/ebtpages/airairqunonattainment.html) that can provide valuable guidance when considering if prescribed burning is an option for a particular area, including the ability to produce maps that highlight areas with chronic air quality problems. In the southern states, a relatively small number of counties have recently been considered in non-attainment for fine particles, resulting in restrictions on prescribed burning. As of April 2005, they were in Alabama (Shelby and Jefferson and parts of Walker and Jackson), Georgia (all of the counties surrounding Atlanta as well as many nearby counties and Walker and Catoosa on the Georgia-Tennessee border), North Carolina (Catawba, Davidson, and Guilford), and Virginia (counties adjacent to Washington, DC).

Fuel loads—The types of fuels that are present are important when evaluating the potential for achieving desired management goals through prescribed burning. For example, some forests may have accumulated so much litter or mid-story vegetation that a wildfire could severely damage or kill the pine overstory. While a series of carefully planned dormant-season prescribed burns performed under moist conditions might slowly reduce fuel levels, there is the possibility that not enough fuel would be consumed to make the effort worthwhile. Rideout and others (2003) found that wet fuels produced spotty fires and consumed little fuel. In addition, hardwoods in a forest may create so much shade and moist litter that a prescribed burn is not possible. In such a case, removal of the hardwoods by way of mechanical or herbicide treatments may be needed before a prescribed burning program is possible.

Effects on fuel—Fire intensity is based on multiple factors, such as fuel characteristics and their spatial distribution, firing techniques, and weather conditions. None of these variables are constant over time or space, so the potential effect of prescribed burning on fuels will vary temporally with fuel moisture and weather at the time of the burn, and spatially depending on the pattern of fuels within a stand.

Ground fuels—Because of its high lignin content and density, duff is normally consumed through smoldering combustion rather than flaming (Miyanishi and Johnson 2002). Once the duff layer starts to smolder, it can continue to burn long after the flaming front has passed. Duff combustion can be a major source of smoke and of mortality of overstory trees if feeder roots have grown into the duff layer or duff has accumulated around the base of a tree and thermal girdling occurs. For example, Varner and others (2005) described unexpected mortality in old longleaf pines after a wildfire, in an area where wildfire or prescribed burning had been excluded for decades. Even though there was no crown scorch, 91 percent of the trees greater than about 14 inches in diameter at breast height (dbh) died within two years. Thick duff layers had accumulated around the bases of the trees and duff combustion was observed for several days. Varner and others (2005) speculate that the trees might have been killed by duff combustion through loss of roots, although thermal girdling or other stresses were also possibilities. For stands with well-developed duff layers, Varner and others (2005) recommended multiple low-intensity burns to gradually reduce the duff layer, which will train the overstory trees to produce roots below the duff layer. Nevertheless, a landowner must consider that these ground fires could severely damage or kill trees in the pine overstory.

Dead surface fuels—Pine needles are the primary fuel that carries fire in loblolly pine forests (Johansen and others 1976) and maintaining pine-dominated litter at low levels is important for minimizing the intensity of a potential wildfire. Prescribed burning can be effective at reducing litter accumulations and maintaining low amounts of litter fuels. However, repeated applications are usually necessary because of the high needle productivity of loblolly pine forests and the subsequent rapid rate of litter accumulation after burning.

The amount of dead fuel consumed by a prescribed burn depends on fuel moisture, fuelbed structure, firing techniques, and weather at the time of the burn. For example, Scholl and Waldrop (1999) examined loblolly pine stands of different ages and structures in the upper Coastal Plain of South Carolina and found that winter burning reduced surface fuel weight by 38 to 80 percent. Waldrop and others (2004) examined multiple pine-hardwood stands with varying soil moisture conditions that were prescribed burned and found that the fire reduced surface fuels on drier sites, but not on wetter sites. Rideout and Oswald (2002) found that surface fuel consumption during a prescribed burn in East Texas was minimal because of high fuel moisture, low wind speeds, and cool temperatures that resulted in a patchy, low-intensity burn. Sparks and others (2002) found that surface fuel consumption in shortleaf pine stands with a hardwood midstory was actually higher during the dormant season (49 percent) than in the growing season (41 percent) despite similar fuel moistures and lower Keetch-Byram Drought index (KBDI) values during the dormant season. The differences in surface fuel reduction were attributed to high relative humidity, low wind speed, greater fuel compaction, and greater prevalence of live fuels during the growing season.

In general, consumption of dead surface fuel by a prescribed burn will decrease with the size of the fuel. For large woody debris like logs, multiple fires may be necessary to completely consume them if the site is wet enough to keep the debris cores moist (van Lear 1993). Consequently, a low-intensity prescribed burn consumes mostly 1-hour time-lag dead fuels (as defined by vegetation with a large surface-to-mass ratio, or otherwise called "fine fuels") whereas multiple fires are needed to fully consume larger fuels. In a shortleaf pine savanna restoration program in the Ouachita Mountains of Arkansas, Liechty and others (2004) found that 27 percent of post-thinning woody debris was consumed by a prescribed burn, with 60 percent of this amount being fuels in the 1-hour and 10-hour time-lag dead fuel classes. Similarly, Scholl and Waldrop (1999) found that burning consumed on average 28 percent of the 1-hour time-lag dead fuels, 15 percent of the 100-hour time-lag dead fuels, and 3 percent of the 1,000-hour time-lag dead fuels.

How quickly the dead surface fuels return to pre-burn levels depends on several factors, such as how open the site is, how many deciduous trees are present, and the productivity of the site. As a general rule, litter re-accumulates quickly during the first few seasons as released nutrient resources are utilized for foliage production, then slows down as resources are depleted. For example, McKee (1982) compared dead surface and ground fuels in unburned pine-hardwood stands with ones burned either annually or periodically (every 3 to 7 years). For annually burned sites, there was about 60 percent less dead surface and ground fuels when compared to unburned stands. In contrast, periodic burns had only 30 percent less than unburned controls, which suggest that the majority of dead surface and ground fuels re-accumulate quickly. The density of trees on a site plays a major role in the rate of re-accumulation. According to Johansen and others (1976), a loblolly pine stand with 70 $feet^2$ per acre of basal area would have an estimated 3.2 tons per acre of dead surface fuels three years after a fire while a stand with 150 $feet^2$ per acre would have 5.7 tons per acre. If there are no further fires, equilibrium is eventually reached between decomposition and litter production.

Live surface fuels—In open loblolly pine forests, most understory plant species re-sprout vigorously following fire. Therefore, prescribed burning strategies for live fuels reduction and maintenance require the application of repeated fires, and the consideration of the ecological responses of multiple species. Grasses and forbs recover rapidly immediately following the burn, but then decrease over time as shrubs recover and become more dominant (Johansen and others 1976). In uneven-aged loblolly pine-shortleaf pine stands in Arkansas, there was a shift in species composition from woody to herbaceous species when using a three-year burn interval, but not at longer intervals (Cain and others 1998). For common live surface fuels, such as sweetgum (*Liquidambar styraciflua* L.) and oaks, it is reasonable to expect an understory to regain its former size within 3 to 5 years.

Repeated prescribed burns can reduce live fuel loadings, but only if the fires occur frequently enough to either exhaust root reserves or kill short-lived plants before they can produce seeds. For example, a long-term experiment at the Santee

Experimental Forest in the Coastal Plain of South Carolina found that annual growing season prescribed burns converted a woody-dominated understory to a herbaceous-dominated one (Waldrop and others 1992). However, prescribed burns every 3 to 7 years were not sufficient to exhaust hardwood root reserves even after 43 years, and the understory was dominated by numerous hardwood stems and short shrubs created by re-sprouting. Although periodic burning can increase the presence of herbaceous species below the hardwood understory, these plants can only compete with the hardwoods for 1 to 2 years after a prescribed burn before the taller woody species eventually shade them out (fig. 3). The effects of prescribed burns on live fuels are generally greater when more frequent burns are performed (every year or so), particularly growing season burns (White and others 1990). Growth of loblolly pine trees is not necessarily related to the reduction in competition as a result of a burn (Waldrop and others 1987), however winter burning is preferred if the growth of young pines is a concern (McKevlin and McKee 1986).

Another important factor in plant community dynamics is season of burn. Reduction of live surface fuels will typically be less if a prescribed burn occurs during the dormant season rather than during the growing season, even if annually treated. For example, 43 years of annual winter burns at the Santee Experimental Forest had about the same effect on hardwood cover as burns during other periods of time, although the annual winter burns did increase herbaceous cover, especially legumes (Waldrop and others 1992). Annual winter burning also increased the density of small (< 1 inch dbh) hardwoods to more than 16,000 stems per acre, mainly because of re-sprouting of sweetgum. Consequently, it should not be assumed that a prescribed burning program will always eliminate live surface fuels and reduce overall wildfire risk.

The susceptibility of live surface fuels to topkill decreases with increasing stem diameter (Hare 1965). Larger plants tend to have thicker bark that provides more insulation, and have foliage and buds that are high enough to avoid damage. Many southern hardwoods will become tolerant of most low-intensity fires once they reach a certain size. For example, Phillips and others (2004) found that after a moderate-intensity winter prescribed burn, the majority of stems killed were in the 1 to 2 inch dbh classes, with limited mortality in larger dbh classes. Boyer (1990) looked at a mature longleaf pine stand with a hardwood mid-story that had been previously managed with periodic dormant-season prescribed burns. In an effort to eliminate the hardwoods by exhausting their root reserves, the stand received two summer burns two years apart. Although 58 percent of hardwoods less than 1.5 inches dbh died, only 13 to 15 percent of trees in the 2 to 3 inches dbh died and 4 to 7 percent of trees in the 4+ inch dbh classes died. The majority of hardwood mortality occurred after the second prescribed burn, likely due to exhausting limited root reserves in saplings.

Susceptibility to topkill also varies between species. Although many mature oaks (*Quercus* spp.) and hickories (*Carya* spp.) have relatively thick bark, species such as red maple (*Acer rubrum* L.), sweetgum, and American beech (*Fagus grandifolia*

Ehrh.) have thinner bark and are presumably more likely to be girdled by fires (Harmon 1984). However, these differences may not translate directly into inter-specific variation in topkill because bark thickness increases with dbh for these species. Thus, older thin-barked species may survive a fire while young thick-barked saplings are killed.

Ladder and crown fuels—Ladder and crown fuels are live and dead fuels that allow a fire to climb from the ground to the crown canopy, and include grasses, shrubs, and trees. For mature stands with a mid-story, prescribed burning is more difficult in stands with ladder or crown fuels. Although the presence of these types of fuel in a mature stand does not preclude the use of prescribed burning, they do limit it to low-intensity fires that will affect only the understory. One major impact of prescribed burning on overstory trees is crown scorch, which will be greatest when overstory trees are young and have foliage close to the surface fuelbed. However, severe crown scorch may have little impact on the survival of larger trees. In a 17 year-old loblolly pine plantation in South Carolina, co-dominant trees that were completely scorched suffered only 20 percent mortality, whereas intermediate trees suffered 20 to 30 percent mortality (Waldrop and van Lear 1984). No dominant trees died as a result of crown scorch. In a 19 year-old naturally regenerated loblolly pine stand in southeastern Louisiana, incidence of severe crown scorch following a winter burn was greatest in dense, lightly thinned plots that had a large number of small trees (Lilieholm and Hu 1987). The only trees that experienced significant fire-induced mortality were in the suppressed crown class.

Crown scorch may actually increase available fuels in the short term as the dead needles and leaves in the crown dry out and become more flammable. If the branches are not killed, the needles and leaves will fall within 2 to 3 weeks and accumulate either on the ground, or will be draped on the remains of understory stems, which are also drying and becoming more flammable. If the branches are killed, abscission will not occur and the leaves and needles can remain elevated for a few months if sheltered enough. Slow decomposition of dead branches as they are broken off by wind and rain will also increase fuel levels on the ground. In examining both natural stands and plantations of slash pine after the 1998 Florida wildfires, Outcalt and Wade (2004) found that tree mortality for stands that were prescribed burned 3 months before the wildfire was the same as stands which had not been prescribed burned in 2 to 3 years. Outcalt and Wade (2004) suggest that the previous prescribed burning had produced heavy needle drape through scorch and a layer of dried small woody stems that combined to form intense conditions during the subsequent wildfire, with post-prescribed burning stress also playing a role in tree susceptibility. However, for stands burned 1.5 years before, mortality was quite low, which is suggestive that there may be a window of decreased potential fire intensity as ground fuels start to decompose but dead surface fuels have not started to accumulate. Regardless, prescribed burning does not necessarily create fire-proofed conditions (park-like and fuel-free forests).

