Pilot Validation of VSMOKE-GIS with Implications for Prescribed Fire Smoke Management Regulations

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Forestry

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April 29, 2011
Blacksburg, VA

Keywords: Prescribed Burning, Smoke Management, VSMOKE, Validation, Regulations

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ABSTRACT

Prescribed burning (Rx) has become increasingly subjected to various regulations. Among these regulations are ordinances that restrict downwind impacts of smoke from prescribed fires. Regulations can severely limit burn managers and private landowners from using Rx as a forest management tool. This research can help us move away from these simplistic regulations, and help promote a regulatory environment in which scientific tools and knowledge are used to prohibit only activities for which the evidence suggests there will be adverse consequences.

This research was divided into three parts that consisted of: (1) a pilot validation of the smoke emission model VSMOKE-GIS; (2) review of southeastern states' smoke management guidelines (SMG); and (3) a geographic analysis of Virginian's current SMG. VSMOKE-GIS showed good accuracy in predicting the $PM_{2.5}$ concentration and location of the smoke plume downwind. Criteria were identified when managing Rx smoke and the strengths, weaknesses, and implications were discussed of the Rx programs. The geographic analysis demonstrated quantitatively how much area may be impacted with minimal apparent benefit. This research should provide a clearer spatial picture of the smoke management barriers associated with Rx on private woodlands in Virginia. These results should be a useful tool in developing a regulatory environment that encourages Rx when the conditions are optimal. We conclude with future recommendations for Virginia.

Acknowledgements

During the three years I spent at Virginia Tech, I had the privilege of working with two outstanding members of the Forest Resources and Environmental Conservation Department. I owe a debt of gratitude to my co-advisors Steve Prisley and Shep Zedaker. Without their assistance and guidance I would not be where I am at today. I would also thank my other committee member Linsey Marr with the Civil and Environmental Engineering Department. Without her assistance on the air sampling part of my research, this research would have not been completed.

I also thank Jan and Kit Kennedy with the Acorn Alcinda Foundation for their funding support and use of their tree farm for one of our study sites. This research could not have happened without their gracious support and use of the Kennedy Tree Farm. I also thank their county forester Gwenn Tyler and their private forestry consultant Bob Warring. Their help at the Kennedy Tree Farm greatly eased the process of selecting the correct stand for our burn there.

The Virginia Department of Conservation and Recreation's Division of Natural Heritage was extremely helpful in completing this project. In particular Claiborne Woodall and Bryan Wender, who allowed me to collect data off of two their prescribed burns. Bryan provided me with information about Difficult Creek and familiarized me around the preserve and showed me other potential preserves where I could collect data off of one of their burns. Claiborne was very courteous and allowed me to collect data on the prescribed burns he managed and gave me many insights on research.

I greatly appreciate the help from the Prescribed Fire Managers, Forest Protection Chiefs, and Fire Weather Supervisors from the forestry agencies in Virginia, South Carolina, Georgia, Florida, and Arkansas. They were very helpful in answering my questions and getting me the data I needed to complete my research. I graciously thank Fred Turck (Virginia), Darryl Jones (South Carolina), Scott Reed (Arkansas), John Saddler (Florida), and Neal Edmondson (Georgia).

I also owe a debt of gratitude to the Virginia Tech Wildfire Crew for their assistance on our prescribed burns and Steve Gaines for his help in the field data collection. These graduate and undergraduate students' help was not required and I appreciate their time they gave me.

Finally, I wish to thank my family. My parents Mike and Rixey, sister and brother-in-law, Michelle and Ossie and my brother Billy, who were always there for me and supported me when I needed them.

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Chapter One

OBJECTIVES AND JUSTIFICATION

Prescribed burning has been accepted as an important silvicultural management tool, and the Federal government has formally recognized its use in wildfire management (USDI and USDA, 1995). The use of prescribed fire has been increasing on federal lands (Yoder, 2002) and nongovernmental organizations (NGO) like The Nature Conservancy (TNC) (TNC, 2010). Haines et al. (1998) reported that from 1985 to 1994 the number of national forests using prescribed fire increased 76 percent. In 1995 prescribed fire was applied to about 900,000 acres of Federal land and it increased to 2.4 million acres in 2010, peaking at 3.1 million acres in 2007 (Yoder, 2002; NIFC, 2011). TNC has significantly increased its use of prescribed fire as well. TNC averaged less than 15,000 acres between 1988 and 1992 (Figure 1.1). Their yearly average acreage burned increased to over 120,000 between 2008 and 2010 (TNC, 2010).

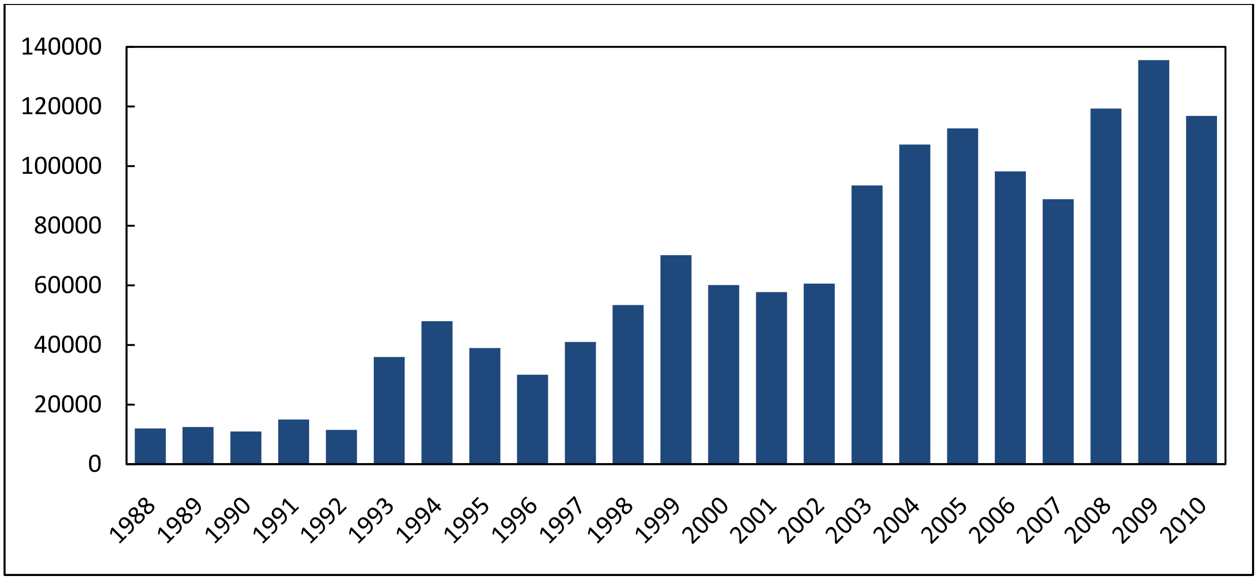


Figure 1.1. Amount of acres prescribed burned in the U.S. by the The Nature Conservancy from 1998 to 2010. Adapted from TNC, 2010.

Despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints such as air quality regulations and liability issues relating to smoke intrusions (Haines et al., 2001). Among these are regulations that have restricted the downwind impacts of smoke from prescribed fires. Since prescribed burning has become increasingly subject to various smoke management and air quality regulations at the federal, state, and local level, private landowners continued use of prescribed burning has emerged into a complex situation. The concern for forest managers is the possibility that these laws have produced unmanageable and unneeded regulation of prescribed fire. The regulation of private forestland has raised the fundamental question of how far the public may go in restricting the rights of private landowners to use their land (Cubbage, 1995).

The problem is that while prescribed burning is increasing on federal lands, these constraints have restricted the use of prescribed burning on private lands. Gass (2009) reported in a Colorado study aimed at reducing the barriers to using prescribed fire on private lands that 25 percent of Colorado's forests are privately owned, yet they only account for one percent of the states planned prescribed burns in a year. These private forests account for about 60 percent of the state's forests needing fuel reduction and in 2006 only 320 acres were actually burned by private land managers (Gass, 2009). Prescribed burning on private lands (by acres) in Virginia remained fairly constant from 1976 to 1992 averaging about 27,000 acres a year (Fred Turck, VDOF, Waverly, VA, 2011, personal communication). However, private landowners have likely felt the constraints of the increasing regulations, and prescribed fire's use has dropped considerably in the past decade. From 2002 to 2008 private lands in Virginia have only averaged 6,424 acres a year of prescribed burning. Whereas prescribed burning on national forests in Virginia have increased their acreage from 655 acres in 1986 to 21,755 acres in 2008 (Fred Turck, VDOF, Waverly, VA, 2011, personal communication). This discrepancy in the use of prescribed fire by private landowners when compared to the federal government and NGO is likely the result of the barriers associated with private landowner's use of prescribed fire.

One of the biggest barriers for private landowners using prescribed fire is compliance with smoke management regulations and the confusing regulatory situation it presents (Gass, 2009). To maintain prescribed burning as a viable silvicultural tool for private landowners, we need better estimates of the smoke effects from prescribed burning operations and need to engage policy makers, agency personnel, and private citizens in the benefits of prescribed fire. With this knowledge we can facilitate improved regulatory decisions recognizing prescribed fire as an effective tool.

Open burning in Virginia is regulated at the state level by the State Air Pollution Control Board (SAPCB) and the Virginia Department of Forestry is involved in the smoke management aspect (VDOF) (VDOF, 1998). However, the state has left it to the local governments to enforce, which has created inconsistencies in open burning regulations across the state and has contributed to the confusing regulatory situation for private landowners and private forestry industries (Mortimer et al., 2006). Local governments have enacted prescribed burning ordinances with the intention to protect water quality, public safety, visual quality, or other amenities (Prisley et al., 2006). However, these municipalities usually do not have a forester or land manager employed. Their intentions are to protect the public and the environment, but have produced unintentional consequences to dangerous fuel build up and have limited private landowner's abilities to practice forest management (Prisley et al., 2006).

Prescribed burning has produced emissions that harm the public health. The emissions of greatest concern from prescribed fires were particulate matter under 2.5 microns ($PM_{2.5}$) in diameter contained in the smoke plume. Virginia has recommended that burn managers complete a smoke management plan to avoid impacting sensitive targets within a 10 mile radius. However, the smoke management plan is not required by law and is not related to the actual science behind the development of a smoke plume. This could produce two consequences: (i) the landowners/burn managers may have taken the recommendation as law but are not actually regulated by it, and (ii) the recommended smoke management plan could place a 'blanket' over the sensitive targets within 10 miles when science and research could possibly show that the distance to sensitive targets affected could be far less. To continue the use of prescribed burning as a silvicultural tool, regulatory ordinances must consider the ability of the smoke to rise, mix, and disperse across the landscape. To determine smoke dispersion, models have provided the information needed to simulate how emissions can be lofted into the atmosphere (Lahm, 2006). The use of smoke prediction models with Geographic Information Systems (GIS) has facilitated better smoke management decisions. With enhanced smoke prediction and smoke impact tools, ordinances can be developed that support prescribed burning under the correct conditions.

Geospatial models combined with GIS have provided a means to assess the spatial extent of smoke impacts from burning and a way that localities in Virginia can be identified that are subject to these regulations, and where burning is precluded. Identification of the localities in Virginia that have prohibited or limited controlled burning has helped to uncover the regulatory barriers to prescribed burning in the state. These regulatory barriers are a generic, one-size-fits-all regulation. This research project can help us move away from these broad regulations. It can promote a regulatory environment in which scientific tools and knowledge are used only to prohibit activities for which the evidence suggests there will be adverse consequences. A model for predicting smoke plumes has helped us predict those consequences, and has allowed us to specifically identify conditions under which burning can be conducted without negative impacts.

The Virginia Department of Forestry (VDOF) has not offered many services for prescriptive burning, and the use of fire as a forest management tool has been addressed differently across the state. The majority of localities did not address prescriptive fires, others have exemptions, and some have required the use of permits or have prohibited it completely (Mortimer et al., 2006). What we did not know are the areas/ownerships that are totally precluded from burning, the ones that have significant barriers to the use of prescribed burning, and the most significant barriers and ways they can be overcame. This gap in the knowledge base was an important problem, because it has prevented prescribed burn managers and private landowners from effectively using prescriptive fires as a forest management tool.

The *long-term goal* of our research was to maintain and increase the ability to use prescribed fire as a forest management tool in Virginia and provide information to aid the VDOF to address prescribed burning in a more holistic fashion across the state. The *overall objective* of this study was to improve our ability to estimate the effects of smoke from prescribed burning operations to facilitate better regulatory decisions. The *specific objectives* were to: (i) use a geospatial model for predicting downwind impacts of smoke in conjunction with GIS to quantify smoke impacts ($PM_{2.5}$ concentrations); (ii) identify the impacts of smoke management policy on the use of prescribed burning in southeastern states; and (iii) demonstrate how a smoke dispersion model can generate improved regulatory decisions with regard to prescribed burning and smoke management. While not a direct objective of this proposal, we feel this study could lead eventually to the development or use of a model for predicting downwind impacts of smoke from prescribed fires that can be used as a management tool by prescribed burn managers.