Application—Because prescribed burning is an established practice, this guide will not give instructions on its use. For detailed information on conducting a burn, the 1989 U.S. Forest Service publication "A guide for prescribed fire in southern forests" is suggested (Wade and Lunsford 1989). In addition, it is imperative that those without burning experience train with a state-certified burn manager before attempting to conduct a prescribed burn.

Season of prescribed burning—The majority of prescribed burns occur during the dormant season (late winter or early spring) when cool temperatures and relatively high fuel moisture limit the danger of escaped prescribed burns and damage to overstory trees. Dormant season burning can be effective at temporarily reducing fuel loads, but may be less effective at eliminating established hardwoods or preventing fuel re-accumulation, and it is best thought of as a way to maintain forest structure and species composition, and as a game management tool. Repeated dormant season burns are sometimes also used to prepare an area for eventual growing season burning if fuel levels are too high, although injury or mortality of the overstory pine trees is still possible.

Growing season burning (mid- to late-spring) is primarily used for hardwood elimination and for promoting an herbaceous-dominated understory at the expense of a woody mid-story. In addition, growing season prescribed burns can be used to encourage flowering in savanna species such as Carolina wiregrass (*Aristida stricta* Michx.). At the Savannah River Site in South Carolina, up to 2,500 acres of pine-hardwood forests are burned during the growing season, primarily in red-cockaded woodpecker (*Picoides borealis*) areas, while up to 3,000 acres are burned during the dormant season (Shea and Bayle 2006). Most stands are on a 3 to 5 year prescribed burn rotation, except for areas near sensitive buildings and roads where burns are spaced out at least 10 years apart. It clear that season of burn and fire frequency are both important for restoring native herbaceous communities, yet the debate is on the relative importance of each (Brockway and Lewis 1997; Glitzenstein and others 2003).

Some land managers use growing season burns to eliminate larger hardwoods and then use dormant season burning to maintain open conditions. For example, at Kisatchie National Forest in Louisiana, about a third of the prescribed burns occur during the growing season, although they are used for hardwood suppression and not for changing the understory species composition. In overstocked stands, growing season burns on a rotation of 2 to 3 years are used to decrease hardwood stocking to an acceptable level and then dormant season burns are used every 3 to 5 years to maintain hardwood levels (Personal communication. 2006. Frank Yerby, District Ranger, Kisatchie National Forest, 2500 Shreveport Highway, Pineville, Louisiana 71360).

Costs—Smidt and others (2005) found that the average cost of contracted prescribed burning in the South was $20 to 30 per acre. Costs can be as low as $10 per acre in situations where the concerns about smoke and fire escape are low or as high as $40 per acre where careful attention needs to be paid around residential or urban areas. Many state forestry agencies will assist or conduct a prescribed burn for small landowners for a price, and some will lend torches and other equipment. In addition, most agencies will assist landowners with drawing up a prescribed burning management plan.

MECHANICAL TREATMENTS

Overview—If prescribed burning is not an acceptable management option, then a mechanical treatment may be effective in reducing wildfire risk by redistributing the fuels closer to the ground, creating a more compact fuel bed. There are two general types of mechanical treatments - those that rearrange biomass and leave it on a site and those that remove biomass from a site. The application of mechanical techniques to fuels management in the South is challenging for several reasons. First, southern forests have rapid vegetation growth rates and a large number of hardwood species that vigorously re-sprout after mechanical treatment. Thus, if the hardwoods are only cut and not killed, it may only take a few years for them to regain their previous size and negate any wildfire risk reduction benefit. Second, wet soils and seasonal wetlands can limit the use of heavy equipment for extended periods during the year. And third, mechanical treatments are relatively expensive compared to prescribed burning.

With the creation of the Healthy Forest Initiative in the early 2000's, one-time funding for mechanical operations became available to public agencies, and this type of treatment increased substantially. On Federal lands in the South, the area of land treated with mechanical methods has risen to over 150,000 acres per year (U.S. Department of the Interior 2006b). However, when compared to the 2003 to 2005 yearly average for prescribed burning on Federal lands in the South (over 1,000,000 acres per year); it is clear that mechanical treatment is still less common. Furthermore, the vast majority of these mechanical operations appear to have been one-time treatments for reducing excessive fuel loads before the reintroduction of burning.

Types of mechanical treatments—Land management agencies have experimented with many types of mechanical fuel treatments, ranging from machines that gather small stems and branches and form them into bundles for collection (Rummer and others 2004), to cut-to-length harvesters that provide stems for small chippers (Bolding and Lanford 2005). Many of these treatments have been found to be unrealistically expensive or time-consuming and have limited applicability for wildland fuels treatments in the South. However, cost figures may change if biomass markets continue to develop for alternative energy sources. Based on numerous interviews, the only common mechanical treatments in the South are mulching (mastication) and chipping, both of which are normally used as one-time precursors to prescribed burning. This limited use of mechanical treatments is based on hardwood re-sprouting rates and treatment costs rather than a lack of information. Although mulching and chipping operations both produce chips, mulching operations leave the chips in the forest while chipping operations remove the chips. A mulching operation is considered pre-commercial, whereas a chipping operation could be considered pre-commercial, commercial, or a combination of the two, depending on how costs are absorbed and the types of chips produced (pulp quality versus furnace quality).

Pre-commercial versus commercial operations—In traditional forestry, a pre-commercial operation is one in which under- or mid-story stems are cut and either left on site or removed, and the operation generally loses money yet leads to increased future profits through higher growth rates of the remaining trees. In contrast, a commercial operation removes stems from the mid- or overstory and a profit is generally made. However, in modern forestry, the difference between the two terms is less clear due to increased use of logging slash and small stems for furnace chips (fig. 4), and multiple wood products generated during harvests (e.g. chips, pulp, and saw-timber). While most examples of mechanical fuel management in loblolly pine forests would be considered pre-commercial operations, the immediate expenditures have to be balanced with the benefit of reduced wildfire risk and the increase in the future value of crop trees (Mason and others 2006).

A money-losing pre-commercial chipping operation (removing a dense understory of small stems) could be performed immediately before a profitable operation (thinning of overstory) to improve access and reduce the risk of post-harvest wildfire. Some federal cost-share programs, such as the Stewardship Incentives Program and the Forestry Incentives Program (although de-authorized in 2002), may recommend thinning of pine stands, but market conditions determine the commercial aspect of the operation.

Crush and chop—Although not very common, the crush and chop treatment is occasionally used for fuel reduction. This method is the most basic mechanical treatment, where weight alone is used to reposition fuels close to the ground. It is normally used in the South during site preparation to kill hardwoods, to prepare an area for prescribed burning, and to facilitate planting. A common form of this method is the roller-drum chopper (fig. 5), where a tractor pulls a water-filled, ribbed metal drum across a site. For overstocked young pine stands where hand thinning is impractical due to the large number of stems, roller-chopping has been used as a low-cost pre-commercial thinning alternative, which also reduces insect susceptibility and wildfire hazard, and promotes growth of the residual trees. However, for fuel management, the technique is crude and only useful in stands where the target trees are small (e.g. < 5 inches dbh) and can be pushed over, and where the machine can travel in relatively straight lines. Moreover, given the width of the chopped rows (10+ feet) and the limited ability of the remaining young trees to close the canopy, there is a strong possibility that hardwoods or other woody species will quickly establish themselves in the rows and negate any fuel reduction benefit. For these reasons, the crush and chop treatment has limited applicability in fuel management.

Mulching—Unlike the crush and chop treatment, a mulching operation is intended to break up fuels into small pieces. Windell and Bradshaw (2000) classified mulching equipment as either vertical-shaft (traditional mowers) or horizontal-shaft (mulchers that grid downward). These can be mounted on a wide range of equipment, that vary from small rubber-tracked machines with 90 to 100 horsepower (HP) grinding attachments (fig. 6) to large machines with 400 HP grinders (fig. 7). Heavy-duty mowers like Bush-hogs are useful when fuels are small enough to be pushed over. However, for sites with an established woody mid-story, machines with front-based cutters are likely needed.

At Fort Jackson in South Carolina, a mulching operation in 2006 was used to treat a pine-dominated under- and mid-story and keep the fuels low enough to the ground (< 36 inches) to allow ATV travel during a subsequent prescribed burn (fig. 8). In essence, the highly maneuverable ASV PosiTrack RC-100 with a Fecon 100 HP mulching head was used more as a mower than as a deliberate mulcher since the stems were just cut and not ground up. Since the machine was not used to mulch and cut, the crew had a high productivity rate (~7 acres per day). A mulching operation at Bankhead National Forest in Alabama in 2005 used a Fecon mulching head on a skidder (fig. 9) in a similar fashion. Both operations produced a fuel bed of severed stems, rather than chips. In contrast, a mulching operation at Conecuh National Forest in 2005 to 2006 with a Fecon RT 400 mulching head (fig. 10) ground fuels into chips and incorporated them into the top 3 inches of soil (fig. 11), to reduce the intensity of a subsequent prescribed burn. This produced a cleaner site, but at a low rate of productivity (~1 acre per day).

Chipping—Although used less often than mulching for fuel management, chipping is becoming more important in the South. The increasing popularity of chips for the energy market is a major factor. Many pulp mills have their own wood-based power plants in order to minimize waste and decrease overall costs. These plants are often connected to regional power grids, and mills may sell their excess power to other power companies. When oil prices are low, the energy-producing parts of these mills are often underutilized. However, as oil prices started increasing in 2005, the demand for furnace (dirty) chips has also risen as fuel prices favor chip-based energy production. However, while rising oil prices may increase the demand for wood chips, the accompanying rise in diesel prices limits how far chip-hauling companies are willing to transport the chips.

Feasibility—For most southern operations, the main fuel targets for mechanical treatments will be the mid- and understory vegetation, although a selective thinning of the overstory is also a possibility. Many mechanical operations are precursors for a subsequent prescribed burning program. Therefore, the feasibility of a subsequent prescribed burning program should also be evaluated. Compared to prescribed burning, off-site problems from mechanical operations are less important while cost, access, and productivity rates are paramount. Mechanical operations may be strategically applied in combination with prescribed burning to be more cost-effective.

Roads—Like the use of prescribed burning, the road system should be evaluated and it should not be assumed that a paved road network is sufficient to get heavy equipment to a site. Three easily overlooked but important aspects of a road system are how sharp the turns are for a large flatbed truck, how much weight the bridges can handle, and if there are areas available at the site for unloading the equipment without causing traffic problems. Stanturf and others (2003b) recognized the limitations of road networks for heavy equipment in the wildland-urban interface and recommended the use of small, maneuverable machines (e.g. ASV PosiTrack RC-100 or Bobcat skid-steer loaders) that can be unloaded and used in tight quarters. However, small equipment is limited in horsepower and this means that there is a practical limit to what size vegetation can be treated and how quickly. For example, a 100-HP mulching head used at Conecuh National Forest in Alabama was limited to small stems and could not effectively cut down large mid-story trees (>6+ inches dbh). The machine was also very slow in mulching large stems once they were on the ground (fig. 12) and if complete mulching of logs is required, productivity can be low. There was a similar problem with mulching large logs with under-powered equipment at Jones State Forest in Texas during a mechanical operation (fig. 13).

Soils—Soil types can play a major role in determining if mechanical operations are feasible and determining what type of equipment should be used. Rutting is a concern in fine and clayey soils under wet conditions, while compaction can become a major issue with multiple machine passes over the same area. While tracked equipment distributes weight of the machines more evenly than wheeled vehicles, they turn by swiveling, and this can create damage to roots or boles of residual trees. The use of smaller and lighter machines reduces these concerns, and these machines can operate in wetter soil conditions with higher utilization rates. State-level best management practices for timber harvesting operations may apply in many mechanical treatment operations.

Slopes—If large parts of the terrain exceed 30 percent slope, then mechanical treatment may not be a realistic option. The Georgia forestry BMP guide recommends that harvesting be limited to slopes under 40 percent, and mechanical site preparation be limited to slopes under 30 percent (Georgia Forestry Commission 1999). Similarly, the Alabama BMP guide suggests 25 percent as the maximum slope for site preparation and recommends that logging on steep slopes is kept to short stretches (Alabama Forestry Commission 1999). During a mulching operation at Fort Benning, Georgia, a wheeled Magnum 500 machine had trouble maneuvering on clayey soils with 15 percent or greater slopes, and had to be replaced with a more expensive, tracked Delta 953C machine.

Target fuels—The most likely target vegetation is a woody mid-story characterized by many small stems and limited visibility. In areas with well- to excessively-drained sandy soils such as Fort Jackson, SC, the mid-story will probably be dominated by volunteer pines and scrub oaks. As soil moisture improves, the woody component will become more dominated by hardwoods and shrubs. For mechanical operations to be successful, the target vegetation must be large and rigid enough to be susceptible to cutting. For example, while not a major component of loblolly pine forests, saw palmetto (*Serenoa repens* (Bartr.) Small) is fairly resistant to mechanical cutting since it is so flexible.

The density of residual trees must be evaluated to avoid damage from heavy equipment. If there are too many residual trees, a machine may not be able to move effectively or quickly through a site. In addition, if stand visibility is limited from inside a cab, it may result in excessive damage to residual trees, or productivity may decline.

The composition of the fuels being treated also affects the type of product that can be produced. Chippers that are designed to produce clean chips (pulp quality) are designed for softwoods (mainly conifers). Some hardwoods will result in increased wear on the chipper teeth. For example, oaks are too hard to be chipped without increased equipment wear but sweetgum is a hardwood that is soft enough to be chipped. Therefore, the softwood-hardwood ratio of target trees plays a major role in the economics of a chipping operation. The types of chippers used in fuel management operations vary by horsepower and purpose. For operations where small stems are being collected by hand, a small chipper similar to those used by arboriculturists, which produces a mixture of leaves and chips, will be effective. This type of equipment is designed for limited use with small diameter material and is not suited for continuous use with whole trees. For commercial operations where larger stems (2 to 3 inches dbh) are being chipped, a more rugged piece of equipment is needed. Commercial chippers can delimb and debark certain species trees, yet this type of equipment is very expensive and difficult to move around, which limits its use in pre-commercial operations.

Available markets for chips or small-diameter stems—A market for small-diameter stems is a function of the cost to get the material from the forest to the purchaser as well as the ability of the purchaser to absorb material. For a chipping operation to be feasible, a realistic economic analysis of local markets is needed. Since most coal power plants require pulverized fuels, woody fuels are typically limited to 2% (fuels blended before injection into the furnace) or 10% (fuels injected separately) (Hughes 2000), therefore there may be a limit to the amount of chips a plant will accept.

Effects on fuels—Since some mechanical operations in the South will be used as precursors to prescribed burning, their effects on fuels should be considered as it relates to a subsequent prescribed burn as well.

Ground Fuels—If large stems are dragged through the forest, the duff layer can be scraped from the center of the skid trails and deposited along the sides. For example, Waldrop and others (2004) found that on relatively dry sites in a Piedmont pine-hardwood forest, the duff and litter layers were reduced by thinning operations only in localized areas, versus widespread uniform reduction by prescribed burning. Otherwise, significant effects to the ground fuels should not be expected unless mulching is used, soils are wet, or rutting occurs.

Dead surface fuels—For mulching operations, the main goal is to convert live fuels into smaller pieces 1 to 5 inches long and reposition them close to the ground. Thus, mulching typically increases loadings of dead surface fuels while reducing loadings of live fuels. Larger dead fuels get treated as well because the process is non-selective. A study of chips produced by two different mulchers (Delta 953C versus Magnum 500) during an operation at Fort Benning in Georgia found that the Magnum 500 produced less chips under 0.25 inch (1-hour time-lag dead fuels) (25 percent versus 38 percent), about the same number of 0.25 to 1.0 inch chips (10-hour time-lag dead fuels) (47 percent), and more 1 to 3 inch chips (100-hour time-lag dead fuels) (28 percent versus 15 percent) (Rummer and others 2006). Since mulched fuels are mostly 1- and 10-hour time-lag dead fuels, they would be expected to burn readily when fuel moisture is low. In addition, the expectation is typically that these fuels will form a compacted fuelbed, which will result in lower fire intensities than in the untreated stand. However, the resulting fuels from a mulching treatment do not compact completely, as they are large, irregularly shaped, and almost strip-like (fig. 14).

One major factor in the production of dead surface fuels after a mechanical operation is the topography of the area and how this interacts with the equipment and impact intensity, especially in the areas where trees are processed. For example, Waldrop and others (2004) compared different topographical areas after a thinning operation and found that dead fine fuels (1- to 100-hour size classes) increased in dry and intermediate areas, with discarded crowns as a major source. In contrast, in wet areas, there was no increase in fine or large fuels, possibly due to limited harvesting within wet areas or the trees being delimbed in drier areas.

Live surface fuels—As the main fuel targets for a mechanical operation, live surface fuels are often in the form of a thick shrub layer that can result in high fire intensities during a prescribed burn. Since this layer is usually dominated by woody species that can re-sprout and grow quickly (e.g. sweetgum and yaupon (*Ilex vomitoria* Ait.), any reduction in live surface fuels from a mechanical operation will be temporary.

Because there is no selectivity, a mulching treatment would be expected to reduce all live surface fuels that are accessible to the cutting head. Inaccessible fuels could be pockets protected by residual trees (fig. 15) or in wet areas susceptible to rutting or compaction. Mulched fuels are left on site, but are usually not thick enough to prevent re-sprouting or seed germination. In comparison, a chipping operation is more selective in what stems are removed. If chips are being harvested for pulp, pines and some hardwoods (sweetgum) may be utilized, while other hardwoods may be avoided. Furthermore, since tree stems are usually brought to the chipper with a skidder, the stems must be big enough to be grabbed, and large enough to be chipped (usually a minimum dbh of 3 to 5 inches). The travel of heavy equipment in a chipping operation can also reduce small live fuels by crushing them. Phillips and others (2004) found that a thinning from below in a Coastal Plain pine-hardwood forest reduced average stem density from 5,075 to 3,725 stems per acre, with the bulk of the reduction in the ≤ 2 inch dbh class.

Ladder and crown fuels—To disrupt the distribution of live and dead vegetation from the ground to the canopy of a stand, so that a fire will not be able to climb into the canopy, vegetation can be thinned or pruned. Pruning operations are usually performed by hand crews that trim the branches of trees up to 8 or 16 feet above the ground (to the height of one-half or one log). Pruning operations are currently relatively uncommon in loblolly pine stands in the South, but remain a viable option for mechanical treatment of trees. Thinning operations target trees that are suppressed, overtopped, and diseased, as well as those healthy dominant and co-dominant trees in the overstory where stand density is a concern. Normal commercial harvesting equipment (i.e., skidders, feller-bunchers, etc.) can be used to harvest larger trees; small machines with low-horsepower mulching heads can maneuver around larger trees, but are limited to the management of smaller-sized trees. Chainsaws can be used to fell small or large ladder fuels. Thinning operations can be commercial (where most of the trees that are cut down are delivered to a mill) or pre-commercial (where the thinned trees are redistributed on a site, and become surface fuels). Note that even in a commercial thinning, large amounts of slash may be left on the site.

Application—If a mechanical treatment is to be followed with a prescribed burn, it is important to schedule the burn at the proper time. If the site is burned during winter to minimize fire intensity from the dead fuels, there will be little impact on re-sprouting woody species. On the other hand, if the prescribed burn is performed soon after spring starts and leaves are being produced, the number of re-sprouting woody species will be reduced. However, if the sprouts are given too much time for growth, the site may produce too many live fuels to be effectively treated at fuel moisture levels suitable for prescribed burning. For example, after a mulching operation at Fort Benning, Georgia, in October (early fall) in different areas, researchers burned the areas either in late winter (4 months later), spring (7 months), or summer (10 months) (Rummer and others 2006). While the winter and spring burns effectively reduced re-sprouting, the summer burn was only effective in dry sites. In most of the bottomland sites, the rapid sprouting produced so much live fuel that the burn was uneven and the researchers felt that the window of opportunity had passed.

Costs—For commercial operations like chipping and thinning, profitability is based largely on pulpwood prices and diesel fuel costs, both of which have been highly variable over the last few years (2005 to 2007). For non-commercial operations, given the high cost of heavy equipment, it is likely that most mechanical fuel reduction treatments will be performed by private contractors who will be either bidding for a contract or providing site-specific estimates. Unfortunately, since mechanical fuel reduction treatments are a relatively new activity in the South, there are few guidelines for contractors or customers on how to estimate expected costs. For any operation, there are multiple financial variables involved, such as fuel type and density, tract size, equipment, and restrictions intended to minimize site damage. Therefore, it is not practical to provide an estimated cost for any particular fuel reduction treatment. As a consequence, anecdotal information from recent operations is used to establish a range of possible prices. Acceptable cost levels may vary considerably, and depend on anticipated land use following the treatment (i.e., forestry, development, etc.).

Mulching—For several recent mulching operations in the southern U.S., costs were highly variable ($200 to 650 per acre) and most operations were underbid. One of the biggest reasons for underbidding was overestimation by contractors on expected productivity rates. Contractors usually pay their crews on an hourly basis, whereas contracts are made on an area basis, so delays in productivity can quickly lead to loss of profitability. These delays can be caused by equipment failure (e.g. grinding teeth breaking), terrain conditions, or other restrictions (only being allowed to work in wildland-urban interface areas during daylight hours). One unexpected source of delays may be excessive over-treatment of fuels by contractors who are skilled at preparing areas for housing developments or agricultural operations. A recent mulching operation at Fort Benning initially planned to use a wheeled Magnum 500. However, the machine could not climb steep slopes (> 35 percent) and had serious problems with getting stuck in soft soils, so a more expensive tracked Delta 953C was brought in to finish the operation. The Magnum was estimated to have cost $258 per acre, whereas the Delta was estimated to have cost about $171 per acre in flat areas and up to $650 per acre in the steep areas (Rummer and others 2006).

Chipping—Although chipping operations have been promoted as a way to reduce wildfire hazard by removing pre-commercial fuels (Bolding and Lanford 2005), the few recent examples in the South suggest that this will be a limited option unless landowners are willing to absorb most of the costs. Since chipping is assumed to be based on the contractor selling the chips (versus leaving them on the site), the economics of the chip market and operating costs are the most important factors for determining the feasibility of an operation. The current (2006) economic conditions in the South do not promote pre-commercial chipping. Starting in the late 1990's, the price of pine pulpwood declined drastically because of overproduction of trees and excess mill capacity (Harris and others 2005) while the cost of diesel fuel has continued to increase. As a consequence, it is becoming increasing difficult to sell pre-commercial thinning chips. In contrast, opportunistic chipping of branches and tops during a commercial harvest may still be profitable.

Bolding and Lanford (2005) described a cut-to-length thinning operation that harvested both commercial (4+ inches dbh) and pre-commercial (0.5 to 4 inches dbh) stems. A harvester (Timbco T-415C) delimbed the commercial stems and then cut them into 20 foot lengths. Pre-commercial stems were cut and piled separately. A Fabtek 546B forwarder then collected the stems and transported them to a loading deck, where commercial stems were loaded into trucks and pre-commercial stems were loaded into a small Bandit 1850 chipper that fed the chips into a waiting trailer. One major limitation was that the chipper could not operate as fast as it was receiving stems from the forwarder. In contrast, recent pre-commercial chipping operations at Kisatchie National Forest during 2003 to 2005 cost only $2 to 5 per acre for the actual operation and $15 to 18 per acre when administrative costs were considered. Since the operations were part of a mid- and understory removal, both clean (pulp quality) and dirty (boiler quality) chips were produced.

Central to the subject of treatment costs is the minimum treatment area. If contractors will be used for an operation, then the minimum treatment area and expected travel times within the area must be taken into account when designing a bid. For example, at Fort Jackson, South Carolina, it was determined that about 1,000 cords of wood in a localized area would be needed for a treatment to be commercially viable (Personal communication. 2006. John Maitland, Forestry Team Leader, Directorate of Logistics and Engineering, Building 2563, Essayons Way, Fort Jackson, SC 29207).

HERBICIDE TREATMENTS

Overview—Herbicides are one alternative for hazardous fuel treatment in the South, particularly for controlling invasive species of plants. Because of regulations and public relations concerns, Federal agencies tend to avoid using herbicides except for treating invasive plants and for limited site preparation. In addition, research on forestry herbicides is largely applied to site preparation and release operations during the first ten years of stand establishment. Hence, there is limited scientific information on herbicide use for hazardous fuel management later in a stand's life, except for a few studies on mid-story tree removal in degraded longleaf pine stands. Finally, the dense nature of under- and mid-story hazardous fuels in a loblolly pine forest does not lend itself well to herbicide treatment. To remove unwanted vegetation below a loblolly pine canopy without harming the overstory pines would require a ground application targeting specific plants.