Our underlying hypothesis was that geospatial models in combination with geographic information technology could be used to accurately predict $PM_{2.5}$ and visibility impacts across the landscape. This hypothesis was based on several months of research demonstrating that the methodology used in Virginia to address prescriptive burning smoke management may be too prohibitive to allow the continued use of prescribed burning as a silvicultural tool for private landowners. The VDOF smoke management plan is a recommendation meant to be followed by burn managers and landowners. This recommendation has not been based on entire science behind smoke production or the likely smoke plume and could be understood by private landowners as a law. New methods and models developed over the past decade for predicting smoke impacts from fires have provided a means to overcome the restrictions limiting the use of controlled burns (Lahm, 2006). GIS has also helped to identify the private land area affected by regulations that restrict prescribed burning.

This report is separated into three parts. It consisted of ***Chapter 2 – A Pilot Validation of the Smoke Dispersion Model VSMOKE***. We tested VSMOKE's accuracy in predicting $PM_{2.5}$ concentrations downwind from prescribed burns and its precision in predicting the projected smoke plume with VSMOKE-GIS. This information aided us in quantifying smoke impacts from prescribed burning and helped us in the second part of our research, ***Chapter 3 – Smoke Management Policies*** and their impact on the ability to use prescribed burning. We identified the policies and restrictions that affect Virginia's private landowners and reviewed other states' policy models and their implications for prescribed burning. This is be followed by ***Chapter 4– A Case Study and Geographic Analysis*** that helped us to quantify how much forest land that is potentially available for burning in Virginia under a hypothetical burn situation.

Chapter Two
PILOT VALIDATION OF VSMOKE-GIS

2.0 – Background

Prescribed burning has been well accepted by professional forest managers as a valuable silvicultural tool to reduce the damage to the environment from wildfires (Haines et al., 2001) and to manage and maintain critical animal and plant habitats. However, despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints associated with increasing residential development and wildland fires becoming in contact with the Wildland-Urban Interface (WUI), air quality and other environmental regulations, and liability issues relating to smoke intrusions (Haines et al., 2001). The most important constraints that have limited the effective use of prescriptive fires on private woodlands are regulatory barriers associated with smoke management.

As the use of prescribed fire continues to increase on federal land (Yoder, 2002), the tools available to fire managers to assess smoke impacts and improve fire management and air quality decisions have grown rapidly (Lahm, 2006). One such model is VSMOKE, a FORTRAN 77 computer program designed as an atmospheric dispersion model (Lavdas, 1996). VSMOKE is a Gaussian dispersion model that estimates the effects of a prescribed burn on air quality and visibility. VSMOKE-GIS is a model based on the same calculations as VSMOKE but allows for the outputs to be displayed in ESRI's ArcGIS software (Lavdas, 1996).

The problem is that air quality standards are becoming more stringent, and there is a need for more sophistication and confidence in the prediction of smoke impact assessment models (Lahm, 2006). However, as Lahm (2006) described, one of the challenges for smoke dispersion models was to characterize their accuracy in predicting smoke plumes, the concentration of pollutants, and the duration of impacts. There have been no studies to validate the predictions of VSMOKE and very few, if any, for other smoke dispersion models (Bill Jackson, U.S. Forest Service, Asheville, NC, 2009, personal communication). For fire managers and air quality specialists to have confidence in smoke dispersion models, there is a need for validation through field observations and measurements of smoke from prescribed burns (Lahm, 2006).

The *main goal* of Chapter Two of this study was to conduct a pilot validation of the model VSMOKE-GIS to characterize its accuracy in predicting downwind impacts of smoke in conjunction with GIS to quantify smoke impacts ($PM_{2.5}$ concentrations). There was one main objective investigated in Chapter Two of the study. ***Objective 2.1 focused on the pilot validation of the model VSMOKE-GIS.*** This included characterizing VSMOKE's accuracy in predicting the concentration of $PM_{2.5}$ downwind from the prescribed burns. ***Our working hypothesis was that VSMOKE-GIS will overpredict the $PM_{2.5}$ concentrations downwind from***

the prescribed burns, because it is a planar model used in uneven terrain where more turbulence and mixing occur.

To achieve the objective of validating VSMOKE, Chapter Two of this research was divided into two phases, (1) conducting several prescribed burns, and (2) evaluating VSMOKE's predictions against field observations from the burns. The first phase of Chapter Two focused on selecting stands for the prescribed burns, collecting field data (before, during, and after the burn), and conducting the prescribed burn. The second phase of Chapter Two focused mainly on applying VSMOKE and characterizing its accuracy in predicting $PM_{2.5}$ concentrations downwind from the burns.

2.1 – Literature Review

Prescribed Burning

McNabb (1995) defined prescribed burning as fire applied in a skillful manner to an area, under a particular set of weather conditions for a specific purpose to achieve certain results. Prescribed burning is accepted by professional forest managers as a valuable silvicultural tool to reduce the wildfire damage to the environment (Haines et al., 2001). A study at Fort Benning, Georgia showed a reduction of wildfires concurrent with the increase use of prescribed burning (Figure 2.1) (GFC, 2008). When used properly, low-intensity fires like prescribed burns have been shown to have little adverse effect on the chemical and physical properties of soil or stand composition. Fewer emissions on a per acre basis are released into the atmosphere compared to wildfires (Wiedinmyer and Hurteau, 2010). However, despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints such as air quality and other environmental regulations, and liability issues relating to smoke intrusions and escaped fires (Haines et al., 2001). When fire is excluded from an ecosystem, it can have a profound effect on the structure of those ecosystems and their economic productivity (McNabb, 1995).

The application of prescribed fire is determined by its objective – a desired outcome or future condition (Vose, 2000). Prescribed fire can have many management objectives. One prevalent objective is to reduce fuel loads and the possibility of threats from wildfires. Other objectives include site preparation, improvement of wildlife habitat, disease control, increase fodder production, appearance, and access (McNabb, 1995). These objectives are used to achieve short term and/or long term ecosystem conditions. For example, returning the forest conditions to those prior to human influence or pre-European settlement, altering the structure and function of the ecosystem, creating and maintaining unique habitats, and increasing the value of commercial species (Vose, 2000).

Prescribed burning is an integral part of silviculture in the United States for forest management, and is recognized as one of the most cost-effective silvicultural tools for pine management (McNabb, 1995). When prescribed fire is applied correctly, its effects on the environment are minimal. Ecosystems have evolved mechanisms to handle repeated burning. Trees resist the overall impacts of burning by developing thick bark, recovering/sprouting quickly, and cone serotiny (Vose, 2000). Although these mechanisms help deal with the effects of prescribed burning, much depends on the intensity and severity of the prescribed burn.

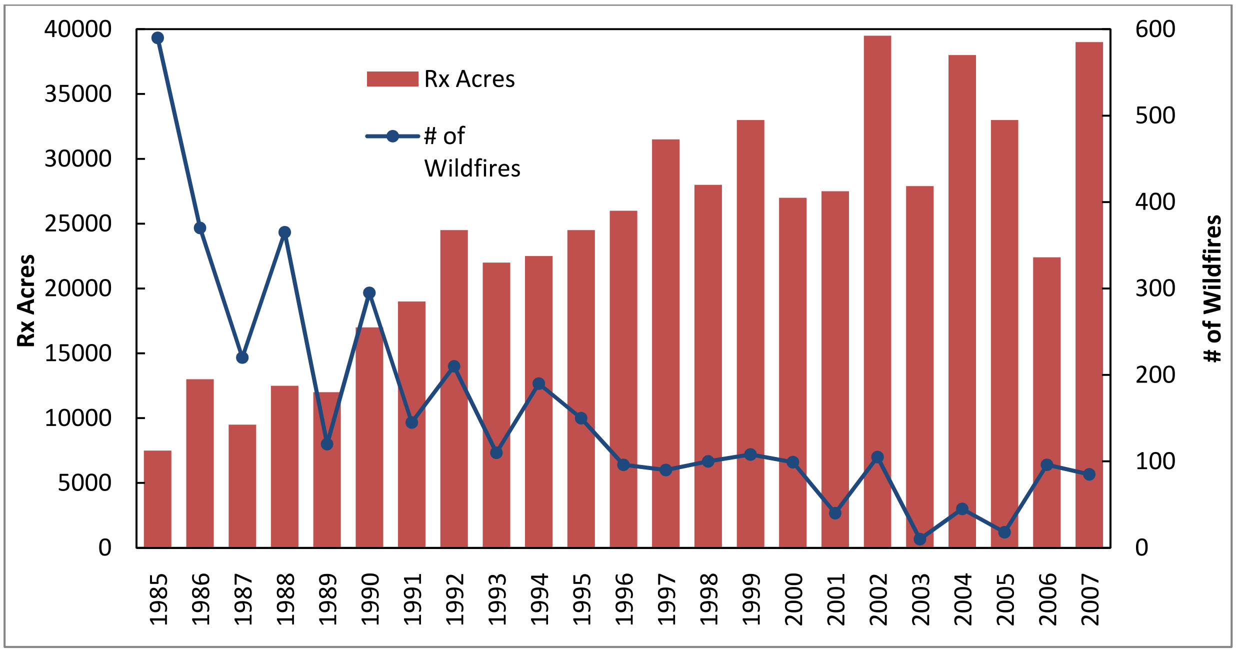


Figure 2.1. Reduction in the number of wildfires concurrent with an increase in the amount of acres prescribed burned at Fort Benning, Georgia. Adapted from GFC, 2008.

When the silvicultural objectives have been formulated and the decision has been made to prescribe burn, the next step is to establish the techniques that will be used (Crow, 1973). The techniques employed depend greatly on the objectives of the burn which dictate the desired fire behavior. Fire behavior can be affected by the season of the burn, weather, ignition technique, amount of fuel, fuel characteristics, and topography (Brender and Copper, 1968; Kauffman and Martin, 1989). Summer fires prevail from June through October and winter ones from November through March (Crow, 1973). Summer fires have been found to produce higher flame lengths and fireline intensities and, thus, greater fuel consumption is associated with summer fires (Brender and Copper, 1968; Kauffman and Martin, 1989). This can be attributed to generally lower fuel moisture contents during the summer. Brender and Copper (1968) found that summer burns were also more effective at controlling understory hardwood stems in a Piedmont Loblolly Pine stand in Georgia. Summer burns are hot, dangerous and more effective, and are generally used for site preparation and hardwood control (Crow, 1973). Fuel reduction burns are usually carried out in the winter.

Ignition techniques can affect the fire behavior, fuel consumption, emissions, and the cost of the fire (Crow, 1973; Brender and Copper, 1968; Johansen, 1987). Backfires have a slower spread rate, are safer, cooler, consume fuel more completely, emit fewer pollutants, and are more costly compared to head fires (Crow, 1973). However, Brender and Copper (1968) found that strip-head fires were less costly, burned faster, and generally less subject to wind changes in hilly terrain compared to backfires. For controlling hardwood understory, Brender and Copper (1968) did not find any significant differences between backfires and strip head fires.

Brender and Copper (1968) found that the total amount of fuel had little effect on the rate of spread, except where there were breaks in continuity for understory burns. They concluded that relative humidity, burning methods, and topography affects spread rates more. Relative humidity also affects the fuel moisture content, which can determine the amount of fuel consumed during the burn (Brender and Copper, 1968; Kauffman and Martin, 1989). A higher relative humidity will increase the fuel moisture content. With low fuel moisture content a higher amount of fuel will be consumed and vice versa (Kauffman and Martin, 1989). Fuel moisture contents below 10 percent or relative humidity below 20 percent produced erratic and unreliable fire behavior (Brender and Copper, 1968). When fuel moisture was above 20 percent and relative humidity above 60 percent, burning efficiency decreased and costs rose. Brender and Copper (1968) also found that in summer burns where loblolly pine needles dominated the litter, fuel moistures and relative humidity at the higher end could be tolerated, but where hardwood litter was dominant, conditions at the lower end were necessary.

<u>Smoke Management</u>

Due to the smoke and emissions released during prescribed burning operations, smoke management must be considered in every prescribed burning plan (Turck, 2009). Achtemeier (2009) defined smoke management as the action taken by a land manager to minimize the environmental impact of smoke. According to the VDOF's Guide to Prescribed Burning in Virginia (Turck, 2009) the three main objectives of smoke management are avoidance, dilution, and emission reduction. A prescribed burn manager wants to avoid smoke-sensitive areas, disperse and dilute the smoke before it reaches the smoke-sensitive areas and reduce the smoke (emissions) produced from the burn site. As the use of prescribed burning continues to increase, the need for better smoke management is evident. This is compounded by the increase in the populations living within the WUI and has resulted in more people being exposed to smoke (Robison, 2007). The combination of increased burning and public smoke exposure has created a need for improved predictive tools for smoke production, dispersion, and weather (Robison, 2007, Lahm, 2006).