The use of herbicides for hazardous fuel management may be a realistic option in certain situations. For example, if the mid-story vegetation has become so large that a prescribed burn would have little effect, an herbicide application can remove them with minimal impact on overstory loblolly pine. Provencher and others (2001) found that a herbicide-prescribed burning treatment was far more effective at removing larger oaks than prescribed burning alone. Although herbicides cannot replace prescribed burning or mechanical operations in cases where dead fuels must be removed or repositioned closer to the ground, they are useful as preliminary treatments to kill or suppress live fuels. Herbicides can also be useful as a follow-up treatment after a prescribed burn or mechanical operation to kill re-sprouting woody species, especially if the goal is to promote an herbaceous-dominated understory.

This section is not intended to show how to apply herbicides, but to provide enough information for landowners to decide whether herbicides are a realistic option for hazardous fuel reduction treatments. Because forestry herbicides can cause off-site damage through improper application and may contain additives like surfactants that can cause health problems, many full-strength herbicides require licenses to purchase and apply. Some herbicides can be bought without permits, but it is recommended that only trained personnel apply the herbicides, since misapplication can result in damage to the loblolly pine overstory, or other on- and off-site problems. Although this guide mentions specific herbicides and their brand names, it does not represent a recommendation of any particular brand.

Feasibility—The effectiveness of using herbicides for fuel reduction treatments is based on the existing vegetation, topography, and other local restrictions. There are three types of situations where herbicides may be practical for fuel management treatments:

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(1) Woody understory vegetation is targeted for removal, and the overstory is able to respond to released resources and fill in canopy openings after an herbicide treatment. The overstory trees must have healthy crowns (at least 1/3 of total height) and be able to respond to the release. In this scenario, competition from the overstory is expected to limit the growth of re-sprouting vegetation in the understory.

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(2) Woody understory vegetation is targeted for removal, yet the overstory canopy is not dense enough to shade out re-sprouting vegetation after a herbicide treatment, thus follow-up treatments (mechanical or prescribed burning) that eliminate live and dead fuels may be needed. This type of forest will have to be regularly treated to slow natural vegetation succession and to maintain low levels of forest fuels.

(3) Invasive, exotic plant species are targeted for removal, and herbicides are

the only effective treatment.

Terrain—Topography affects herbicide treatments by limiting the type of equipment that can be effectively used. For example, on slopes greater than 20 to 30 percent, efficient and non-destructive ground application may be limited, particularly if the potential for herbicides to move during heavy rainfall events is high. Although high slope areas can be bypassed during treatment, this may result in high fuel zones that may negate any long-term benefits of a fuel reduction program.

Soils—Sandy soils that drain water quickly can limit the effectiveness of soil-active herbicides. If there is too little rain, herbicide movement towards the roots of the targeted plant species may be limited. Conversely, too much rain will cause herbicides to quickly leach out of the upper layers of soil. In contrast, clayey and loamy soils can quickly immobilize soil-active herbicide, which means that either soil application should be avoided or the application rate should be increased.

Target vegetation—The size of the target vegetation in a fuel reduction treatment can be a good indicator of the potential effectiveness of a herbicide. Generally speaking, larger plants require more herbicide to effectively remove them. Wilkins and others (1993b) found that oaks greater than 6 inches dbh were unaffected by the soil active hexazinone (Velpar™). Similarly, Nelson and others (2006) found that basal application of either imazapyr or triclopyr decreased in effectiveness as white oak (*Quercus alba* L.) dbh increased, but not green ash (*Fraxinus pennsylvanica*

Marsh.), black cherry *(Prunus serotina* Ehrh.), flowering dogwood (*Cornus florida* L.), or red oaks (*Quercus* spp.). According to Jones and Chamberlain (2004), broadcast applications of imazapyr and imazapyr+glyphosate had no effect on hard-mast producing species (e.g. oaks) that were >4 inches dbh.

Some hardwood and woody species are not affected by certain forestry herbicides and this can limit fuel reduction treatment effectiveness. For example, elms (*Ulmus* spp.) are not affected by imazapyr, while sassafras (*Sassafras albidum* (Nutt.) Nees) is not affected by hexazinone. Similarly, Nelson and others (2006) found, in South Carolina pine-hardwood stands where stems 1 to 4 inches dbh received a basal (ground-level) herbicide treatment, that imazapyr alone (e.g. Arsenal™) killed 87 percent of waxmyrtle (*Morella cerifera* (L.) Small) and 31 percent of sweetgum, while triclopyr alone (e.g. Garlon™) killed 100 percent of both species. Many fire-dependent herbaceous species such as wiregrass are tolerant of imazapyr (Litt and others 2001). Even a non-selective herbicide such as Garlon 4™, which controls most hardwoods, has little effect on grasses. In addition, some herbicides cannot be mixed together, or may be less effective in combination than if applied alone. Therefore, mixing herbicides for specific target vegetation is not always possible.

Effects on fuel—Since herbicides can take several weeks to kill live vegetation, the effects of a treatment will not be immediately seen. If live trees are the target vegetation, leaves or needles will fall within a few months, followed by branches over the next 1 to 2 years. It may require several years for large stems to decay sufficiently to begin breaking up and falling. Dead fuels killed by herbicides may increase the susceptibility of an area to a severe wildfire for some period of time until decay of the fuels begins (e.g., Brose and Wade 2002).

Ground fuels—Because herbicides are designed to affect plant metabolic processes, their direct effects on decomposition and duff are limited. Fletcher and Freedman (1986) found that while high concentrations of some herbicides decreased decomposition rates in the forest floor due to toxicity, the thresholds were at least 50 times normal forestry application levels. However, if a wildfire season and a vegetation growing season coincide, an herbicide application during the growing season would significantly add to the litter layer once the leaves or needles begin to fall. If there is a sufficient dead shrub layer, leaves from the overstory may become draped across the vegetation (Outcalt and Wade 2004).

Dead surface fuels—The production of dead surface fuels from a herbicide treatment would be a gradual process as branches begin falling and stems start to fragment and collapse. For example, Brose and Wade (2002) examined the use of triclopyr (Garlon 4) in a 17 year-old slash pine plantation with a heavy gallberry (*Ilex glabra* (L.) Gray), and found that while the herbicide treatment did eliminate the understory vegetation, there was a time lag before wildfire hazard decreased, as the dead surface fuels remained upright for two years and became needle-draped. In contrast, in a mature longleaf pine forest that had been burned for over 60 years, Gagnon and Jack (2004) found that an application of hexazinone (Velpar™) killed 70 percent of the hardwood mid-story, while prescribed burning alone removed only 2 percent. However, without a subsequent prescribed burn, there was an increase in woody debris after the herbicide treatment, most likely from the dead branches of the herbicide-treated mid-story vegetation. Gagnon and Jack (2004) suggest that an herbicide-alone management regime would eventually create high levels of forest fuels.

Live surface fuels—Since most forestry herbicides are applied at rates less than the recommended maximum (Shepard and others 2004), complete elimination of the understory vegetation is unlikely. Furthermore, since no forestry herbicide kills all plant species, and effects vary based on the vigor of plants, soil conditions, and amount of herbicide applied, some vegetation usually survives. For example, Boyd and others (1995) examined the long-term effects of an herbicide release operation in a loblolly pine plantation. Four herbicide treatments (Pronone™, Velpar™, Roundup™, and Arsenal™) were tested. Seven years after treatment, there were no differences in hardwood basal area between treated and untreated plots. The use of herbicides does not guarantee total kill of a woody species plant. Often, depending on the herbicide used, there is only partial top kill of a plant or partial removal of the plant's root stock. Vigorous re-sprouting can then occur, much like what happens after a prescribed burn.

Depending on the herbicide used, some understory vegetation may not be affected, and quickly expand once their competitors are removed. For example, in a Central

Florida sandhill site with a heavy oak mid-story, Wilkins and others (1993b) found that hexazinone (Velpar™) released grasses (including wiregrass) and saw palmetto, while successfully eliminating oaks less than 6 inches dbh. Since the herbicide treatment was intended to prepare the area for regular prescribed burning, the highly flammable saw palmetto was not expected to become the dominant understory vegetation.

Ladder and Crown fuels—If sufficient herbicide is used, the mid-story vegetation will die quickly, although the leaves or needles would remain attached because no abscission layer between them and the stems would be formed. This could create a temporary increase in flammable ladder fuels.

Application—For hazardous fuel management, herbicides are most useful as a one-time application to eliminate or suppress the mid-story vegetation that has grown too large to be affected by a prescribed burn or prevents its use (i.e., too much shade). If the objective is to kill or suppress mid-story vegetation that has grown too large for prescribed burning, then stem injection (fig. 16) is probably the most effective treatment. On the other hand, if the mid-story vegetation is composed of numerous small stems, then a backpack-based broadcast application (fig. 17) or basal bark application may be the most cost-effective methods. If prescribed burning is an option, then spraying the re-sprouting vegetation after a prescribed burn may be more effective than burning alone (Mitchell and others 2005).

Costs—The cost of a particular herbicide application is dependent on the amount of acreage to be treated, the mode of application (e.g. broadcast spray versus stem injection), and the type and amount of herbicides used. Since these factors are variable, it is not feasible to provide a general cost for herbicide fuel reduction treatments. Smidt and others (2005) estimated that aerial mid-rotation release for pine plantations averaged about $65 per acre during 2004. Tyler and Pongetti (2006) estimated early and mid-rotation herbicide application costs $60 to 105 per acre for the herbicides alone. As a general rule, cost per acre will be highest for manual application of individual tree treatment (stem injection), due to labor costs, and lowest for aerial applications. For small tracts, manual application may have a lower total cost than mechanized or aerial applications since equipment move-in costs may be high.

BIOLOGICAL TREATMENTS

Overview—The use of livestock to suppress hazardous fuels has a long history in the U.S. Because cattle grazing was an established practice with important economic consequences for local communities, natural resource managers decided to use increased cattle densities to suppress fine fuels like grasses, with the incidental effect of cattle breaking up small slash by way of trampling (Zimmerman and Neuenschwander 1983). With wildfires reduced in size and intensity, pine seedlings could then be released, and forests could rapidly increase in tree density. This can come, however, with an accompanying increase in live and dead surface fuels, as well as ladder fuels, depending on the vegetation consumed by livestock.

According to Campbell (1948), about three fourths of the shortleaf-loblolly pine-hardwoods forest type in the mid-central South was grazed in the mid-1900's, with 15 to 35 acres needed per cow, due to dense tree stocking and subsequent limited herbaceous vegetation. For southern forests in general, Campbell (1948) estimated that native forage only provided sufficient food for half the year. Most native grasses are warm-season species that die or become dormant during the winter, which means that there is little forage for livestock during the winter months. While livestock grazing in southern forests is not extensively used for fuel reduction purposes today, it can potentially be used to reduce certain types of live fuels. For example, sheep grazing practices have been used extensive in Florida to control saw palmetto. While many farmers allow their animals to roam forests for food, poor forage quality of native plants may limit the practice.

In the modern South, livestock grazing in loblolly pine stands is limited to either the first few years of stand establishment or to low-density forests that are regularly burned (Schultz 1997). Silvopastoral systems have been promoted by state agencies as a way for landowners to increase their revenues (e.g. Husak and Grado 2002), and these systems are based on rows of trees separated by exotic pasture grasses that are regularly prescribed burned or mowed. Because livestock prefer grasses and forbs grown in open conditions, these systems are somewhat impractical for loblolly pine production. Although the use of livestock in greenbelts (herbaceous dominated strips designed to slow a wildfire down) is a possibility, this would not solve the fuel management problem in the adjacent forests.

Feasibility—The effective use of livestock for fuel management in loblolly pine forests is based on saturating an area with enough livestock that they are forced to consume less-palatable vegetation. One drawback is that livestock forced to eat low-nutrition forage may not gain the weight expected by landowners. The root systems of the browsed plants may be damaged, but if not killed, re-sprouting plants will regain their former size within a few years. Although livestock could be kept permanently in an enclosed forest, they probably will need supplemental feeding areas or adjacent pastures to compensate for these problems.

Effects on fuel—Since livestock seek out the most nutritious food and tend to avoid dense vegetation where travel and escape is hindered, their impacts on fuels will be uneven in terms on both location and vegetation consumed. Tsiouvaras and others (1989) reported that the intensive use of goats in a Monterey pine (*Pinus radiata* D. Don)-red gum (*Eucalyptus camaldulensis* Dehnhardt) forest in California reduced understory and mid-story cover by 41-48 percent. Furthermore, through trampling, the goats reduced 1- and 10-hour time-lag dead fuels by 33 percent and 58 percent and the litter layer by 27 percent. However, it is important to bear in mind that this one-day study used 600 goats within an enclosed 1-ha plot, or 242 goats/acre. In addition, the goats did not kill most of the plants, thus the live fuels re-accumulated within a year.

Ground fuels—Livestock do not consume ground fuels (duff), although their movement could compact these types of fuels along the trails they create.

Dead surface fuels—Livestock do not consume dead fuels unless preferred live forage is unavailable. Thill and Martin (1979) found that cattle in a fenced-in forest in Louisiana consumed dead leaves only during fall and winter, when it constituted 11 percent of their diet. However, this consumption was likely due to poor diet rather than the nutritional value of dead leaves. Since livestock prefer to avoid areas with heavy slash, their impact on large dead surface fuels will be limited. As with ground fuels, trampling can break up smaller-sized dead fuels, but at the cost of potential erosion and soil compaction.

Live surface fuels—As a general rule, livestock will consume herbaceous plants first, followed by woody plants with limited chemical defenses in their leaves (e.g. sweetgum). Livestock will consume leaves with high chemical defenses (e.g. pines) only when other vegetation is not available. In the Louisiana study, cattle consumed the leaves of water oak (*Quercus nigra* L.) only during fall and early spring, when it accounted for about 6 percent of their diet (Thill and Martin 1979). During the winter, waxmyrtle and deerberry (*Vaccinium stamineum* L.) made up 17 percent and 7 percent of the diet, respectively, both of which have rigid waxy leaves and likely low nutritional value. The loss of weight in forest-browsing cattle during winter is well-known, even in open forests (Campbell 1948).

In areas where the invasive cogongrass (*Imperata cylindrica* (L.) Beauv.) has become established, livestock cannot be used to control it since its leaves are high in silica and have saw-like edges (Faircloth and others 2006). Similarly, saw palmetto leaves are too tough to be eaten by cattle (Bennett and Hicklin 1998), however, sheep and goats have been used to control saw palmetto even though it may have little dietary value.

Ladder and Crown fuels—Even though livestock will consume the leaves of certain vines (e.g., Carolina jessamine, *Gelsemium sempervirens* (L.) Ait. f.), vines normally do not form a major fire hazard in loblolly pine forests. Because livestock are limited to the height which they can browse, their impact on ladder fuels is limited to disrupting the ladder of vegetation from ground level to about 5 feet above ground.

Application—Livestock grazing can be used as a solution to certain fuel reduction problems when landowners have both timber and livestock-related objectives. There will likely be a trade-off among the objectives, given the low nutritional value of some forest vegetation and the trampling damage to soils and regenerating trees.

Costs—The use of livestock for hazardous fuel management in forests is not currently a common practice in the South, thus treatment costs are unavailable. Based on Western operations, the expected main cost sources would be the transportation of the livestock, the fencing system required, and the maintenance of watering areas.

FUEL TREATMENTS IMPACTS AND MITIGATION

The previous section discussed the factors that influence the feasibility of each type of treatment, with an emphasis on operational constraints and treatment effects on fuels. In this section, the wider impacts of fuel treatments for a number of social and ecological factors such as water quality and wildlife will be discussed. For some negative impacts, mitigation techniques are available (e.g. re-seeding an erodible firebreak). However, for other negative impacts, no feasible mitigation options are available and they may have to be accepted as environmental costs. The key is to find a balance between avoiding environmental damage while achieving desired treatment goals.

SOILS AND WATER QUALITY

The protection and maintenance of water quality can be a major issue for fuel management treatments, especially in steep terrain or in areas with highly erodible soils. There are two main concerns when treating hazardous fuels: sediment production through soil disturbance, and damage to streamside management zones (riparian zones). If soil disturbance is severe enough, it can produce significant overland flow of sediment. In contrast, damaged streamside management zones can result in increases in water nutrient and stream temperature levels, and increased sediment loading in streams.

Prescribed burning itself does not usually affect water quality unless it is so intense that it consumes the duff and litter layer and exposes soils near streams. Normally, the impact of prescribed burning on erosion can be limited if it is conducted under moist conditions where complete forest floor consumption does not occur (Swift and others 1993). However, high intensity fires can consume the entire litter layer and expose the soil to potential erosion. In addition, poorly designed firebreaks can easily become sources of erosion if placed on a slope and facilitate water movement to a stream. Most state-level water quality Best Management Guides address firebreak placement and construction. Thus, potential problems can usually be avoided, especially if firebreaks are re-seeded with grasses. Alternatively, the U.S. Forest Service does not put firebreaks in wetlands, instead they allow prescribed burns to venture into streamside management zones and go out naturally. While it is possible to conduct a prescribed burn within a streamside management zone, care must be taken so that the area continues to perform its intended function. This means maintaining sufficient litter to slow down overland flow and avoiding excessive overstory mortality.

Similar to prescribed burning, mechanical operations can increase sediment production if significant soil disturbance occurs. Simply using heavy equipment will result in some soil disturbance, and mitigation (e.g. erosion fences or hay bales) may be needed. If perennial streams must be crossed by equipment, temporary bridges may be needed to avoid damaging stream banks, which can add significant cost to an operation. If a mulching treatment incorporates fuels into the soil (fig. 11), there may be increased erosion since the soil is looser and roots have been severed. In steep areas or areas with erodible soils, the use of tracked equipment instead of wheeled machines should be encouraged since tracked equipment generally has a lower surface pressure. If properly applied, forestry herbicides have little effect on water quality if they are not applied over or near water bodies (Michael 2004). Given the limited mobility of most herbicides once in the soil, subsurface movement to water is unlikely. Because herbicides do not expose soil, erosion is unlikely unless the ground equipment used significantly disturbs the soil.

PLANT COMMUNITIES

The effects of forest fuels treatments on plant communities vary by treatment type and the structure of the residual (live) vegetation.

Effects of prescribed burning—The effects of a fire in a forest with accumulated fuels will be more intense than a fire in a forest that is regularly burned. Therefore, the effects of a prescribed burning program must be considered separately for the first high-intensity prescribed burn and subsequent less intense burns. If fuels are in the form of a dense understory, and fire has been excluded for some time, the first prescribed burn will likely kill most of the small hardwood, pine, and herbaceous understory, and could thermally girdle some of the mid-story loblolly pines. Young saplings will probably be killed, as they will not have sufficient root reserves either to re-sprout or be competitive with older woody species also re-sprouting. Long-suppressed herbaceous species will probably respond with increased growth, although they will only be able to maintain this until other vegetation in the understory starts producing a large number of leaves.

For repeated prescribed burns, the cumulative effect on plant communities will depend on the timing (season) and the frequency (return interval) of the burns. If subsequent prescribed burns occur every 1 to 2 years, then the herbaceous layer will start to reestablish itself. For example, a long-term Forest Service experiment at Francis Marion National Forest in South Carolina compared the effects of winter prescribed burns applied at different frequencies (every 1, 2, 3, or 4 years) and found that annual and biannual prescribed burns promoted fast-growing grasses and forbs while longer frequency burns promoted woody plants (Glitzenstein and others 2003). Similar results were found in a study by White and others (1990) in South Carolina. A three-year burn interval in loblolly pine stands in Arkansas produced stand structures with less understory cover than was found in stands that were treated with a six- or nine-year return interval (Cain and others 1998). The relationship between fire frequency and understory woody plant persistence is best thought of as a war of attrition, where root reserve levels and topkill frequency determine how long it will take to effectively eliminate the woody plants. If a prescribed burning management plan is based on burning every 3 to 5 years, the woody species will likely not be removed. Periodic burning (3+ year return interval) in either season (winter or summer) or annual winter prescribed burns can facilitate the development of hardwood seedlings, while also reduce the amount of more established, but relatively small hardwood trees (Waldrop and others 1992). These findings are mainly due to the sprouting of hardwoods, such as sweetgum, from established root systems. An annual summer burning program can damage significantly the root systems of hardwood trees and keep them under control (Waldrop and others 1987).

Effects of mechanical treatments—The under- and mid-story plant species associated with loblolly pine forests can change with different types of mechanical treatments. Phillips and others (2004) showed that distinctive plant communities can be associated with different combinations of mechanical and prescribed burning treatments. Tanner and others (1988) described reduced saw palmetto abundance, cover, and biomass for at least 3 years after drum chopping or plowing. One pass of a drum chopper can crush a plant; a second pass can sever stems from roots, and lift the roots out of the ground. Tanner and others (1988) suggested that a single pass of a drum chopper during saturated soil conditions may be sufficient. However, in areas where species such as saw palmetto readily re-sprout from severed stems, a two-pass treatment may be necessary. Although some plant species readily sprout from roots and are not effectively controlled by mechanical treatments (Tanner and others 1988), nevertheless a mechanical treatment that exposed mineral soil in an open-canopied pine stand could cause a change in species abundance or diversity (i.e., an increase in pine seedlings or a change in understory plant species composition).

Effects of herbicides—Some herbicide treatments can kill a large number of plants, greatly affecting the plant composition of a forest. If stem injection or granules are used, the effects may be limited to a single tree or a small area. The majority of the forestry literature on herbicide effects on plant community dynamics is based on site preparation or early release operations. These studies have shown that a single herbicide treatment usually has little effect beyond 2 years. For example, Keyser and Ford (2006) looked at the effects of applying different ratios of imazapyr (Arsenal™) and sulfometuron methyl (Oust™) at different loblolly pine plantations in the Virginia Piedmont during site preparation, and found that most decreases in herbaceous cover were limited to the first year. Similarly, Wilkins and others (1993a) found that while a hexazinone site preparation treatment significantly decreased cover for most woody species for at least the first 1 to 2 years, herbaceous cover was reduced for the first year on all sites and for at least two years in wet areas. According to Shepard and others (2004), most forestry applications of herbicide are based on rates far less than the recommended maximum rates, which could partially explain the limited effects of herbicides.

Invasive plants—In loblolly pine forests, there are currently two main invasive, exotic plant species of concern, cogongrass and *Lespedeza* species, that present significant wildfire hazards.

Cogongrass—A fast-growing rhizomatous grass that can quickly take over an understory (fig. 18), cogongrass is currently found mainly in coastal areas, although it has the potential to spread into uplands. It can form dense monocultures that accumulate large amounts of dry fuels. When these areas burn, the resulting fires are intense, enough to kill small trees and other competitors. Since cogongrass rapidly re-sprouts after a fire, prescribed burning actually helps the species to increase its dominance. In addition, a single application of an herbicide has a limited effect on established plants, thus multiple applications are needed to kill the entire root system (Faircloth and others 2006). Since it can easily grow roots from broken rhizomes, single or periodic mechanical treatments only increase the rate of spread of cogongrass. To effectively eliminate this species, a long-term integrated herbicide-mechanical program is needed that is designed to exhaust the root reserves (Jose and others 2002). If cogongrass is present in the understory, its complete elimination should be considered a priority. Like kudzu (*Pueraria montana*), a small population of survivors can quickly reestablish pre-treatment levels, so a treatment program should be complete or the effort will be wasted.

Lespedeza species—Because it has densely packed leaves that contain volatile oils and the ability to re-sprout vigorously, both exotic and native species of lespedeza can form flammable clumps that facilitate high-intensity fires. At the Bankhead National Forest in Alabama, a bicolor lespedeza (*Lespedeza bicolor* Turcz.)-dominated understory formed such thick conditions that it required a mulching operation to prepare the area for prescribed burning (fig. 19). Noxubee National Refuge in Mississippi also has problems with clumps of exotic lespedeza, which can create intense fire conditions, although it is an isolated problem along roads, rather than a wider-spread problem.

Other invasive plants that may be future problems—Chinese tallowtree (*Sapium sebiferum* (L.) Roxb.) appears to be limited to wet areas for now, although it has the potential to become a pest species in upland loblolly pine forests. Because the exotic privets (*Ligustrum* spp.) can form a thick understory layer in a forest, they are usually found in moist conditions that limit the danger of wildfire. Finally, even though kudzu and Japanese honeysuckle (*Lonicera japonica* Thunb.) are aggressive vines, they are either limited to forest edges (kudzu) or do not normally accumulate enough fuel in the mid-story to act as a fuel ladder.