Smoke from prescribed burns can adversely impact air quality, visibility, and can cause health problems for sensitive individuals. Prescribed burns produce smoke that is composed primarily of water vapor, however it produces pollutants that can harm the public (Turck, 2009).

Pollutants that are released during burning include particulate matter, hydrocarbons, carbon monoxide, nitrogen dioxide, and sulfur dioxide. With respect to public health, particulate matter is the pollutant of concern. The other pollutants are released in negligible amounts or are diluted in the open air (Turck, 2009). Particulate matter can greatly reduce visibility. With respect to visibility the major concern for burn managers is the possibility of degrading the visibility in a Class I Air Shed – EPA designation of a pristine area, where little deterioration of visibility is allowed (Wark et al., 1998). Class I Air Sheds include wilderness areas and some national parks. The Grand Canyon Visibility Transport Commission (GCVTC) found that emissions from wildland fire and prescribed fire are likely to be the single greatest impact on visibility in a Class I Air Shed (Sandberg et al., 2002). The GCVTC also stated that during intense fire activity, smoke from wildland fires is likely to make visibility days for the Grand Canyon in the lowest 20 percent.

Particulate matter not only affects visibility, it can also affect the health of certain individuals. The particulate matter of concern are those particles smaller than 2.5 microns in diameter ($PM_{2.5}$). These particles are small enough in diameter to be breathed in and can cause respiratory problems (CDPH, 2008). Wildfire smoke also contains significant quantities of other respiratory irritants (formaldehyde and acrolein) which compound the effects of $PM_{2.5}$. It also causes eye irritation and can aggravate the breathing of sensitive individuals (VDOF, 1998, CDPH, 2008). Healthy individuals are usually not affected by the smoke from prescribed burns due to the generally short exposure. Sensitive individuals are affected most – those with asthma or respiratory disease, cardiovascular disease, elderly, children, pregnant women, and smokers (CDPH, 2008).

Regulations concerning prescribed burns originate from air quality laws, forest fire control laws, laws concerning property damage and personal injury from escaped fires, and environmental laws such as the Endangered Species Act and the Clean Water Act (Haines and Cleaves, 1999). Of these regulations air quality laws affect prescriptive burning the most. As more people move into the WUI, tighter regulations have been enacted for prescribed burning. An increased interest has developed in forestry burning as an air pollution source and has forced governments to regulate prescribed burning within their jurisdiction. These air quality regulations, though often not severe, are usually only enforced upon complaint (Hauenstein and Siegel, 1980). Examples of air quality regulations that pertain to prescribe burning include obtaining a permit, prohibiting burns near roads and inhabited areas, restrictions on windrow burning, prohibiting the use of heavy, oil based starter fluids, restrictions on time of day and season of burn, and prohibiting activities that impair visibility (Haines and Cleaves, 1999).

Table 2.2. EPA's $PM_{2.5}$ Air Quality Index values, level of health concern, and their corresponding concentrations for 1-hr and 24-hr.

$PM_{2.5}$ 24-hr Avg. Concentration (µg/m^3)	$PM_{2.5}$ 1-3 hr Avg. Concentration (µg/m^3)	Index Value	Level of Health Concern
0 – 15.4	0 – 38	0 – 50	Good
15.5 – 35.4	39 – 88	51 – 100	Moderate
35.5 – 65.4	89 – 138	101 – 150	Unhealthy for Sensitive Groups
66.5 – 150.4	139 – 351	151 – 200	Unhealthy
150.5 – 250.4	352 – 526	201 – 300	Very Unhealthy
250.5 +	> 526	301 – 500	Hazardous

Throughout the United States prescribed fire is increasingly scrutinized and regulated (Cubbage, 1995). The hazards associated with prescribed fire are a result of the increasing residential development and wildland fires becoming in contact with the WUI, and the threat of having smoke impacts on these areas and the individuals there. Regulations for these hazards can be attributed to the increasing social conflicts between urban and rural residents in rapidly urbanizing communities (Martus, 1995). The most prominent hazards that arouse conflicts between urban and rural residents are: human health hazards, highway accidents associated with smoke, probability of an escaped fire resulting in personal injury or property loss (Haines and Cleaves, 1999). These hazards are the driving force behind prescribed fire regulation. Coupled with the potential liability associated with prescribed fire smoke and escape, hazards are the primary factor for litigation (Sun, 2007).

Smoke Models

Smoke emission and/or dispersion modeling is a well-defined system that can communicate the impact of smoke on ambient air quality (EAMC, 2006). There are three main types of smoke/air quality models, including: (i) emissions production models, (ii) simple approximation systems, and (iii) dispersion models. Emission production models predict the total amount of pollutants produced from a burn, but they do not predict the movement of pollutants through the atmosphere (EAMC, 2006). Examples of emissions production models include the Fire Emission Production Simulator (FEPS) and Emissions Production Model (EPM). Simple approximation systems give the user a relative index to indicate the potential impacts prescribed fire smoke may have on a particular site (EAMC, 2006). An example of a simple approximation system includes the ventilation index. Dispersion models predict the smoke and pollutant concentrations as they move through the atmosphere and can be used to communicate the potential impacts to health and visibility (EAMC, 2006). Examples of dispersion models include VSMOKE, CALPUFF, and DaySmoke.

Smoke dispersion models are valuable tools in smoke management, especially for screening and planning (Breyfogle and Ferguson, 1996). Smoke dispersion is considered a second-order fire effect, which occurs over a long time frame – days, months, or years (Reihardt et al., 2001). However, to model smoke dispersion, it is necessary to have estimates of smoke production, a first-order fire effect that occurs at the time of the fire or within seconds or minutes. Smoke production is often modeled at the stand level. However, as smoke disperses, it moves spatially so that smoke dispersion models generally have a broader spatial extent (Reihardt et al., 2001). Spatial extent is used to group the models into local models (day and night) or regional models. Regional models predict the impacts of prescribed fire smoke across large areas (hundreds of miles), whereas local models predict the impacts of smoke locally (generally less than 70 miles). Examples of regional models include BlueSky and Southern Smoke Simulation System (4S). Local daytime models include VSMOKE, CALPUFF, and DaySmoke (Achtemeier, 2009). One of the more deadly smoke impacts, in terms of personal injury, is the movement of smoke at night. There are a few models that have been produced to predict the movement of smoke at night on the local scale; they include PB-Piedmont and Superfog (Achtemeier, 2009).

Dispersion models can be further subdivided based on how the smoke is dispersed in the model. They include plume, puff, particle, and grid models (EAMC, 2006). The application of the model dictates the type of model used. Plume models are used generally in flat terrain where concentrations are evaluated near the burn. Puff models can be used in complex terrain with variable weather and where the information desired about long-range transport of pollutants is achievable (EAMC, 2006). Particle models are similar in application to puff models but require trajectory information. Grid models are generally used at the regional scale and can simulate many fires at one time (EAMC, 2006).

Of the above models only VSMOKE is complete and operational (Achtemeier, 2009). Although VSMOKE is complete and operational there are no studies to validate it and very few, if any, for other smoke dispersion models (Bill Jackson, U.S. Forest Service, Asheville, NC, 2009, personal communication). This illustrates one of the challenges for all smoke dispersion and impact models – being able to characterize their accuracy of predicting smoke trajectories, concentration of pollutants, and duration of impacts (Lahm, 2006). Long term investment in these models' development and modifications needs to continue to better assess smoke impacts from prescribed burns (Lahm, 2006).

VSMOKE is a smoke screening model developed by the Forest Service for application in the Southeast (Bill Jackson, U.S. Forest Service, Asheville, NC, 2009, personal communication). It is a steady-state, local daytime smoke dispersion model that estimates the effects of prescribed burning on air quality and visibility. It predicts downwind concentrations of particulate matter at 31 fixed distances, and how far and how well a person may see through the smoke plume at each distance (Jackson et al., 2009; Achtemeier, 2009). VSMOKE has an interface with FEPS to get estimates of the amount of fuel consumed and the emissions factors. The emission factor is used along with the amount of land burned, fuel load, and duration of impact to obtain the emission rate. This emission rate can then be combined with meteorological data to obtain estimates of the effects of prescribed burning on air quality.

Enhanced fire management decisions come from increased knowledge about smoke emissions and models that project downwind smoke impacts (Lahm, 2006). Smoke projection models, combined with GIS tools and meteorological data, allow better prediction of the projected smoke plume and its impacts on the surroundings. Early smoke management models used fixed weather information to provide simplistic estimates (Lavdas, 1996). These models are being scrutinized as more people come into contact with the WUI, the decreasing tolerance of smoke, and tighter air quality regulations (Goodrick et al., 2006). For models to effectively predict smoke plumes and their impacts, they must simulate how fire emissions are lofted into the atmosphere by considering complex meteorological data, fuel consumption, emissions, and heat release characteristics of prescribed burns (Lahm, 2006). To effectively use a model to predict smoke dispersion and impacts, validation through field measurements of smoke from prescribed burns should be carried out to characterize the accuracy of their prediction of smoke trajectories, the concentration of pollutants, and the duration of impacts (Lahm, 2006).

<u>Model Validation</u>

A model can be defined as an abstract representation of reality by means of mathematical equations in a computer program to simulate a process, predict an outcome, or characterize a phenomenon (Prisley and Mortimer, 2004; Helms, 1998). Prisley and Mortimer (2004) acknowledge that it is commonly accepted in the scientific literature that models are essential tools in many areas of environmental management and regulation. When models are used for developing policies and implementing regulations, there is a need for some form of evaluation of the model's accuracy and reliability (Prisley and Mortimer, 2004). The model developers and users, the decision makers basing their decisions on the model results, and the people affected by the decisions made from such models all have the right to know whether a model and its results are correct (Sargent, 1998). Schlesinger et al. (1979) defined model validation as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model."

Models are developed generally for a specific purpose or application; its validity should be determined with respect to that purpose (Sargent, 1998). There is no universal approach to validating a model, and it is often too expensive and time consuming to determine that a model is absolutely valid (Prisley and Mortimer, 2004; Sargent, 1998). A model is considered valid when adequate tests have been conducted in the context of its purpose, domain, and structure and sufficient confidence is obtained in its intended application (Sargent, 1998; Beck et al., 1997; Monserud, 2003).

There are three basic approaches to determine if a simulation model is valid or invalid. The most common approach is for the development team to make the decision whether the model is valid. This approach is a subjective decision based on the results of various tests and evaluations (Sargent, 1998). Another approach uses a third party that is independent of the developers and anticipated users called independent verification and validation (Sargent, 1998). This approach produces a subjective decision as well and is generally used when there is a large cost associated with the problem the simulation model is being used to help (Sargent, 1998). The last approach is to use a scoring model where scores are assigned subjectively to the various aspects of the validation process and combined to determine an overall score for the simulation model (Sargent, 1998). The threshold for a particular passing score is determined before validation.

There are three aspects of the modeling process that are relevant to validation: the conceptual model, the computerized model, and the operational aspect (Sargent, 1998). Conceptual model validity or composition of a model refers to testing the theories and assumptions in the mathematical/logical/verbal representation of the problem entity for the intended purpose of the model (Sargent, 1998; Beck et al., 1997). The conceptual model or composition is an internal measure of model reliability, and its validity is usually addressed by scientific peer review (Prisley and Mortimer, 2004). The computerized model is the conceptual model implemented on the computer. It is verified by ensuring the computer programming and implementation is correct (Sargent, 1998). Operational validity or performance refers to the process of determining the accuracy and usefulness of the model's outputs for its intended purpose and applicability (Sargent, 1998; Beck et al., 1997). The operational or performance is an external measure and its validity is usually addressed by statistical comparisons with field data (Prisley and Mortimer, 2004; ASTM, 2000). Most of the evaluation and validation testing takes place here (Sargent, 1998). Prisley and Mortimer (2004) identified a fourth approach that appears regularly in the literature, sensitivity analysis. Sensitivity analysis examines the degree of variation in the model output that is affected by the variation in the input parameters (ASTM, 1992). Sensitivity analysis provides insights into model robustness, model parameters, and variability of model outputs (Prisley and Mortimer, 2004).

Model validation is critical in the development of a simulation model (Sargent, 1998). When models are used to inform agency decisions or promulgate regulations, there will usually be judicial and public scrutiny; a model used for a purpose other than intended could produce poorly designed policies (Prisley and Mortimer, 2004). When ecological and environmental models are applied in the regulatory environment, they can have significant impacts on policy development, economics, regulations, and social concerns (Prisley and Mortimer, 2004). These models must be able to withstand both scientific and judiciary review.

2.2 – Research Methods

The pilot validation effort was divided into two phases: conducting the prescribed burns and evaluating VSMOKE's predictions against field observations from the burns. Initial efforts in conducting the prescribed burns phase focused on study site and stand selection. The second task in conducting the prescribed burns included intensive field data collection of fuel loading. Fuel loading was collected using modified procedures described by Brown (1974). The last task of phase one consisted of carrying out the prescribed burns.