WILDLIFE

Loblolly pine forests are widespread and not linked to specific habitat conditions, therefore few endangered species are specifically associated with loblolly pine. The red-cockaded woodpecker (*Picoides borealis*), although primarily associated with longleaf pine forests, can also nest in open stands of large loblolly pine trees. Because there already exists ample information on management for this species (e.g. Masters and others 1998; Conner and others 2002), it will not be addressed here. The majority of birds found in southern pine forests prefer open stands with minimal mid-story vegetation. Conner and others (2002) compared bird populations in loblolly pine-shortleaf pine stands, where the canopy was both open and closed. During the breeding season, they found that there was greater species richness, abundance, and diversity in open pine stands than in closed pine stands. Bird species not found in open pine stands tended to be common generalist species that required a hardwood mid-story. During the non-breeding season, there was greater richness and abundance in the open stands than in the closed stands, possibly due to increased grasses and shrubs. Thus fuel reduction treatments that reduce the mid-story can create an open stand structure which may be beneficial to many bird species.

For wildlife in general, there are two main issues of concern when fuel reduction treatments are considered: loss of large snags and loss of down logs. Both are common in southern fuel reduction operations and have major long-term implications for wildlife.

Loss of snags—Large snags are ecologically important as they provide nesting, roosting, and foraging opportunities for various species of wildlife. Loblolly pine forests are sub-climax communities and unlike older forests, do not produce many large snags over a long period. Rather than a slow but steady attrition of overstory trees in an uneven-aged forest, snag production in loblolly pine forests is largely a bi-modal process, with high inputs first during initial crown closure and then a lower rate through pine senescence during succession to a hardwood stand (van Lear 1993). However, most of the trees that die during the early crown closure are small diameter stems that have little importance as a cavity sources. While they may serve as habitat for insects, their low volume to surface area ratio (a measure of how quickly they dry out) may limit this role.

As the size of bird species increases, larger snags are required, which suggests that a range of snag sizes is needed to support a diverse bird community. Several papers have attempted to estimate the number of snags needed in southern pine forests to support average-sized populations of different cavity-nesting bird species. For example, Harlow and Guynn (1983) studied the availability of snags in 1 to 100 year-old pine-dominated stands in the Coastal Plain of South Carolina. Using an estimated average bird population which assumed that cavity nesters needed three snags per year (two for breeding and one for fledglings), they determined that only 20 percent of the estimated demand for 5 to 9 inches dbh snags was being meet while only 6 percent of the demand for snags ≥10 inch dbh was being provided. Harlow and Guynn (1983) hypothesized that lightning is the principle source of large snags in mature pine forests, and could produce about 0.3 large snags per acre per year. At a Piedmont site, Moorman and others (1999) found that regardless of initial snag diameter, the majority of snags fell by age six and longevity was independent of diameter. Since most cavities were not excavated until snags reached age 6, Moorman and others (1999) suggest that snags that can be used for cavities are ephemeral and likely only usable for 1 to 2 years.

Given the slow and uneven production of large snags in a loblolly pine forests, retention of large snags could be considered a priority for wildlife management in loblolly pine forests. The U.S. Forest Service attempts to retain snags for wildlife habitat, and some of the long-term management plans provide guidelines on the minimum number of snags to be retained during harvesting operations. However, snags can also be fire and safety hazards, and during fuel reduction operations, the removal of snags is often a priority item. For example, a 2006 mechanical mulching operation at Conecuh National Forest in Alabama required the contractor to remove or mulch all snags over 10 inches dbh as well any snags that could fall outside the Forest boundary. This was intended to reduce the risk of a prescribed burn getting into the overstory as well as to comply with OSHA regulations. In addition, the Forest had a red-cockaded woodpecker population and was legally required to place the protection of living cavity trees above the needs of non-endangered snag-using species. In contrast, during a mechanical mulching operation at Jones State Forest in Texas, which also had a red-cockaded woodpecker population, the only snags removed were ones deemed to be immediately hazardous to humans, and the resulting forest had many remaining large snags.

If snags are removed during fuel reduction operations, then a reduction in the characteristics of the bird community is likely. In a 50 year-old loblolly pine plantation in which snags were removed, Lohr and others (2002) found that some secondary cavity-users like the tufted titmouse (*Baeolophus bicolor*), the brown-headed nuthatch (*Sitta pusilla*), and the Carolina chickadee (*Poecile carolinensis*) were able to use alternate sites (dead limbs, stumps, and crevices), but the great crested flycatcher (*Myiarchus crinitus*) was not. Insectivorous birds may also decline since snags also represent a feeding site, although loss of fallen logs has more impact.

Down logs—While the loss of snags affects mostly cavity-using birds, the loss of down logs impacts many vertebrate species, and can cause a cascade effect of species loss. Unfortunately, down logs are often targets of fuel reduction operations during mulching and prescribed burning operations. This contradiction means that treatments to reduce the wildfire hazard of a forest can also reduce its wildlife value. For example, Lohr and others (2002) found that the loss of down logs had minimal impact on most non-breeding birds, which tended to be foliage-gleaners. In contrast, for the breeding birds, abundance was reduced by almost 50 percent and species richness decreased 45 percent. These species tended to rely on insects associated with down coarse woody debris and on the additional forest structure that the woody debris provided.

Many herpetofauna (amphibians and reptiles) are also negatively affected by a loss of down logs. Since logs are insulated, they form a gradient of temperatures from warm sunlit sides to cooler areas under the log (Whiles and Grubaugh 1993). Herpetofauna use this gradient to find the best place to lay their eggs or sun themselves and may use logs as hibernation sites. In addition, down logs contain a large number of insects and are a valuable feeding area. Greenberg (2001) compared reptile and amphibian populations in (a) undisturbed, mature, relatively dry hardwood forests, (b) forests with hurricane-created gaps that had been either salvage-logged (most boles removed, but branches left), and (c) forests with hurricane-created gaps left intact (boles not removed). Reptiles responded positively to the disturbance, with higher populations in the gaps than in the intact, standing forest. The unlogged gaps had significantly higher percent down logs than the other two, yet there was no difference in reptile populations between the gap types, thus the percentage of down logs does not appear to have a major influence on reptile populations. Greenberg (2001) also found that the xeric (relatively dry) habitat amphibians were highly tolerant of harvesting disturbance, but suggests that amphibians in wet areas might not be as tolerant of disturbance.

The presence of a thick litter layer can reduce the need for down logs for some species.

Salamanders tend to have limited ranges and restricted microhabitat needs. Since Ambystomatid salamanders use underground burrows, they may survive without down logs if the litter layer is thick enough to keep the ground cool and moist. For example, Moseley and others (2004) found that mole salamanders (*Ambystoma talpoideum*) were not negatively affected by the removal of most down logs and pine litter in a 50 year-old loblolly pine stand as long as enough litter remained to buffer temperatures and humidity in burrows. In contrast, they found that Plethodontid salamanders require down logs for burrows and cannot use tunnels as substitutes.

Larger mammals that utilize loblolly pine forests are mostly wide-ranging generalists and disturbance tends to increase forage or prey production in early-successional habitat. In contrast, smaller mammals such as rodents can be affected by loss of down logs, especially if they are insectivores or use down logs for some portion of their life cycle. Loeb (1999) suggested that large gap formation probably initially reduce small mammal populations, but the presence of down logs helped populations to recover. However, looking at the six most common small mammals in young loblolly pine stands, Mengak and Guynn (2003) found no obvious habitat preferences, and suggested that small mammal habitats are complex combinations of multiple microhabitats. For example, while down logs may be an important factor for golden mice (*Ochrotomys nuttalli*) and cotton mice (*Peromyscus gossypinus*), different factors influence other species. McCay and Komoroski (2004) examined the impact on shrew populations of removing all logs $\geq$ 4 inches diameter in loblolly pine plantations. They found that the southern short-tailed shrew (*Blarina carolinensis*) and southeastern shrew (*Sorex* *longirostris*) were unaffected by the loss of down logs, although the least shrew (*Cryptotis parva*) did decline, possibly due to low initial population levels. Mengak and Guynn (2003) predicted that activities such as thinning would be expected to mostly benefit small mammals since they encourage understory growth while mid-rotation burning would negatively affect small mammals by reducing woody shrubs.

PUBLIC RELATIONS AND TREATMENTS

When conducting fuel treatments, it is important to consider the impacts of operations on other people and their activities inside and outside the forest. Land managers have the professional obligation of ensuring that their operations do not endanger the public or create unnecessary inconveniences. In addition, maintaining good relations with neighbors is a necessary requirement of land management, regardless of the landowner. In many cases, the media and public will tolerate inconveniences but will not tolerate being uninformed.

For mechanical operations, the impacts of moving heavy equipment have to be balanced with the available road system and nearby housing. For rural operations, consideration may be limited to ensuring that clay or gravel are not left on paved roads during or after treatment. In areas where roads may be narrow and turn-outs limited, traffic management is vital to ensure that residents remain supportive of the activity. Another factor that may not seem obvious is the timing of work. In order to maximize productivity, contractors tend to start operations early in the day, which can become an issue in the wildland-urban interface. While restrictions can be placed on operations so that they do not start until a reasonable hour, contractors may not be willing to work under such conditions since lost productivity may translate into financial losses. In contrast, ground-based herbicide operations may have little impact on traffic or noise. However, public relations are just as important since the use of herbicides has a negative connotation to the general public and misconceptions about herbicide effects on neighboring yards or streams can be damaging to public support of the activity.

The off-site effects of prescribed burning are heavily regulated and a burn manager would be expected to account for them when planning a prescribed burn. A more subtle aspect of managing off-site effects is the long-term commitment needed for a permanent burning program and whether this commitment is shared by the neighbors. Unhappy neighbors can affect a burning program through complaints, and if local residents do not support a burning program, its long-term sustainability is questionable. Thus, an aggressive public relations program is a vital part of a prescribed burning regime. For example, the Bankhead National Forest in Alabama maintains a phone list of local residents to be called before a prescribed burn, in order to minimize conflict and to determine if people with health problems need to be temporally evacuated. Similarly, Loomis and others (2001) described how a prescribed burning educational program in Florida increased public support for the practice. Miller and Wade (2003) illustrated how the success of a prescribed burn increased support of the program from local residents.

FUEL REDUCTION IMPACTS ON EXTRACTABLE RESOURCES

A number of common extractable resources can be found in loblolly pine forests, including commercial forestry products (pulpwood and sawtimber), pine straw, mushrooms, and game species such as quail, turkey, and deer. Other non-timber forest products include floral greens, medicinal and dietary supplements, and specialty wood products (e.g. burls, twigs, branches). Because fuel treatments tend to improve access and increase the amount of herbaceous forage available, their impacts on extractable resources will generally be favorable, although damage to overstory trees is always a possibility.

Effects on overstory pine—The understory in a loblolly pine stand has a diminishing influence on overstory growth as the trees age and increase their dominance of the site. Thus, reducing the understory by any fuel treatment method will not release the overstory from significant competition. Crown scorch, however, from a prescribed burn, can reduce the crown ratio (crown length divided by tree height), which would decrease the growth rate of a tree for several years. This decrease in productivity could be compounded by losses of surface organic matter and nutrients or decreases in soil porosity (Tiedemann and others 2000). While healthy loblolly pines can replace needles lost to scorch within one to two seasons, this replacement acts as a drain on productivity and it may take several years for growth rates to return to pre-fire levels. In addition, crown scorch is highly visible and perceived poorly by the general public regardless of our scientific knowledge on the subject.

McInnis and others (2004) described two East Texas mid-rotational loblolly stands that were either treated with herbicide, prescribed burned, or both. For the prescribed burning treatment, subsequent growth of the overstory trees was either not affected, or negatively affected (depending on the study site). The same was true for the herbicide - prescribed burn treatment. The herbicide-alone treatment did increase the growth of the overstory trees. McInnis and others (2004) suggested that the negative effects from the crown scorch had been greater than the any benefits derived from the herbicide treatment. Similarly, for a prescribed burned 14 year-old Piedmont loblolly pine plantation, Tew and others (1988) found a decrease in diameter growth with increasing crown scorch, as compared with nearby unburned trees. Even trees with only 0 to 3 percent scorch grew less than the controls, which Tew and others (1988) suggested might have been due to secondary soil factors such as root death or soil chemistry changes. However, general tree stress or damaged cambial tissues are also possible explanations. Declines were greatest during the first year, and there were no differences in diameter growth by the fourth year. Potential pulpwood timber value may decline after fire if bark char causes a concern for the pulping process or if nitrogen recently applied is volatilized and lost. Other research suggests only minor effects of crown scorch on loblolly pine growth (Waldrop and van Lear 1984).