Using the data collected in phase one, the pilot validation of VSMOKE focused on testing our underlying hypothesis that VSMOKE will overpredict $PM_{2.5}$ concentrations downwind from the prescribed burns. Validation of VSMOKE focused initially on locating sites to collect $PM_{2.5}$ concentrations. Locations to sample $PM_{2.5}$ were based on the predicted smoke plumes from VSMOKE-GIS and were modified in the field to ensure data collection as the wind shifted. Information collected from sampling $PM_{2.5}$ concentrations from the prescribed burns was compared with the predicted values at those sampling sites from the model VSMOKE-GIS. This comparison allowed us to complete the second task in phase two –evaluate VSMOKE and VSMOKE-GIS's predictions against field observations from the burns. This enabled us to characterize VSMOKE's accuracy in predicting downwind smoke impacts from prescribed burns.

2.2.0 – Phase 1: Conducting the Prescribed Burns

2.2.0.0 –Introduction- The ***goal*** of the research conducted in pursuit of phase one was to successfully monitor multiple prescribed burns, producing enough smoke to characterize VSMOKE's accuracy while still minimizing the downwind smoke impacts to local residents and communities. It was imperative that the burns were conducted under the appropriate meteorological conditions to produce enough smoke ($PM_{2.5}$ concentration) that would register with the aerosol measurement instrument. We still needed to ensure that the weather permitted good atmospheric dispersion, so that: (i) smoke intrusions and visibility impairments would be minimal to prevent air pollution, and (ii) smoke would disperse and dilute before it reaches smoke-sensitive areas. Our ***approach*** was first to collect pre-burn field data on fuel loading for the selected stands. Then we conducted the burn and collected post-burn field data in the same manner as the pre-burn data. This data was then used to provide more accurate measurements of the amount of $PM_{2.5}$ produced ($\mu g/m^3$) per amount of fuel burned (tons/acre). Doing this improved our understanding of estimates of $PM_{2.5}$ released from prescribed fires under given weather conditions. These results should have a significant contribution to prescribed burning smoke management.

2.2.0.1 – Task I, Study Site and Stand Selection- We monitored several prescribed burns carried out in Virginia to provide the smoke data to pilot validate VSMOKE-GIS. Since VSMOKE-GIS is a decision support system for prescribed burn operations that is used on flat to rolling terrain (Harms and Lavdas, 1997), the prescribed burns were executed on similar terrain. The study sites were located in the Virginia counties of Halifax and Buckingham.

The first validation burn took place at Difficult Creek Natural Area Preserve just east of the town of Scottsburg, Virginia (Figure 2.1). The preserve is 818 acres and was once grassy and prairie-like with scattered pines and hardwoods where fire played a role in its natural landscape before European settlement. Since European settlement the natural landscape has been displaced by loblolly pine stands. The preserve is actively managed for several rare plants with prescribed fire to re-establish the open grassy conditions of its pre-settlement past. There are numerous interior forest roads around each unit that provide access to the units and for firelines. The DCR planned to burn Unit 6 based on their management objectives. Unit 6 has woods roads around the northeast and northwest boundaries and a state route and private road to the southeast and southwest respectively. The unit is 54 acres and located on the western side of the preserve (Figure 2.1). The unit has never been burned since the DCR obtained it and consists of mixed hardwoods and loblolly pine with mostly Sweet Gum and Red Maple. The DCR was in control of the prescribed burn and was in charge of locating downwind sensitive sites, notifications and the decision to burn or not burn.

One of the burns took place on the Kennedy Tree Farm in Buckingham County, just outside the town of Dillwyn. It is 1,300 acres and is actively managed for loblolly pine. Among the various stands are several loblolly pine stands in different successional stages, hardwood stands, and loblolly pine and mixed hardwood stands (Aksamit, 2008). There are numerous interior forest roads that provided access to the stands as well as many streams; both provided firelines with minimal effort. When selecting the stands to burn at the Kennedy Tree Farm, we looked for stands that had been thinned and did not contain a dense understory to avoid dangerous fuel build up and the possibility of uncontrolled fire. Ideal stands were 20 to 40 acres that were at least 18 years old. It was preferred that the stands were at least five years from harvest to prevent the degrading of saw wood during the burn. We selected Stand 13, based on the Kennedy's management strategy and silvicultural objectives. Stand 13 is 39.5 acres and is located on the southeast portion of the Kennedy property (Figure 2.1). We did not plan to burn the entire stand. The stand has a woods road running through it and the section we planned to burn was 29 acres with the woods road as a fire line. However, with limited crew members available the day of the burn we were only able to burn 13.7 acres. Stand 13 is a Loblolly Pine stand with some understory hardwoods. The stand was planted in 1974 and was last thinned in 1996.

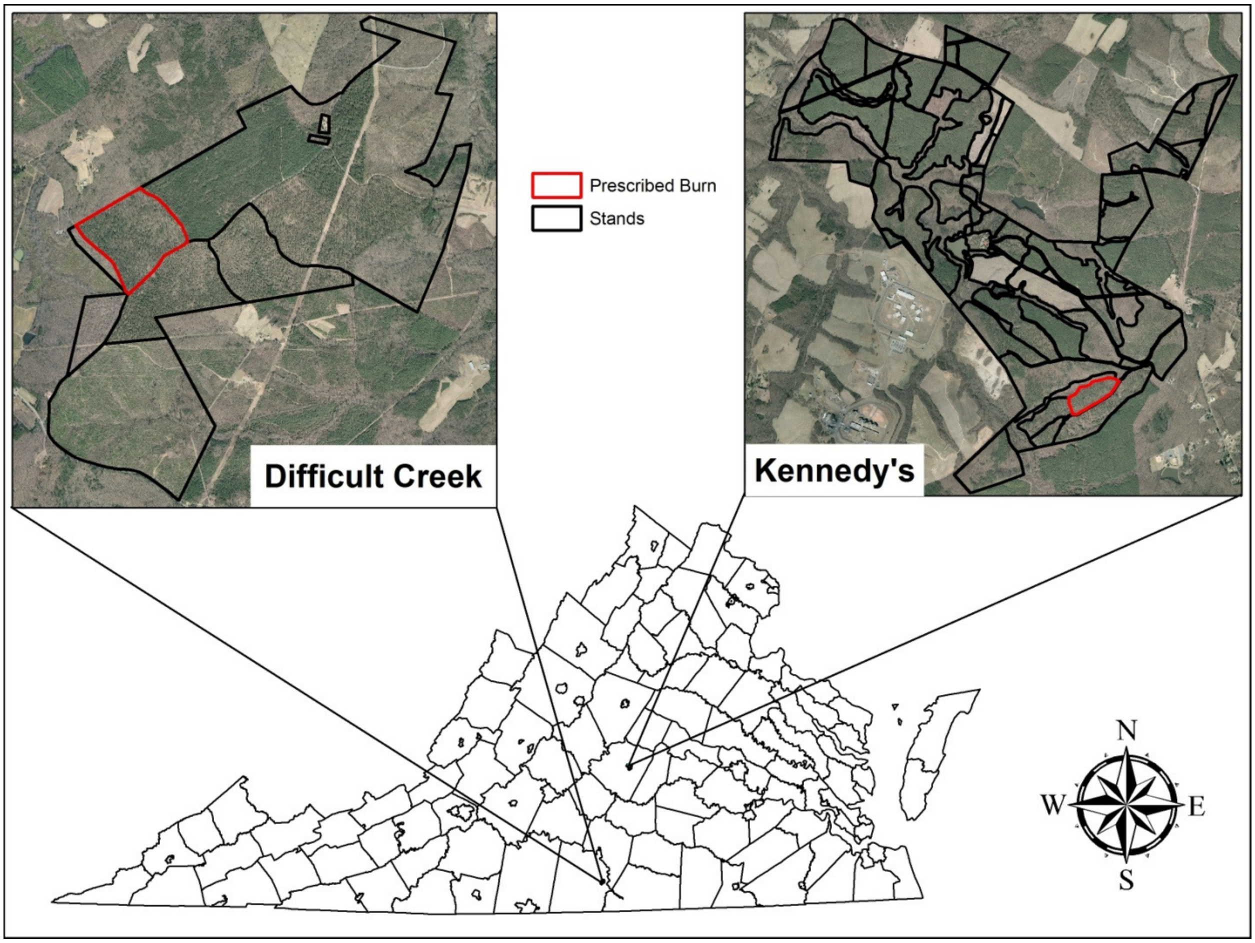


Figure 2.2. Map of Virginia showing the locations of the Difficult Creek and Kennedy burns. Map insets show the property boundaries and stands with the location of each stand that was burned.

There were a few obstacles located on or near the Kennedy Tree Farm that required special considerations during the prescribed burn. There was a power line corridor, a gas pipeline corridor, houses, and areas of logging slash and extreme fuel build up. These areas were given special consideration to ensure they were not burned. Other sensitive sites located near the property include the state prison, neighboring houses, and local roads. Buckingham Correctional Center borders the property on the southwest side of the property, and a few occupied houses were located southeast of the property. The optimal wind during the burn would have to be south to southwest to avoid smoke intrusions, and the location of the burn was chosen to ensure there were no occupied dwellings within 1,000 feet of the planned burned. There were also two state roads that were considered to avoid visibility impacts and liability from smoke intrusions. State route 631 borders the property to the east and runs through the property on the northern side. State route 682 is located at the northeast corner of the property and runs south-north. To conduct the burn we looked for a mixing height of 500-2,000 meters, a transport wind speed of 9-20 mph, atmospheric stability that was neutral to slightly unstable, and one to three inches of rain three to seven days before the burn. The ventilation factor had to be at least 2,000 to dilute the smoke and avoid visibility impairments along these roads. The ventilation rate is the ability of the atmosphere to disperse the smoke, and it is calculated by multiplying the mixing height by the transport wind speed.

2.2.0.2 – Task II, Field Data Collection- Before and after the prescribed burn we collected data on fuel loading and vegetation to assess the impacts of the prescribed burn and to provide input data for VSMOKE. Also, we looked for potential sites to set up the particulate monitor and weather station, to gather $PM_{2.5}$ concentrations from the burn and weather data to use for inputs in VSMOKE. We measured $PM_{2.5}$ with two of TSI Incorporated's DustTrak 8520 Aerosol Monitors. The DustTrak is a portable, battery-operated laser photometer that measures PM based on 90^o light scattering. It gives real-time digital readouts and has a built in data logger that can store up to 31,000 data points (TSI, 2002). The DustTrak measures the concentration of particulate matter at cutpoints of 1.0, 2.5, and 10 micrometers, depending on the size-selective inlet used and records concentrations from 0.001 to 100 mg/m^3(TSI, 2002).

The DustTrak was calibrated to ISO 12103-1, A1 test dust, which is Arizona road dust (TSI, 2002). To ensure accurate measurements of the $PM_{2.5}$ from the prescribed burns, the DustTrak was calibrated to the type of particles that were emitted from our burns. Therefore, we collected fuel from the planned burn locations and burned the fuel to produce the particles needed to calibrate the DustTrak. To calibrate the DustTrak we used a Leland Legacy pump and Whatman 47-mm Teflon filters. The fuel was burned with the DustTrak and the pump and filter located approximately five feet downwind to ensure that we collected enough particles (> 1 mg) on the filter for calibration. Both instruments were operated simultaneously for about 2-3 hours. The DustTrak gave the concentration of $PM_{2.5}$ in ug/m^3. To obtain the concentration from the pump and filter the Whatman 47-mm filters were weighed before and after testing. The difference in weight was divided by the volume of air sampled. With both instruments giving the concentrations, the calibration factor used for the DustTrak was calculated according to the TSI's DustTrak Manual, (TSI, 2006):

$$NewCal = \left(\frac{Reference\ Concentration}{DustTrak\ Concentration}\right) \cdot CurrentCal$$

Where NewCal was the new calibration factor we used, CurrentCal was the calibration factor used when calibrating the DustTrak, Reference Concentration was the $PM_{2.5}$ concentration that was sampled with the Leland Legacy Pump, and the DustTrak Concentration was the concentration measured with the DustTrak. The calibration factor was calculated to be 0.742.

A Davis Vantage Vue weather station and the compatible data logger, WeatherLink were used to record the desired weather parameters during burning operations. The weather station was used only on the Kennedy burn because it was not obtained until after the Difficult Creek burn. We located the station for the Kennedy burn 288 meters northwest of the burn at the top of a hill in a stand that had been clear-cut a year earlier. The station was elevated to 20 feet. The Vantage Vue was set up to record data at five minute intervals. The station recorded five minute averages for temperature, relative humidity, wind speed and direction. The Vantage Vue specifications for resolution are: one minute for time, 1% relative humidity (RH), 0.1°F temperature (T), and one degree and one mile per hour for wind direction and speed. It has an accuracy of: ±8 seconds per month for time, ±3% RH, ±1°F for T, ±3 degrees for wind direction, and ±2 miles per hour or ±5 percent (whichever is greater) for wind direction (Davis, 2009). For each five minute interval the high and low temperature and peak wind gusts and direction were also recorded. We averaged these data over hour-long periods for use as inputs for VSMOKE, which operates on an hourly basis.