Mechanical fuel reduction treatments can cause bark damage of residual overstory loblolly pines, allowing decay agents or pathogens to enter a tree and perhaps girdle part of the stem. In addition, heavy equipment can injure or kill loblolly pine root systems through soil compaction or rutting. Careful planning can reduce some of these problems, although the understory being treated may be so dense that bark injury to residual trees is inevitable.

Non-timber products—The impact of fuel reduction treatments on non-timber resources will vary. Pilz and others (2004) described how prescribed burning in Oregon affected mushroom production and suggested that fire (or lack thereof) can be used to promote different species. Since many mushrooms utilize downed woody material for food, mulching operations may encourage some species, but treatments to reduce down wood will discourage mushroom growth. Croan (2004) evaluated the potential of loblolly pine wood wastes from mechanical treatments to produce gourmet and medicinal mushrooms and found that some economical species could use the material. If logs from fuels reduction treatments remain on site and are able to produce marketable mushrooms, such as shiitake (*Lentinula edodes*) or oyster (*Pleurotus spp.*), they can maintain productivity for up to six years (Hill 1999).

Game species—Prescribed burning and other fuel reduction treatments during certain seasons can affect bobwhite quail (*Colinus virginianus*) populations through destruction of nests and food reserves and the removal of vegetation that acts as nesting, roosting, or cover habitat (Maas and others 2003). However, Wilson and others (1995) showed that bobwhite quail populations could increase with stand improvement treatments (thinnings) and prescribed burning. Fuel reduction treatments that create bare patches of soil encourage the growth of herbaceous vegetation that either acts as a food source or attracts insects (Maas and others 2003). Fall, winter, or early spring treatments are recommended to avoid affecting quail during the nesting season (Moore 1957).

Like bobwhite quail, prescribed burning and other fuel reduction treatments affect eastern wild turkey (*Meleagris gallopavo*) populations through destruction of food reserves as well as through the removal of vegetation that acts as nesting, roosting, or cover habitat (Maas and others 2003). Annual clearing of understory through burning or other treatments is not advised for turkey management. Rather, a patchy treatment on a 2 to 4 year return interval is advised to produce the understory vegetation that is most favorable for turkey nesting and breeding. Exum and others (1987) indicated that turkey hens nested in a wide variety of habitats and selected them based on the availability of woody vegetation that was present with an adequate density. Turkeys consume a broad diet, including insects and the seeds of numerous grasses, shrubs, and vines. The fruit of dogwood, black cherry, and oaks are also consumed (Williams and Austin 1988), therefore maintaining a mixture of habitat types in or nearby a loblolly pine forest seems necessary. When feasible, it is probably best to burn on a planned schedule of more then 1/3 of the number of stands per year.

White-tailed deer (*Odocoileus virginianus*) are relatively mobile and can move away from fuel reduction treatment areas and find refuge in other habitats (Ivey and Causey 1984). Deer are attracted to recently burned pine stands due to changes in food availability (Dills 1970), although pine-hardwood stands are preferred due to the exposure of acorns as a result of the treatment (Ivey and Causey 1984). Fuel reduction treatments can increase the quantity and quality of woody and herbaceous food for deer, which subsequently affect deer population growth, development, reproduction, and survival. Unfortunately, fuel reduction treatments can also reduce the cover necessary for escape or hiding purposes (Maas and others 2003).

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APPENDIX A - IMPORTANT CONCEPTS FOR UNDERSTANDING FUEL TREATMENTS

In this section we discuss the general physical, biological, and ecological principles that are critical to understanding both the impacts of management practices on forest fuels and the influences that these modifications will have on fire behavior and effects. The aim is not to provide a comprehensive treatment of these subjects, but instead to introduce a set of general of concepts and definitions that are useful for understanding how fuel treatments affect fire behavior and fire severity. This information will draw on standard fire science references (Burgan and Rothermel 1984; Pyne and others 1996) as well as examples from a variety of different ecosystems to provide an introduction to fuels, fire behavior, and treatment effects.

KEY FUEL CHARACTERISTICS

Although fuels vary widely in their physical, biological, and chemical properties, the major influences of fuels on fire behavior can be characterized using a relatively small number of variables. The three most important of these variables are fuel load, the surface area to volume ratio of the fuel, and fuelbed depth (Burgan 1987). The fuel load represents the dry weight of live and dead fuels in an area and is normally expressed as tons per acre. Although fuel load is a commonly used as a metric of potential wildfire hazard, there is no simple correlation between fire intensity and total fuel mass. Only a portion of the total fuel load, the available fuel, will support combustion, depending on fuel moisture levels. Additionally, the size distribution and spatial arrangement of fuels strongly influence the process of combustion.

The surface area to volume ratio is a measure of how much space is enclosed by a surface. This concept is important for forest fuels since it influences how quickly moisture is gained and lost and how much energy is needed to ignite the fuel, with high surface to volume ratio fuels requiring less energy. In general, the ratio decreases with decreasing fuel particle size, and is also influenced by particle shape. Fuelbed depth in combination with the fuel load determines the compaction of the fuelbed. Expressed as the packing ratio, it is the ratio of the oven-dry fuel bulk density (computed with respect to the total volume of the fuelbed) to the oven-dry fuel particle density. Other fuel characteristics that can affect fire behavior include chemical properties that determine heat content and flammability, physical and biological properties that affect the dynamics of fuel moisture, and horizontal and vertical spatial arrangement.

FIRE CHARACTERISTICS

Fire behavior is characterized using one or more metrics of fire intensity, which are defined by the physical characteristics of the fire itself. These metrics include spread rate, flame length, fireline intensity (heat production per unit length of the flaming front per second), and heat per unit area (total heat produced during the residence time of the flaming zone). As spread rate, flame length, and fireline intensity increase, fire suppression becomes increasingly difficult, and the potential for extreme fire behavior such as spotting, fire whorls, and crown fire increases. Fire severity, defined as the effects of fire on vegetation, soils, and other ecosystem properties, is a function of both fire intensity and the physical and ecological characteristics of the site. Longer flame lengths emit heat higher in the forest canopy and increase the potential for crown scorch and crown fire initiation, whereas greater heat per unit areas results in a larger heat pulse and greater impact on below-ground properties. These elements of fire behavior will not always respond in a similar fashion to changes in fuels. For example, a fuelbed composed of dead grasses may have a relatively high spread rate but release only a small amount of heat per unit area. In contrast, a fire burning under similar weather conditions in fuels dominated by large dead wood will have a slower spread rate, but longer flame lengths and greater heat output per unit area (Pyne and others 1996).

Predicting the effects of fuel treatments on fire behavior is challenging in part because the influence of any single fuel variable depends on other fuelbed characteristics. For example, the effects of reducing fuel loading are contingent upon changes in fuelbed depth. Each fuelbed has an optimum packing ratio that is a function of the fuel size distribution (Burgan and Rothermel 1984). If depth remains relatively constant and packing ratio decreases below the optimum level as a result of lower fuel loads, reductions in the rate of fuel consumption and the preheating of adjacent fuel particles will lead to lower spread rates, flame lengths, and fireline intensities (Burgan 1987). In contrast, reduced loading of live fuels and large woody fuels may eliminate a significant heat sink and lead to increased fire intensity in some situations. Decreasing fuel particle size increases the surface to volume ratio of fuels, which increases the rate of combustion, decreases the need for preheating, and generally leads to higher spread rates, flame length, and fireline intensity.

However, fine particles are more easily compacted than large particles, and fire intensity may be reduced if the packing ratio increases above the optimum level for a particular fuelbed.

Another challenge in understanding the effects of fuel treatments on fire behavior is that the behavior observed in a particular fuelbed will vary as a function of weather. At any given time, only a portion of the total fuel load will be available fuels that can influence the behavior and effects of a fire. The amount of available fuel is influenced by fuel size, spatial arrangement, and fuel moisture, which vary over time with precipitation and evaporation. Different types of fuels (large versus small, live versus dead) respond to the environment at different temporal scales. Thus, it is important to understand how fuel treatments influence fire behavior over the full range of weather conditions likely to be observed at a site, ranging from moderate conditions suitable for prescribed burning to extreme conditions where the potential for large, destructive wildfires is highest. For example, when live and dead fuel moistures are relatively low, a shrub-dominated fuelbed will have much higher spread rates than compacted hardwood litter. When fuel moisture is high, hardwood litter has a higher spread rate, although spread rates in both fuel types are relatively low (Pyne and others 1996). It is also important to recognize that vegetation also influences microclimate within a stand. Thus, treatments that modify fuels can also affect patterns of wind and fuel moisture within the fuelbed.

FUEL TYPES

Fuels are often organized in terms of vertical layers, which include ground fuels, surface fuels (consisting of a live and dead component), and elevated fuels (consisting of crown fuels in the forest canopy and ladder fuels that may connect the canopy with the forest floor) (Pyne and others 1996). The criterion of 6 feet is typically used to separate surface fuels from elevated fuels. A fire may be confined to a single layer (e.g. ground fire, surface fire), or may encompass multiple layers. For example, both passive crown fires (torching) and active crown fires occur in conjunction with surface fires (Scott and Reinhardt 2001). Each of these classes of fuels exhibits distinctive relationships with moisture and fire behavior and they provide a convenient framework for characterizing fuels and their responses to treatments.

Ground fuels—These are either located below the soil surface or at the mineral soil-organic layer interface and include duff, organic soils, large roots, stumps, and buried logs. This layer is characterized by its tendency to produce smoldering fires that may not be readily visible as well as an important possible source of post-fire smoke. For ground fuels, duff is the most important component during hazardous fuel treatments for both burning and mechanical treatments. Duff is composed of decaying organic matter in the fermentation and humus layers of the forest floor and is very important for nutrient cycling and topsoil formation. The top of the duff layer transitions into non-decomposed litter and the bottom is located at the mineral soil horizon. In loblolly pine forests that are regularly burned, little duff is produced since there is not enough accumulated litter and soil moisture to promote the process.

However, in forests where fire has been excluded for decades, a significant amount of duff can form if moisture conditions permit. Tree roots tend to concentrate within the duff layer and can be destroyed if the duff burns or is compacted by heavy equipment. In contrast, in poor-quality Piedmont soils with hard clay surfaces, there may be little or no duff formation due to low litter and soil moisture, past management practices, and erosion.

The distribution of other ground fuels such as roots, stumps, and logs will be highly variable both within and between sites, reflecting the history of natural disturbances and land use. Rapid fire spread through ground fuels is not normally a hazard. Organic soils (e.g. Histosols) are found in some forested and herbaceous wetlands (Varner 2004), but are not likely to be a major concern in most loblolly pine forests except for some coastal areas where former wetlands now have a loblolly pine overstory. However, the long residence time of a ground fuels fire can result in much higher mineral soil temperatures than a fast-moving surface fire (Hartford and Frandsen 1992). The intense and sustained heat from ground fires can result in loss of soil organic material and damage to both roots and the cambium at the base of trees (Ryan and Frandsen 1991; Stephens and Finney 2002). Smoldering combustion in the ground fuel layer presents a problem for fire suppression and prescribed burning because pockets of residual ground fire can smolder undetected for weeks and re-ignite a fire long after the initial front has passed. In addition, the large amounts of smoke produced by smoldering combustion of ground fuels can increase off-site risks associated with either wildfire or prescribed burning.

Dead surface fuels—These include litter, branches, logs, and any other dead woody material that accumulates on the surface of the ground. In addition, live plants in the surface fuel layer such as grasses and shrubs can contain dead stems and foliage. The surface area to volume ratio of dead fuels largely determines the rate at which fuel moisture is gained or lost in response to environmental change. Because most branches and stems are cylindrical in shape, they can be classified into one of four time lag moisture classes based on average diameter. The time lag for each class represents the time needed for a fuel particle at the midpoint of the size class to reach two thirds of the surrounding atmospheric moisture levels.

Fuels in the 1-hour time-lag dead class (< 0.25 inch diameter, characterizing vegetation with a large surface-to-mass ratio) are comprised of needle and leaf litter, grasses, and small twigs. These fine fuels have the greatest influence on fire spread, and are the most sensitive to short-term weather fluctuations. Larger fuels in the 10-hour (0.25 to 1 inch diameter) and 100-hour (1 to 3 inches diameter) time-lag dead classes are predominantly dead branches and woody stems. These larger fuels dry out more slowly than 1-hour time-lag dead fuels. Heavy concentrations of these larger fuels can retard fire spread by serving as a heat sink when their internal moisture levels are high. However, when fuel moisture is low enough, 10- and 100-hour time-lag dead fuels can burn at high intensities and for a longer time than 1-hour time-lag dead fuels. Related to the issue of fuel moisture is the position of the fuel. Barber and van Lear (1984) found that loblolly pine dead fuels on the ground decomposed 50 percent faster than elevated slash. For a few years, small branches decompose faster than larger pieces, until hardening of the branch surface occurs. There was a general decay rate of 7.2 percent, so that 50 percent of slash is lost by year 10 and 90 percent is lost by year 32.

The 1,000-hour time-lag dead fuels (> 3 inches diameter) do not influence the spread of most surface fires, but can ignite under extremely dry conditions or when pre-heated by adjacent smaller fuels (Brown and others 2003). Under these conditions, fire in 1,000-hour fuels can burn at extremely high intensities, creating problems for fire suppression. Large pieces of wood, particularly those in an advanced stage of decay, can smolder for days and create problems with smoke and re-ignition. Smoldering logs can also heat soils to lethal temperatures and have a similar impact as ground fires burning in duff. Because dead wood typically covers only a small portion of the forest floor, these effects will be spatially heterogeneous and highly localized. After major disturbances such as insect outbreaks or hurricanes, a significant amount of fuels in these larger size classes may be created. The problems they present relate primarily to the amount of smoke that these fuels might contribute in a later wildfire or prescribed burn, these fuels make suppressing a wildfire more difficult, and they may limit access or hinder construction of fire lines, thus impeding prescribed burning. After major disturbances a short-term pulse of fine fuels may also occur, but these fuels will decompose after a few years.

Live surface fuels—These include grasses, forbs, and shrubs that are less than 6 feet in height. In loblolly pine forests, herbs and grasses are most abundant following agricultural abandonment, timber harvest, or prescribed burns. Common species in loblolly pine forests include broomsedge (*Andropogon virginicus* L.), ragweed (*Ambrosia artemisiifolia* L.), crabgrass (*Digitaria sanguinalis* (L.) Scop.), and heath aster (*Aster ericoides*) (Schultz 1997). Understory trees and shrubs can form a dense layer, particularly in open stands that are infrequently burned. Species occurring throughout the range of loblolly pine include flowering dogwood, American holly (*Ilex opaca* Ait.), hawthorn (*Crataegus spp.*), blueberry (*Vaccinium spp.*), beautyberry (*Callicarpa americana* L.), and viburnum (*Viburnum spp.*). Pawpaw (*Asimina triloba* (L.) Dunal), waxmyrtle, gallberry, and yaupon are also important in the Coastal Plain. While saw palmetto is common in the flatwoods of the Coastal Plain and can be a major fire hazard, however, it is normally not a major component of loblolly pine forests.

An important distinction between dead and live fuels is that moisture in dead fuels is controlled entirely by external weather influences, whereas moisture in live fuels is regulated by the internal physiological mechanisms of the plants. Live fuels can either contribute to or retard fire behavior depending on moisture levels and the amount and spatial arrangement of dead fuels. When fuel moisture is high, live fuels serve as a heat sink and do not contribute to fire spread. When fuel moisture is low, combustion of dead fuels can readily preheat and ignite the foliage and small branches of live plants, leading to increased fire intensity. Larger branches and stems of live plants are typically not consumed by fire.

Live fuel moisture exhibits spatial trends associated with site characteristics, and season trends associated with the phenology of various plant species. Fuel moisture in deciduous woody species typically increases with leaf development in the spring and decreases once seasonal growth has been completed. Evergreen woody species typically have lower fuel moisture than deciduous species, and can exhibit complex seasonal trends. Grasses and herbs are the most sensitive to seasonal or weather-driven changes in fuels moisture. As fuel moisture drops below 100 percent, an increasing portion of the grasses and herbs dry out and effectively function as dead 1-hour time-lag dead fuels (Scott and Burgan 2005). When fuel moisture reaches 30 percent, herbaceous plants become fully cured and function as dead fuels.

Ladder and crown fuels—Characterized by being higher than six feet, these fuels include shrubs and trees, vines, and suspended dead foliage and branches. The vertical distribution of these fuels is a principal factor in determining crown fire risk. When live foliage is continuously distributed from the surface up of to the canopy, a surface fire may propagate into the canopy and result in torching of individual trees (Scott and Reinhardt 2001). If fire reaches the canopy, the probability of active spread is related to the bulk density of foliage and small twigs in the forest canopy, as well as the spatial continuity of tree crowns. Standing dead trees are more likely to smolder than to support flaming combustion, and are typically not considered to be ladder fuels. However, smoldering at the base of snags can weaken them and cause them to fall, creating a potential fire spread hazard if snags are located near firebreaks.

FUEL LOADING AND FUELBED STRUCTURE

Immediate reduction of fuel loads can only be achieved through combustion or physical removal of fuels from a site. In most situations, prescribed burning is effective at reducing the loading of fine dead surface fuels. However, the effects of prescribed burning on fuels can vary considerably depending on the condition of the fuelbed and weather at the time of the burn. In general, fuel consumption by fire will increase with decreasing particle size and decreasing fuel moisture (Scholl and Waldrop 1999; Waldrop and others 2004; Knapp and others 2005; Perrakis and Agee 2006). Although the majority of 1-hour time-lag dead fuels are typically consumed under a wide range of burning conditions, larger sizes will be consumed only when fuel moisture is relatively low. Consumption of duff and litter also increases with decreasing moisture at the time of the burn. Prescribed burning results in widespread mortality or topkill of understory plants, but typically only the foliage and smallest branches are actually consumed, whereas larger stems become part of the dead surface fuel load.

In contrast to burning, mechanical and herbicide treatments usually redistribute fuels rather than reduce them. These effects can vary considerably depending on the type of equipment used and the management prescription applied. Thinning of overstory trees can reduce crown fire hazard by removing ladder fuels and reducing canopy bulk density. However, if residues are left untreated, higher loadings of fine dead fuels can increase the potential for high-intensity surface fires (Agee and Skinner 2005). Thus, combined treatments of thinning with subsequent prescribed burning are generally more effective at moderating subsequent wildfire behavior and reducing damage to overstory trees than thinning alone (Cram and others 2006; Raymond and Peterson 2005; Stephens and Moghaddas 2005). Although mechanical treatments have been reported to reduce fuel loading in the litter and duff layers through disturbance of the forest floor (e.g. Kalabokidis and Omi 1998; Brose and Wade 2002), these findings may reflect compression of surface and ground fuels rather than an actual decrease in fuel loads (McIver and others 2003).

Other management practices such as whole-tree harvesting, physical removal of logging slash, raking fuels away from tree boles, and compaction of the surface fuelbed can also help to mitigate the effects of surface fuel accumulation after mechanical treatment (Jerman and others 2004; Fulé and others 2002; Kalabokidis and Omi 1998). Fuel compaction above the optimum packing ratio reduces the amount of oxygen available for combustion and increases the amount of heat required to propagate fire through the fuelbed (Burgan and Rothermel 1984). In addition, tightly compacted fuelbeds retain more fuel moisture and reduce effective wind speed more than loosely compacted fuelbeds. Fuels can be compacted through the use of bulldozers of other heavy equipment that physically compress the surface fuelbed. In ponderosa pine forests in northwestern Arizona, compression of thinning slash with a bulldozer reduced crown scorch and tree mortality in a subsequent prescribed burn (Jerman and others 2004).

Mechanical cutting and mulching of understory vegetation reduces live fuel loads and increases fuel compaction, but also increases the total loading of dead surface fuels. Mulching increases compaction of fuels by reducing fuelbed depth and increasing the observed packing ratio, and at the same time, reducing fuel particle size and decreasing the optimal packing ratio. These changes should reduce spread rates through the compacted fuels, but the slow-moving fires that result can generate an extended heat pulse into the soil that exceeds the lethal threshold for plants (Busse and others 2005). In the northeastern U.S., grinding of live fuels in dogwood and catbrier (*Smilax rotundifolia* L.) dominated fuelbeds reduced fire intensity in subsequent prescribed burns (Richburg and others 2004). Sensitivity analysis of the BEHAVE model also demonstrated that fuelbed depth and the resulting packing ratio are key parameters affecting fire behavior in greenbrier (*Smilax rotundifolia* L.) dominated fuels in the northeastern U.S. (Ohman 2006). In mixed-conifer forests of the Sierra Nevada, cutting and mastication of small trees and shrubs reduced predicted fire spread and flame lengths under low fuel moisture conditions, but increased fireline intensity (Stephens and Moghaddas 2005).

SPATIAL PATTERNS OF FUELS

Effects of fuel treatments are spatially variable within each treatment unit. The effects of prescribed burning will vary spatially depending on the heterogeneity of fuels and environmental conditions (Waldrop and others 2004). Prescribed burning conducted when overall fuel moisture is high tends to leave more unburned patches than those conducted in drier conditions (Knapp and others 2005). Mechanical operations can also result in spatial heterogeneity due to machine movement and skid trails. In some instances, slash may be concentrated in piles during mechanical operations. Spatial heterogeneity in fuels should theoretically reduce spread rates within a treatment unit, although fire severity may be higher in areas with concentrated fuels. Large-diameter fuels are more likely to be consumed when they are aggregated into piles than when they are scattered. Most research on fuel treatments and fire behavior to date has considered treated areas as homogeneous units, and there is little data to support generalizations about the effects of within-stand fuel heterogeneity on fire behavior.

The vertical distribution of ladder and canopy fuels influences crown fire risk. Thinning treatments that reduce the density of smaller trees can reduce torching of individual residual trees by raising the height to the base of the live canopy. Removal of larger trees reduces the risk of active crown spread by breaking up the continuity of the canopy and reducing canopy bulk density (Scott and Reinhardt 2001). However, these modifications to the canopy fuels may be offset by other changes caused by thinning. As discussed previously, accumulations of untreated slash from thinning operations can result in increased flame lengths and fire intensities that counteract the effects of canopy fuel modifications. Furthermore, increased mid-flame wind speed and more rapid drying of fuels in open-canopied stands can also result in higher fire intensity compared to a closed-canopy stand with similar surface fuels.

The spatial distribution of fuel treatments at a landscape scale is also an important consideration, because it will seldom be feasible to treat all areas with high fuel accumulations. Treatment locations can be prioritized by examining the spatial pattern of fuels in relation to the pattern of human populations and critical infrastructure. In general, areas that have both high fire hazard and are close to developed areas will be assigned higher treatment priorities than more isolated wildland areas (Zhang 2004; Wimberly and others 2006). Other approaches to prioritizing treatment locations use deviation from historical reference conditions as a baseline (Hann and Strohm 2003).

Once critical areas have been identified, the spatial arrangement of fuel treatments within these areas must be considered. Fuelbreaks are linear corridors within which one or more types of fuel treatments are applied. Fuelbreaks are implemented with the objective of providing firefighters a location that enhances the probability of controlling a wildfire, not with the expectation that the fuelbreak itself will stop a fire (Agee and others 2000). The size and location of fuelbreaks, along with the treatments applied within, will be contingent upon the characteristics of the local landscape. In the South, fuelbreak placement and design is likely to be driven mostly by the interface between wildland fuels and development. Fuelbreaks located at the boundaries of developed areas can serve the duel purpose of protecting property from fires spreading out of forested areas, and protecting forest resources from the spread of human-ignited fires.

A complementary strategy involves the dispersal of individual treatment units across the landscape. Simulations have demonstrated that treatment of a relatively small portion of an area can reduce the spread of large wildfires, particularly if treatments are placed in a regular, rather than a random or clustered, pattern (Finney 2001; Loehle 2004). As with fuelbreaks, the expectation is not that the treatments will actually stop wildfires, but that they will reduce fire intensity enough to facilitate fire suppression. Dispersed fuel treatments, combined with other strategies, such as fire-safe landscaping, may prove to be the most effective strategy in intermix areas where large numbers of dispersed structures limit the effectiveness of linear firebreaks.

In addition to their immediate effects on fuels, modifications of stand structure can also influence succession and the accompanying fuel dynamics. Treatments that reduce overstory canopy density also provide more resources to the forest understory, and can result in increased rates of live fuel accumulation in the surface fuel layer. In contrast, by reducing overstory basal area these same treatments can reduce the rate of litterfall and dead fuel inputs from the forest overstory (Brender and others 1976; Johansen and others 1976).

List of Figures

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