Fuel Loading- Before and after each burn we collected data to calculate the fuel loading. This enabled us to predict the amount of smoke produced and to calculate the amount of fuel consumed by the prescribed burns. We collected fuel loading data based on modified methods from Brown (1974). There were 10 (Difficult Creek) and 7 (Kennedy) fuel loading sample points. Parallel diagonal transects were located throughout the stand at a fixed distance apart. Along these diagonal transects one to two fuel loading sample points were located four to five chains apart. At each fuel loading sample point four fuel transects, 50 feet long and six feet high, were established.

The first fuel transect was oriented in a direction determined by a random azimuth. The following three fuel transects were oriented 90° from the previous one in a clockwise direction. Along the first six feet of the 50 foot transect, 1-hr fuels (<0.25 in. diameter) and 10-hr fuels (0.25 – 1 in diameter) were tallied. From zero to 12 feet along the transect, 100-hr fuels (1 – 3 in diameter) were tallied, and 1000-hr fuels (>3 in. diameter) were tallied along the entire 50 foot transect. For 1000-hr fuels the diameter was recorded as well as the condition of the fuel (sound or rotten).

Each fuel transect was also further sub-sampled to obtain measurements for slope, duff depth, and litter depth. The slope of each fuel transect was recorded with clinometers reading from the fuel loading sample point to the end of the fuel transect. The duff and litter depths were recorded at three locations along the fuel transects. Litter and duff samples were collected at each fuel loading sample point to obtain measurements for bulk density. Bulk density was calculated following the methods of Ottmar and Andreu (2007). The oven dry mass (lbs) of the litter and duff sample were divided by the area of the sampling square (144 in^2) divided by the average layer depth (in) to determine bulk density for each sample. The results were then converted to pounds per cubic foot.

We also collected data to calculate the specific gravity. At each fuel loading sample point we collected two pieces of 1-hr and 10-hr fuels and one piece of 100-hr fuels to obtain measurements for specific gravity. Specific gravity was defined by the oven dry weight of a piece of woody fuel divided by its volume (ASTM, 2004). Three to four inch pieces were collected, and the volume measurements were recorded (length and average diameter). All the fuel samples (1-hr, 10-hr, 100-hr, litter, duff) were then dried at 149^o F until the mass of the fuel had less than a two percent drop in 24 hours. To obtain measurements of specific gravity for loblolly pine 1000-hr fuels, we used the formula developed by Radtke, et al. (2009):

$$D = 0.69 - 0.0428\,Decay - 0.0313\,Position - 0.0058\,Lat$$

where D was the specific gravity, Decay and Position were the integer decay classes 1 – 5 and position classes 1 – 4, respectively. Lat referred to the latitude location of the site in decimal degrees.

The measurements taken from the fuel transects were then used to calculate fuel loading values as described by Brown (1974). The following equations were used to determine fuel loading in tons/acre for each fuel class at every sample point (Brown, 1974):

A): 1-hr, 10-hr, and 100-hr tons/acre = (11.64 * n * d^2 * s * a * c) / NL

where:

11.64=	Units conversion constant
n=	# of woody piece intersections
d^2=	Avg. sq. quadratic mean diameter (in^2)
s=	Specific gravity
a=	Non-horizontal angle correction factor
c=	Average slope correction factor = $\sqrt{(1 + (\text{percent slope} / 100)^2)}$
N=	# of fuel transects per sample point
L=	Length of sampling plane (ft)

B): 1000-hr tons/acre = (11.64 * n * $\sum d^2$ * s * a * c) / NL

where:

11.64=	Units conversion constant
n=	# of woody piece intersections
$\sum d^2$=	Sum of squared diameters (in^2)
s=	Specific gravity
a=	Non-horizontal angle correction factor
c=	Average slope correction factor = $\sqrt{(1 + (\text{percent slope} / 100)^2)}$
N=	# of fuel transects per sample point
L=	Length of sampling plane (ft)

C): Litter and duff tons/acre = (dd * dbd * 1.815)

where:

d=	Avg. depth (in.)
bd=	Bulk density (lbs/ft^3)
1.815=	Constant

2.2.0.3 –Task III, Conducting the Prescribed Burns- The Difficult Creek burn was carried out by Virginia's Department of Conservation and Recreation's (DCR) Division of Natural Heritage. The Kennedy burn was carried out with the help of Virginia Tech's Wildland Fire Crew (VTWFC). The DCR and VTWFC carried out the burns, ensured the prescribed burns did not escape, and mopped up after the burns were completed. All the appropriate firelines were constructed before the burns took place with the help of the VDOF at the Kennedy Tree Farm. We used existing barriers like streams and logging roads where possible to reduce the cost of line construction. Any areas with high fuel loads or areas with the potential for the burns to blow up were identified and avoided, if possible.

Ideally, we wanted to have one burn during the dormant season and one burn during the growing season. The dormant season burn was to take place at the Kennedy Tree Farm after the leaves had dropped off the trees (November – before spring foliage begins). The ideal weather conditions were to be 30 – 50 percent relative humidity, 1 – 3 mph mid flame wind speed, a mixing height of at least 500 meters, a ventilation factor of at least 2000, atmosphere stability that would be slightly unstable and a wind direction that would be south to southwest. The growing season burn was to take place at Difficult Creek after spring foliage but before September. The weather conditions for the growing season burn was to consist of relative humidity values between 35 and 65 percent, 20 foot wind speed that would be less than 15 mph, a mixing height of at least 500 meters, a ventilation factor of at least 2000, and an atmosphere stability that would be slightly unstable. The ideal wind direction was to be south to southwest.

For both prescribed burns strip-head firing techniques were utilized. The strip-head technique produced enough smoke to measure the $PM_{2.5}$, and the intensity could be adjusted accordingly. The fires were lit in strips 20 to 50 feet apart perpendicular to the wind. The crews first created a safe line with a backfire from the downwind fire line. Once the safe line was created the crews started the head fire. They then began lighting the strips starting on the downwind side adjusting the distance between strips until the desired intensity is achieved. Once the entire stand had burned, it was monitored until it could be safely left alone without the fear of re-ignition.

2.2.1 –Phase 2: Validation of VSMOKE-GIS

2.2.1.0 – Introduction- Better estimates of $PM_{2.5}$ from prescribed burns can improve both our understanding of smoke management, and our ability to model and predict the impacts of smoke from prescribed burns. Our initial ***approach*** for Phase two was to determine sampling sites to collect the $PM_{2.5}$ during the prescribed burn. This data was then used to assess VSMOKE's accuracy of $PM_{2.5}$ concentrations, which will improve our ability to predict the impacts from prescribed burn operations. This knowledge could help to improve Virginia's smoke management guidelines and was the base of Part II of this project – Smoke Management Policy.

2.2.1.1 – Task I, Sample Site Location- While the prescribed burn was carried out, we collected $PM_{2.5}$ samples. We collected samples before, during, and after ignition to ensure the $PM_{2.5}$ concentrations were a result from the prescribed burn. To identify the original sample locations we used VSMOKE-GIS. With VSMOKE-GIS we entered the fuel loading data, along with the predicted weather conditions for the day of the burn. We used the resulting plume prediction and concentration prediction to identify sample locations. The input variables that affected the location of the plume and concentrations were: fuel loading and fuel moisture by fuel size class, location and area of the burn, ignition pattern, background concentration of $PM_{2.5}$, and length of time to burn. The input meteorological variables included: wind speed and directions, mixing height, relative humidity, and stability.

We ran VSMOKE-GIS with the predicted wind direction as well as two 30^o angles, one in each direction, in case of a wind shift. We ran the model multiple times with varying inputs for duration of burn and weather conditions, because none of these variables are certain and could change at any time during the burn. We had multiple sampling sites. The original $PM_{2.5}$ sampling sites were first chosen based on the average centerline predicted plume (plus two 30^o offset arcs). Other sampling sites were chosen as the burn is carried out to ensure that we are sampling within the plume. We attempted to sample within the portion of the plume where $PM_{2.5}$ concentrations could be potentially harmful to sensitive individuals and one sampling site that can be harmful to the general public. The first sampling point was located on the centerline of the plume from the predicted wind. This sampling point was relatively close to the burn (< 0.25 miles) where 1-hr $PM_{2.5}$ concentrations are predicted to be harmful to the general public. At this sampling point we had a DustTrak 8520 (DT) held stationary throughout the burn. This unit was referred to as DT #1. Other sampling points were located further away along the centerline of the plume and respective 30 degree arcs at varying distances between 50 and 1,000 meters where levels of $PM_{2.5}$ are harmful to sensitive individuals (elderly, children, people with respiratory problems). These sampling points were used as navigation points with a Garmin eTrex GPS that identified the route to measure $PM_{2.5}$ with the second DT. This DT was referred to as DT #2. These original sample points served as a base for our sampling locations. However, because the weather is not constant and wind direction did vary from the predicted, we were forced to modify our sampling locations. The stationary sample site for DT #1 was not modified. The sampling points for DT #2 had to be modified on both burns. We located the new sampling points by visual location of the smoke plume. All sampling sites chosen during burning operations were recorded with a GPS, and then loaded into ArcMap.

The DT has software that allows the user to set predefined sampling modes. The sampling modes could be adjusted to collect data over a given sampling time. The software allows the user to adjust the logging interval so that the DT will average the concentration over a given time for a set number of times for the predefined sampling time. DT #1 was stationary and measured $PM_{2.5}$ concentrations at that fixed position during the entire burn. DT #1 had a logging interval of one minute. Therefore, it logged a concentration every minute based on the average concentration over the previous minute. DT #2 was mobile and recorded concentrations along the sampling route. DT #2 had a logging interval of 10 seconds and was used with a GPS. We combined the GPS data and DT #2 data by rounding their time to the nearest 10 seconds. This gave us a location (X and Y coordinate) for each 10-second concentration measurement. Sampling was done by walking downwind from the burns, originally going to the planned $PM_{2.5}$ sample points and then modified during the burn to ensure $PM_{2.5}$ collection was done at the downwind direction from the burns.

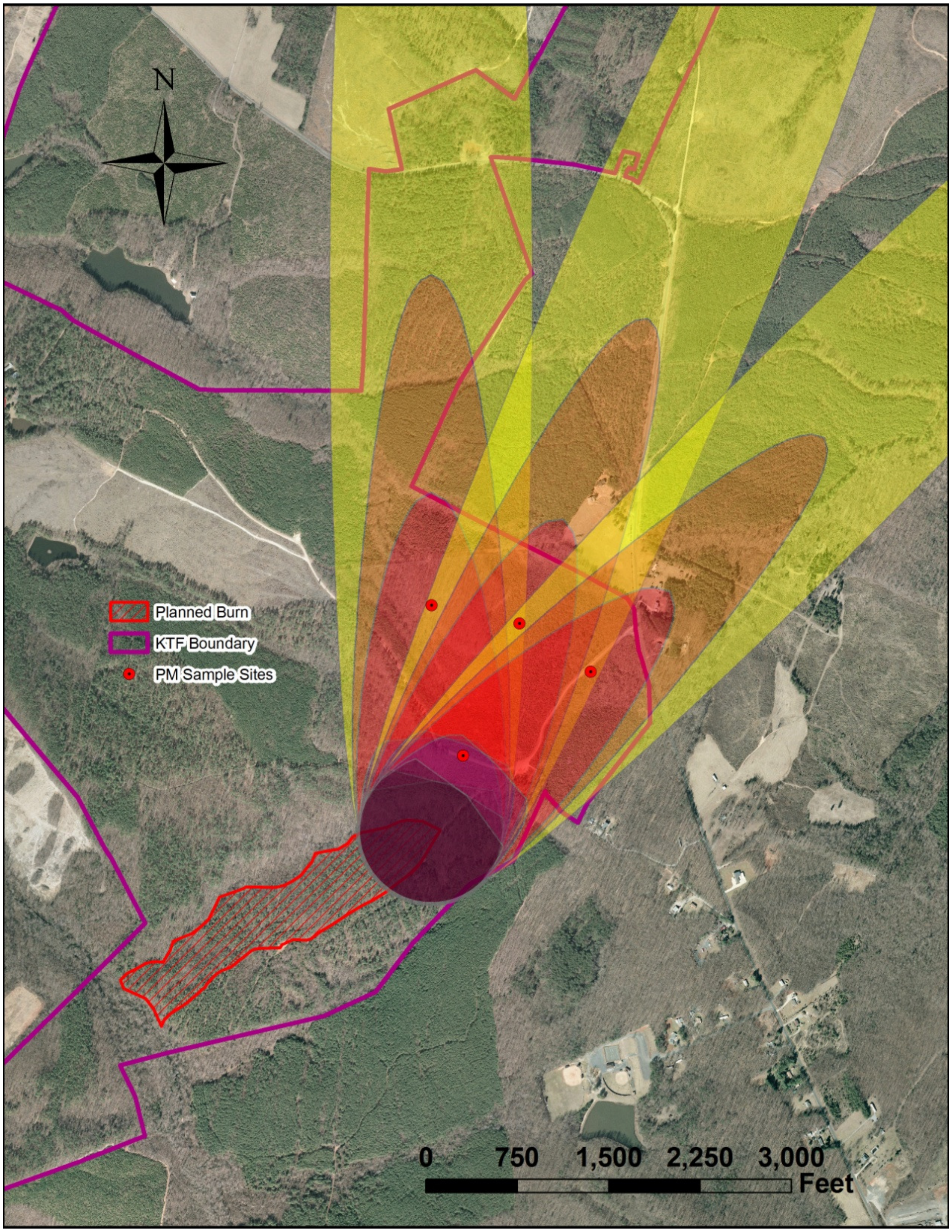


Figure 2.3. Map of the original set of planned $PM_{2.5}$ sampling sites at the Kennedy Tree Farm (KTF) with VSMOKE's predicted smoke plume (center plume) and double 30 degree angles to account for wind shifts. Smoke plumes are color coded to EPA's AQI values for $PM_{2.5}$ 1-hr concentrations (Table 2.1). Displayed sampling sites were based off of VSMOKE's predicted plume and double 30 degree angles.

2.2.1.2 –Task II, Evaluate VSMOKE-GIS Predictions- Building on insights and experience gained from conducting the prescribed burns and collecting the $PM_{2.5}$ concentrations, Task II – Evaluating VSMOKE and VSMOKE-GIS's Predictions was undertaken. Task II focused on characterizing the models' ability to accurately predict $PM_{2.5}$ concentrations and the location of the smoke plume. Evaluating VSMOKE's predictions was carried out in two steps. The first step was to compare the burn site conditions and weather parameters observed for the two burns. We looked at the predicted weather for the day of the burn, the observed weather, site conditions, and the burn parameters. The second step consisted of generating the data to be analyzed, computing statistics and comparing the two burn's data.

For the first step we compared the two sites conditions and their respective prescribed burn. Site conditions we considered included: fuel loading, acres, and fuel moisture. After collecting post burn fuel loads and calculating the prescribed burns' consumption we were able to compare the two burns. We analyzed the ignition techniques employed on both burns and ignition time. Other burn criteria included time of day and date of burn, relative intensity, length of burn, and observed weather. Weather parameters included: cloud cover, temperature, relative humidity, 20 foot wind, stability, mixing height, transport wind, and ventilation rate. These inputs were examined over the entire burn as well as how they changed on an hourly basis. This data provided better estimates of the impacts from prescribed burns, and how these impacts change throughout the burn as the conditions vary during the burn change. The predicted weather for the day of the burn was also compared to the observed weather. This allowed us to compare our predicted VSMOKE plume to the actual smoke plume and the VSMOKE posteriori plume – the VSMOKE plume with the actual observed meteorological variables and calculated consumption as inputs.

This weather and burn data was combined with the actual time it took to carry out the burn. Then the data was used as inputs into VSMOKE to obtain new predictions of the resulting smoke plume and $PM_{2.5}$ concentration estimates. We ran VSMOKE for each hour during the prescribed burns with the weather obtained from our weather station. This created a plume for every hour on the hour during the burns. In ArcGIS we selected the DT observations that corresponded to the correct plume. For example, hour of simulation = 1300 would select those DT readings that had a value in the time field from 12:30:00-13:29:59. We then assigned those DT readings with the predicted VSMOKE value. Each DT reading then had a DT concentration and a VSMOKE prediction. Because VSMOKE produces an average of the predicted plume for a given hour, the stationary DT readings (DT #1) were averaged over the given hour of simulation. For analysis and comparison, the DT concentration and VSMOKE predictions were reclassified into six categories. The reclassification was a numeric value from one thru six corresponding to the EPA's Air Quality Index level of health concern (Table 2.1) with one being "Good" to six "Hazardous"

With each observation having a reclassified value of one thru six for the DT and VSMOKE we were able to asses VSMOKE's accuracy. Contingency tables were created for each burn assessing the agreement between the DT and VSMOKE. Agreement meant that the DT and VSMOKE field had the same value (1-6). Percentage in total agreement was calculated. Agreement within one class, meaning $|DT - VSMOKE| = 1$ was calculated as was the respective percentage within one class. The reclassified DT readings and VSMOKE predictions were categorically ranked and their spatial association was assessed with a non-parametric ranking statistic, Spearman's Rank Correlation (p). After p was calculated for each burn, its significance was tested at alpha equals 0.0001.

2.3 – Results and Discussion

The main goal of this chapter of our research was to conduct a pilot validation of the model VSMOKE-GIS to characterize its accuracy in predicting downwind impacts of smoke in conjunction with GIS to quantify smoke impacts ($PM_{2.5}$ concentrations). We conducted one prescribed burn and were able to collect data from two other prescribed burns conducted by Virginia's Department of Conservation and Recreation (DCR), Division of Natural Heritage.

2.3.0 –Phase1: Fuel loading, weather, and site conditions

The first burn for this study was carried out by the DCR and was used to work out the sampling strategy for setting up our data collection procedures and was excluded in our data analysis for the pilot validation of VSMOKE. Following the first burn at Difficult Creek Natural Area Preserve on Units three and four, we were able to modify our data collection from insights gained while collecting trial data. The data from the trial burn helped us in modifying our data collection and sampling methods to generate more data suitable for comparison with VSMOKE. The trial burn served as a vital learning point in our research and enabled us to gain a better understanding of the complications associated with validating smoke emission models.

2.3.0.0 – Difficult Creek Prescribed Burn- The first burn for validation purposes was at Difficult Creek Natural Area Preserve. The DCR carried out the burn in Unit 6. We calculated Unit 6 to have a fuel loading of 12.56 tons per acre before the burn. Data collected after the prescribed burn estimated the fuel loading at 4.5 tons per acre with the prescribed burn consumption at 64.17% (Table 2.2).

Table 2.2. Difficult Creek Unit 6 fuel loads (tons/acre) by fuel class before and after the prescribed burn with the amount consumed by percent and tons/acre.

	1-hr	10-hr	100-hr	1000-hr	litter	duff	total
Pre Burn	0.34	2.54	1.86	0.65	4.39	2.78	12.56
Post Burn	0.16	1.5	0.68	0.24	0.82	1.1	4.5
Amount Consumed	0.18	1.04	1.18	0.41	3.57	1.68	8.06
Percent Consumed	52.94%	40.94%	63.44%	63.08%	81.32%	60.43%	64.17%

The Difficult Creek burn was conducted on April 13, 2010. The burn had a total ignition time of two hours and 15 minutes starting at 11:15. The first hour of ignition consisted of back firing the north line until sufficient black was achieved to prevent the south winds from blowing the fire across the control lines. Once sufficient black was achieved, the crew began strip head ignition techniques until 13:30 when ignition was completed. During the burn the highest temperature recorded was 78 degrees Fahrenheit with the lowest relative humidity being 30 percent. The stability that day was a class two with a mixing height of 8,010 feet. The 20 foot winds started out from the south and were shifting west as the afternoon progressed. During the burn the winds were light, less than five miles per hour mostly coming out of the southwest. The shifting winds caused us to modify our sampling methods with respect to geographic location. As the winds shifted to more of a west wind our $PM_{2.5}$ sampling had to shift towards the east. This also occurred at the Kennedy burn, and the unforeseen wind shifts and patterns is one of the problems associated with validating smoke emission models.

Table 2.3. Weather, burn conditions, and fuel moistures observed at the Difficult Creek and Kennedy prescribed burns used to validate VSMOKE.

Weather								
Burn	Cloud Cover	Temp (^{o}F)	RH (%)	20' Wind (mph/ direction)	Stability Class[a]	Mixing Ht. (ft.)	Transport Wind (mph/ direction)	Ventilation Rate[b]
Difficult Creek	Mostly Clear	78	30	Light S-W	2	8,010	8 W	64,080
Kennedy	Clear	47	18	4-7 SW-W	2	6,000	14 W	84,000

Burn Conditions					**Fuel Moisture (%)**			
Burn	Date	Burn Size (acres)	Time of Ignition	Sampling Time (hr)	1-hr[c]	10-hr[c]	100-hr[c]	1000-hr[c]
Difficult Creek	4/13/10	54	11:15-13:30	3.5	6	9	13	18
Kennedy	2/11/11	13.7	14:00-17:00	3	8	10	15	30

[a] Measure of the atmospheric turbulence from one to six, with one being the most unstable or most turbulent class and six being the most stable or least turbulent class.

[b] Ventilation Rate equals transport wind speed (mph) multiplied by the mixing height (ft) and is an estimate of the atmosphere's capacity to disperse smoke.

[c] Timelag where 66 percent of the mass will reach equilibrium with the atmosphere in water exchange for the specified time. Fuel class diameters are 1-hr: <0.25inch, 10-hr: 0.25-1 inch, 100-hr: 1-3 inches, and 1000-hr: 3-8 inches.

The Difficult Creek Burn was larger and much more intense compared to the Kennedy Burn. The fuel moisture was lower and total ignition time was 45 minutes shorter at Difficult Creek (Table 2.3). Considering the Difficult Creek Burn was four times the size of the Kennedy burn, these lower fuel moistures and quicker ignitions made for a more intense prescribed burn.

The intensity of the Difficult Creek burn was achievable because there were 14 crew members on the burn. With a high intensity burn at Difficult Creek and a lower intensity burn at the Kennedy site, we were able to do a general comparison of VSMOKE's accuracy with respect to the intensity of the prescribed burn observed.

2.3.0.1 – Kennedy Tree Farm Prescribed Burn- The Kennedy prescribed burn was conducted on February 11, 2011 in Stand 13. The burn was carried out by our research team with help from some members of the Virginia Tech Wildfire Crew. We had planned to burn 29 acres of Stand 13. However, due to time constraints and limited crew available we were only able to burn 13.7 acres. Data collected before the burn estimated the fuel loading at 16.4 tons per acre. Following the prescribed burn we calculated the fuel loading at 13.7 acres with the fire consuming 2.7 tons per acre (Table 2.4). This prescribed burn was much lower in intensity compared to Difficult Creek, only consuming about 17 percent of the total fuel available. The weather leading up to the burn did not sufficiently dry out all the fuels after receiving precipitation. With the weather and crew size limitations, the burn had a lower intensity, and did not consume as much fuel as the Difficult Creek Burn.

Table 2.4. Kennedy burn Stand 13 fuel loads (tons/acre) by fuel class before and after the prescribed burn with the amount consumed by percent and tons/acre.

	1-hr	10-hr	100-hr	1000-hr	litter	duff	total
Pre Burn	0.32	1.46	1.31	1.35	3.45	8.52	16.42
Post Burn	0.14	1.18	1.13	1.26	1.80	8.18	13.69
Amount Consumed	0.18	0.28	0.18	0.09	1.65	0.34	2.73
Percent Consumed	56%	19%	14%	7%	48%	4%	17%

We began ignition on the Kennedy burn at 14:00 and completed ignition at 17:00 with a total ignition time of three hours. The first 30 minutes ignition consisted of back firing the north east corner of the stand until sufficient black was achieved. Once back firing was complete we doubled our ignition rate to two drip torches and began strip head ignition techniques. Around 16:45 we began to see a decrease in fire activity as relative humidity began to rise. The decrease in fire activity caused us to create a scratch line about mid way through the stand and began mop-up operations. With the decrease in fire activity at the end of the burn and the backing fire at the beginning, there was minimal fire activity for the first and last 45 minutes of the burn. The middle two hours of the Kennedy burn saw the highest fire activity.

During the burn the highest temperature recorded was 48 degrees Fahrenheit with the lowest relative humidity being 18 percent. The low relative humidity enabled us to complete the burn, due to insufficient drying of the fuels prior to the burn. The stability that day was a class two with a mixing height of 6,000 feet (Table 2.3). The 20 foot winds started out from the southwest and were shifting west as the evening progressed. During the burn the winds were four to seven miles per hour mostly coming out of the west-southwest. The shifting winds caused us to modify our sampling method locations, similar to the previous burn at Difficult Creek.

2.3.1 –Phase 2: Validation

We measured $PM_{2.5}$ with the DustTrak (DT) aerosol monitor as the prescribed burns were being carried out. The GPS data and DustTrak mobile data were combined by joining the two data sets by rounding their time to the nearest 10 seconds. The data were collected (hh:mm:ss) to 10s of seconds. This allowed us to assign the $PM_{2.5}$ concentrations to specific locations.

2.3.1.0 – Difficult Creek Prescribed Burn- For the Difficult Creek burn there were 349 observations that included both stationary readings – averaging the concentration over one minute intervals, and mobile readings – 10 second averages. 232 of 349 DT readings, or 66 percent were in agreement with the VSMOKE predictions (Table 2.5). Of the observations that were not in agreement, VSMOKE underpredicted $PM_{2.5}$ concentrations for 28 and overpredicted concentrations for 89. There were 323 DT readings of the 349 or 93 percent that were within one class of VSMOKE's prediction.

Table 2.5. Contingency table for the Difficult Creek burn comparing the reclassified DustTrak (DT) readings to VSMOKE predictions with the classes based on the EPA's Air Quality Index (AQI) classes. Class one corresponds to a level of health concern that is "good" to class six being "hazardous" (Table 2.1). Highlighted cells are where the DT and VSMOKE totally agreed (yellow) and where they were within one class (blue). The bold lines separate the data into four quadrants based on AQI class.[a]

	VSMOKE						
DT Avg. Reclass	1	2	3	4	5	6	Total
1	195	1	0	3	1	2	202
2	1	2	59	0	0	1	63
3	1	1	0	1	0	3	6
4	0	0	0	4	4	11	19
5	0	0	1	0	1	3	5
6	0	0	0	3	21	30	54
Total	197	4	60	11	27	50	349

[a] The break for the quadrants was based on the AQI class with a level of health concern that is "unhealthy" for everyone, Class 4 and higher.

Table 2.5 highlights VSMOKE's value as a planning tool and confirms our underlying hypothesis – that VSMOKE will more likely overpredict $PM_{2.5}$ concentrations than underpredict. The four quadrants in the table suggest the likelihood of VSMOKE over or underpredicting $PM_{2.5}$ concentrations. The breaks for the quadrants were based on the EPA's level of health concern for the individual AQI classes. Classes four through six have a level of health concern of "unhealthy" to "hazardous" for everyone and classes one through three have a level of "good" to "unhealthy for sensitive groups." The top right quadrant shows the VSMOKE predictions that were overpredicted when the DT readings were low. The bottom left quadrant identifies the DT readings that were high when VSMOKE predicted them to be low. The bottom left quadrant had only one of the 349 observations, suggesting that VSMOKE is not likely to predict concentrations that are harmless when they are actually unhealthy and shows that when VSMOKE is in disagreement, it errs to the conservative side. That is, that VSMOKE is more likely to overpredict $PM_{2.5}$ concentrations. The DT readings that were high and underpredicted by VSMOKE could be attributed to the time interval the concentrations were averaged over. Our mobile readings were instantaneous readings and VSMOKE produces a prediction for a given hour. If we were to measure our DT concentrations averaged over an entire hour it is likely our DT concentrations would be lower.

Statistically, VSMOKE showed good agreement with the DT readings. The VSMOKE predictions versus the DT readings had a linear relationship (Figure 2.3). The linear relationship between the DT readings and VSMOKE predictions illustrates VSMOKE's accuracy in predicting the downwind location of the smoke plume. The classes we used to represent the concentrations predicted by VSMOKE and the DT readings were categorically ranked and we computed the nonparametric rank statistic. The Spearman's Rank Correlation (p) was 0.936. This shows good strength of the association between the DT readings and VSMOKE predictions and can be described using an increasing monotonic function. We found p to be significant at alpha equals 0.0001.

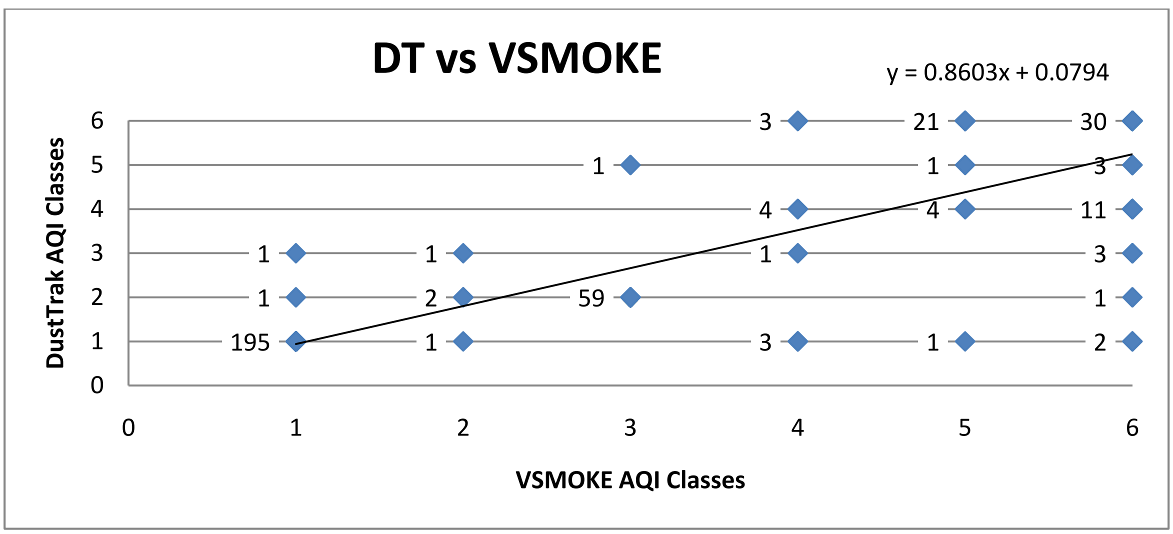


Figure 2.4. The linear relationship between the DT readings taken during the Difficult Creek burn and the VSMOKE predictions with the line of best fit shown. The numbers to the left of the data points represent the number of observations.

2.3.1.1 –Kennedy Tree Farm Prescribed Burn- The Kennedy Burn was the third burn for this research and second burn for which we collected data to be analyzed. This gave us plenty of preparation for collecting data and allowed us to modify our methods even more after both

Difficult Creek burns were completed. We were able to increase the number of data observations on the Kennedy burn and were more prepared for our data collection when the wind shifted. We had 801 observations on the Kennedy burn compared to 349 for the Difficult Creek burn (Table 2.6). For our stationary readings we had 197 DT readings out of 227 that were in agreement with VSMOKE and 387 out of 574 of our mobile DT readings. That is 87 and 67 percent agreement respectively and a total (stationary and mobile) agreement percentage of 73 or 584 of our 801 combined DT readings. Of the 801 observations on the Kennedy burn, VSMOKE underpredicted 106 or 13 percent and overpredicted 111 observations or 14 percent. When we looked at the DT readings that were within one class of VSMOKE we had a much higher agreement with 703 of the 801 observations or 88 percent agreement (Table 2.6). Of the 574 mobile observations we had 89 points that were off by one class, with 56% of them over predicted by VSMOKE. The observations that were underpredicted generally fell in class one by VSMOKE and were a class two with the DT. When they were not classified as class one by VSMOKE, there were 18 observations that were underpredicted with VSMOKE by one class. All 18 observations straddled the border between classes, being within 10's of meters of the correct classification.

Table 2.6. Contingency table for the Kennedy burn comparing the reclassified DustTrak (DT) readings against their VSMOKE predictions with the classes based on the EPA's Air Quality Index (AQI) classes. Class one corresponds to a level of health concern that is "good" to class six being "hazardous" (Table 2.1). Highlighted cells are where the DT and VSMOKE totally agreed (yellow) and where they were within one class (blue). The bold lines separate the data into four quadrants based on AQI class.[a]

	VSMOKE						
DT Avg. Reclass	1	2	3	4	5	6	Total
1	547	37	32	22	0	0	638
2	21	4	6	7	0	0	38
3	8	3	16	7	0	0	34
4	6	2	8	17	0	0	33
5	3	0	0	37	0	0	40
6	2	0	0	16	0	0	18
Total	587	46	62	106	0	0	801

[a] The break for the quadrants was based on the AQI class with a level of health concern that is "unhealthy" for everyone.

Once again the quadrants in the contingency table in Table 2.6 highlight areas where VSMOKE overpredicted (top right) and underpredicted (bottom left). The majority of our observations were in the top left quadrant and none of our observation locations were predicted in classes five or six by VSMOKE. This was due to shifting winds and will be discussed below.

The agreement between VSMOKE and DT readings was not as strong at the Kennedy burn when compared with the Difficult Creek burn. The VSMOKE predictions versus the DT readings showed a slight linear relationship (Figure 2.4). We tested the strength of association between the DT and VSMOKE by calculating the Spearman's Rank Correlation (p), because the data were categorically ranked and at the Kennedy burn showed little linear correlation. For the Kennedy burn p=0.622 and the association can be described as an increasing monotonic function. We found that the DT readings and VSMOKE predictions were spatially associated and was significant at alpha equals 0.0001.

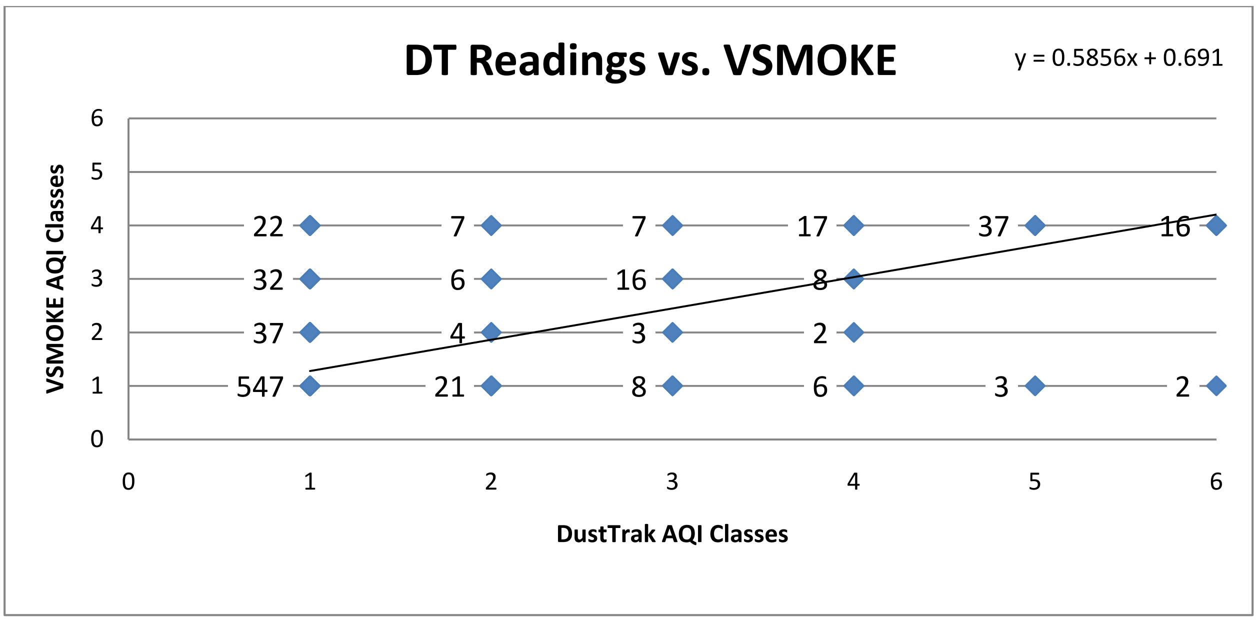


Figure 2.5. The slight linear relationship between the DT readings taken during the Kennedy burn and the VSMOKE predictions with the line of best fit shown. The numbers to the left of the data points represent the number of observations.

The contingency tables in Table 2.5 and Table 2.6 are skewed toward class one. At both the Difficult Creek and Kennedy burns DT #1 was held stationary throughout the burn at a location expected to be downwind from the burn based on the predicted wind direction for the day of the prescribed burn. However, for the Difficult Creek burn we had shifting winds and on the Kennedy burn the predicted wind of the day of the burn was forecast to be southwest, but ended up being west-southwest shifting to a west wind by completion of the burn. This created a large number of data observations from the stationary DT readings that were classified as a class one. This resulted from our stationary DT being located outside the VSMOKE plume, shown in Figure 2.5 where it did not record many high concentrations.

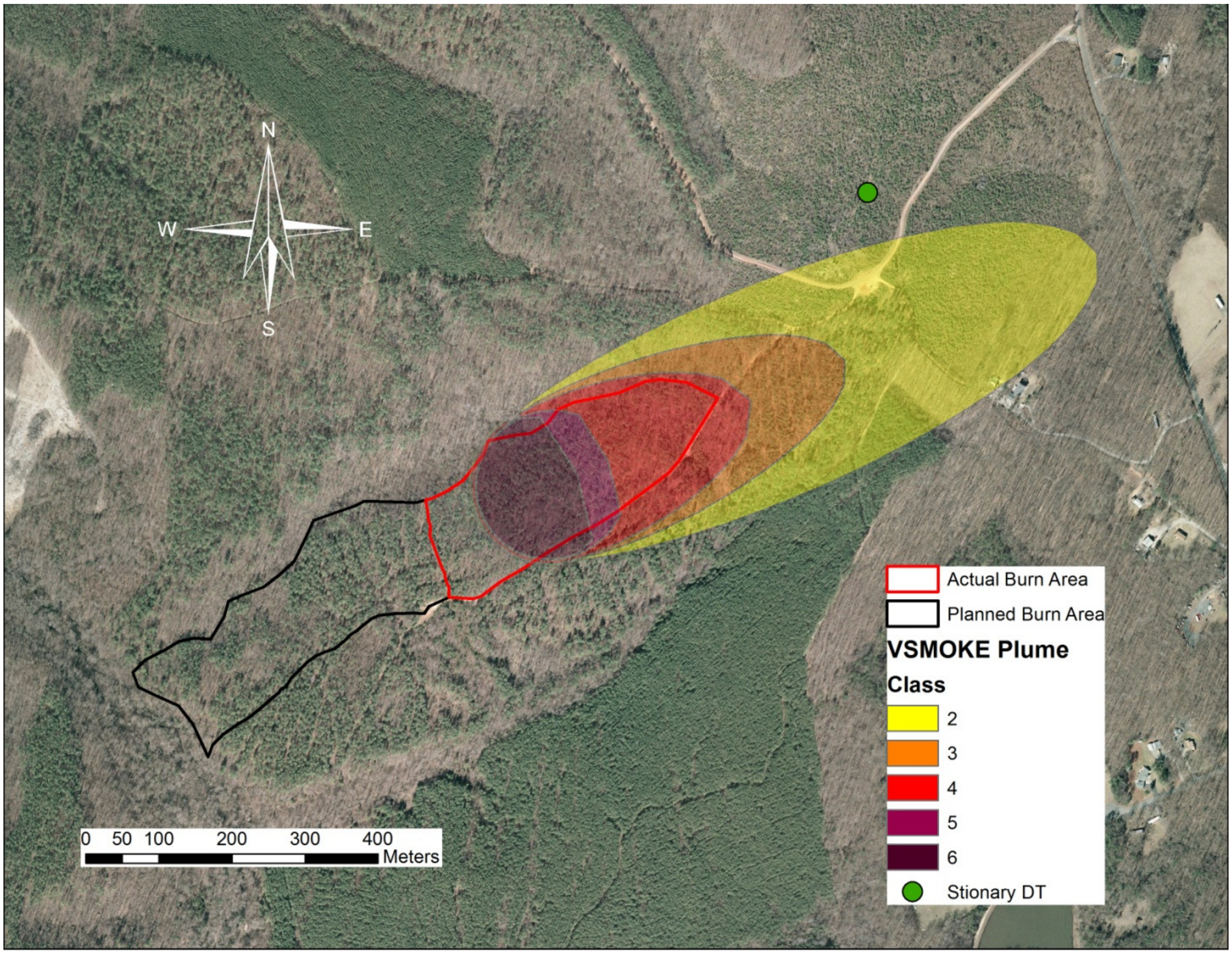


Figure 2.6. Map of the projected VSMOKE plume at the Kennedy burn illustrating how the incorrect forecasted wind direction can cause the smoke plume to miss our stationary DT #1 location.

This is one of the difficulties associated with spatial validation of prescribed burn smoke plume models. VSMOKE produces only an hourly snapshot of the predicted plume. Smoke released from prescribed burns is not constant and depends on many factors. Figure 2.6 shows how variable the concentrations of $PM_{2.5}$ are with respect to time at a fixed location on the Difficult Creek burn. If smoke was released at a constant rate the graph would be more similar to a bell curve. However, factors like weather, ignition techniques, and stand conditions all affect smoke production. The weather can change within minutes, in particular wind direction and gusts. A forest stand is not uniform throughout, and will contain varying fuel loads and fuel types at different locations. It is nearly impossible to ensure ignition per unit area is held constant. Ignition techniques must be adapted to the characteristics of the stand. Ignition techniques and stand conditions can create vast differences in smoke production over time. These changes in wind speed and direction, stand characteristics and ignition techniques can create a great deal of variability in the concentrations over time (Figure 2.6) and can produce challenges when validating smoke emission models. Validating a smoke emission model is not a controlled experiment where variables and inputs are held constant.   However, this inherent variability in smoke production is associated with any prescribed burn. This variability is what all burn managers must deal with when managing their prescribed fire smoke and is why burn managers have pre-burn check list and “watch out” situations identified before a burn. VSMOKE and any other models or methods employed to regulate or manage smoke will undoubtedly incorporate this variability in their methods to minimize impacts. Therefore, pre-burn methods and strategies should always incorporate techniques to halt the burn if conditions persist to transport smoke to sensitive areas.

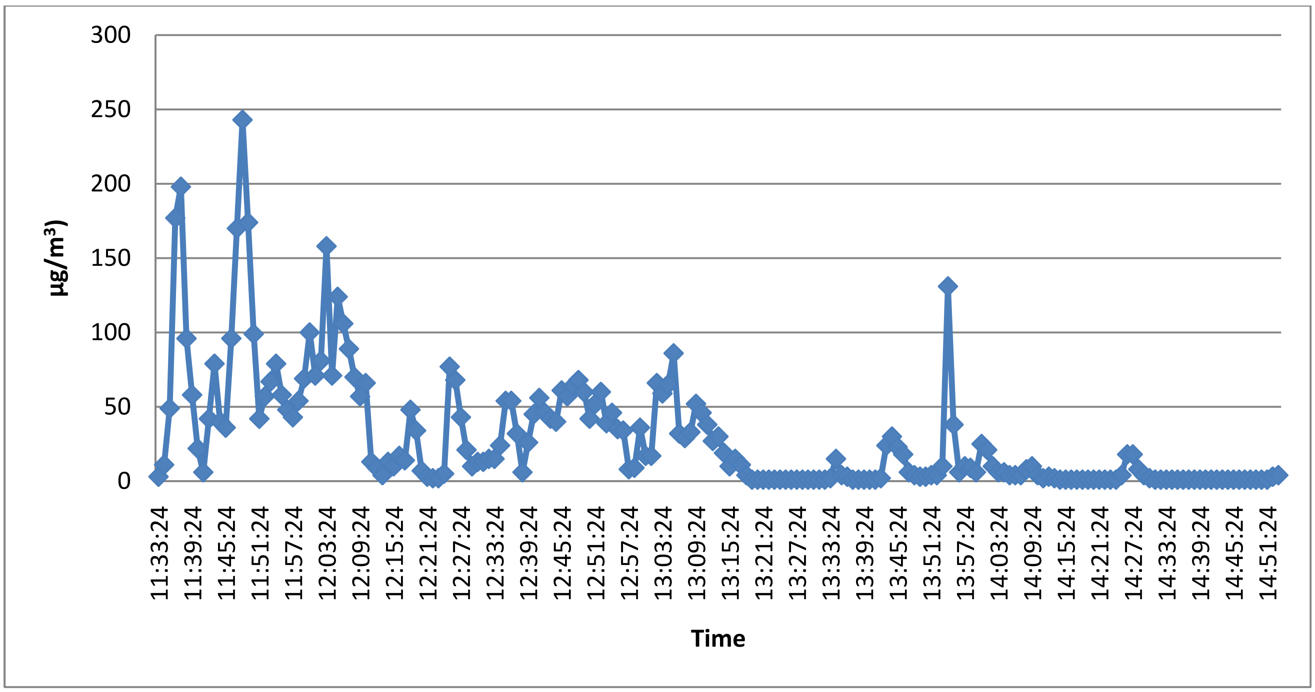


Figure 2.7. Variability of $PM_{2.5}$ concentrations against time at the Difficult Creek burn from the stationary DT.

Burn conditions and time constraints resulted in very different fire behavior for the two burns, allowing us to collect data from both a low intensity and high intensity burn. We found that the Difficult Creek burn, a higher intensity prescribed burn showed greater agreement between the VSMOKE predictions and DT readings. The Difficult Creek Burn had fewer observations in total agreement at 66 percent but had more in agreement within one class at 93 percent, whereas the Kennedy burn had 73 and 88 percent respectively (Table 2.7). This high number of observations in total agreement at the Kennedy burn can be attributed to the increase in observations during the Kennedy burn and can be seen in the contingency table in Table 2.6 where most observations were in class one.

Table 2.7. Statistics comparing the VSMOKE predictions against the DT readings from the Difficult Creek and Kennedy burns.

Burn	# of Data Observations	% Total Agreement	% Agreement Within One Class	Spearman Coorelation
Difficult Creek	349	66	93	0.936[a]
Kennedy	801	73	88	0.622[a]

[a] Significant at alpha = 0.0001

The maximum distance downwind that VSMOKE predicted the plume on the Difficult Creek burn was 1.53 miles and at the Kennedy burn was 0.55 miles. At the Kennedy burn VSMOKE did not predict any of the data points to be a class five or six. The lower intensity prescribed burn that occurred at the Kennedy's produced most of the VSMOKE class five and six predictions inside the stand, where DT sampling did not occur. At the Difficult Creek burn we had VSMOKE class five predictions extending out a third of mile from the stand. On both burns we took samples with the DT within 75 meters of the stand being burned and recorded concentrations with the DT in classes five and six. We found that VSMOKE showed a higher degree of association on prescribed burns with greater fire intensity and more acres burning. Since we only collected data on two burns it is difficult to suggest the minimal size prescribed burn that VSMOKE accurately models. However, as a planning tool, it was apparent that VSMOKE is successful at predicting the downwind location of the smoke plume and those areas that could be affected by smaller prescribed burns.

2.3.1.2 – Recommendations- After collecting our data and analyzing it from the prescribed burns and assessing VSMOKE's accuracy we discovered modifications for our research and future research in smoke emission modeling validation. VSMOKE adequately predicted the location of the resulting smoke plume for both of our burns and demonstrated its value as a planning tool for burn managers. However, we found that VSMOKE's use and accuracy for predicting the downwind concentration of particulate matter varied on our burns. The smaller Kennedy burn was less accurately modeled by VSMOKE especially within 75 meters of the burn. Since VSMOKE projects the smoke plume from a single point, we believe that on the smaller burn at the Kennedy's it was harder for VSMOKE to project the plume and concentrations from a single point. Since we were limited to two burns for this research, we were not able to conclude the ideal size of a prescribed burn that VSMOKE works best with. Future research and validation with VSMOKE and other smoke emission models may benefit by including prescribed burns with varying intensities and sizes and perhaps identify the optimal size of a burn for VSMOKE modeling. Another consideration for smaller burns is to project multiple plumes for a given hour from different points within the burning fire, rather than project one plume for a given hour at a single point. These plumes could then be combined or converted to a raster to produce one single plume for validation during that specific hour.

We also found that our VSMOKE predictions showed more association with the stationary DT readings compared to our mobile readings. We were limited to two DT units for this research (a used DT costs $2000). Model validation would work better with more units or people to help with measuring concentrations. We only held one DT at a constant location during the burns and had one person to operate the other DT that was used as the downwind land tract was traversed to record concentrations. Having multiple aerosol monitors and people to record the particulate matter concentration will allow future studies to record more stationary observations and allow a person to move the stationary DTs as the plume shifts. Perhaps a minimum of four to five monitors would be suitable with two to three people collecting samples. The mobile readings were averaged over a shorter time period of 10 seconds versus one minute for the stationary readings. The longer log time for averaging could mitigate the outlier concentrations recorded with the mobile readings due to the variability of smoke production over time. Mobile readings were recorded with a GPS to assign each concentration a geographic location. With GPSs having location errors associated with them, having more stationary particulate matter samplers could possibly alleviate these errors if post GPS data collection is done for the stationary locations to correct their coordinates.

It has been noted that of the observations where VSMOKE and DT readings did not agree, most were within one class of agreement. We suggest this was likely due to the location of our DT readings being located within 10s of meters of the correct VSMOKE class. This could be attributed to GPS errors or the variability in production of smoke. One way this could be corrected in future smoke emission modeling research is to create buffers around the DT locations. Then assess VSMOKE's accuracy based on the buffer and not the point. We categorized our VSMOKE predictions based on the observation location and which VSMOKE concentration plume it was located in. With buffers around the location of the DT readings, a point will not have to fall within a certain concentration plume. One could use the highest or lowest VSMOKE prediction it overlaps with, the median of the overlapping VSMOKE classes or the VSMOKE class that contains the highest percentage of the buffer circle. The size of buffers to be used would depend on the research purpose and which smoke emission model, GPS, and aerosol monitor is used. However, one suggestion for buffer radius could be the magnitude of GPS error.

One other barrier that we encountered during our research was the wind variability. In both our prescribed burns for this research we had to modify our particulate matter sampling methods with respect to the geographic location, although we were much more prepared for this on the Kennedy burn. Prior to the burn, we had set up sampling points we planned to visit based on the predicted wind direction. For both our burns the wind was either shifting or different during the burn compared to what was predicted. We were forced to make changes in the sampling points we visited. This can be seen in Figure 2.7 below. We did this mostly by visual observation of the smoke plume. Although we tried to maintain the same distance to the burn, it did not always occur. Future studies may wish to set up sampling points based on any acceptable wind direction for the prescribed burn and have those points extend out at least 30 degrees to allow for wind shifts. This could involve obtaining permission from adjacent landowners to collect smoke data.

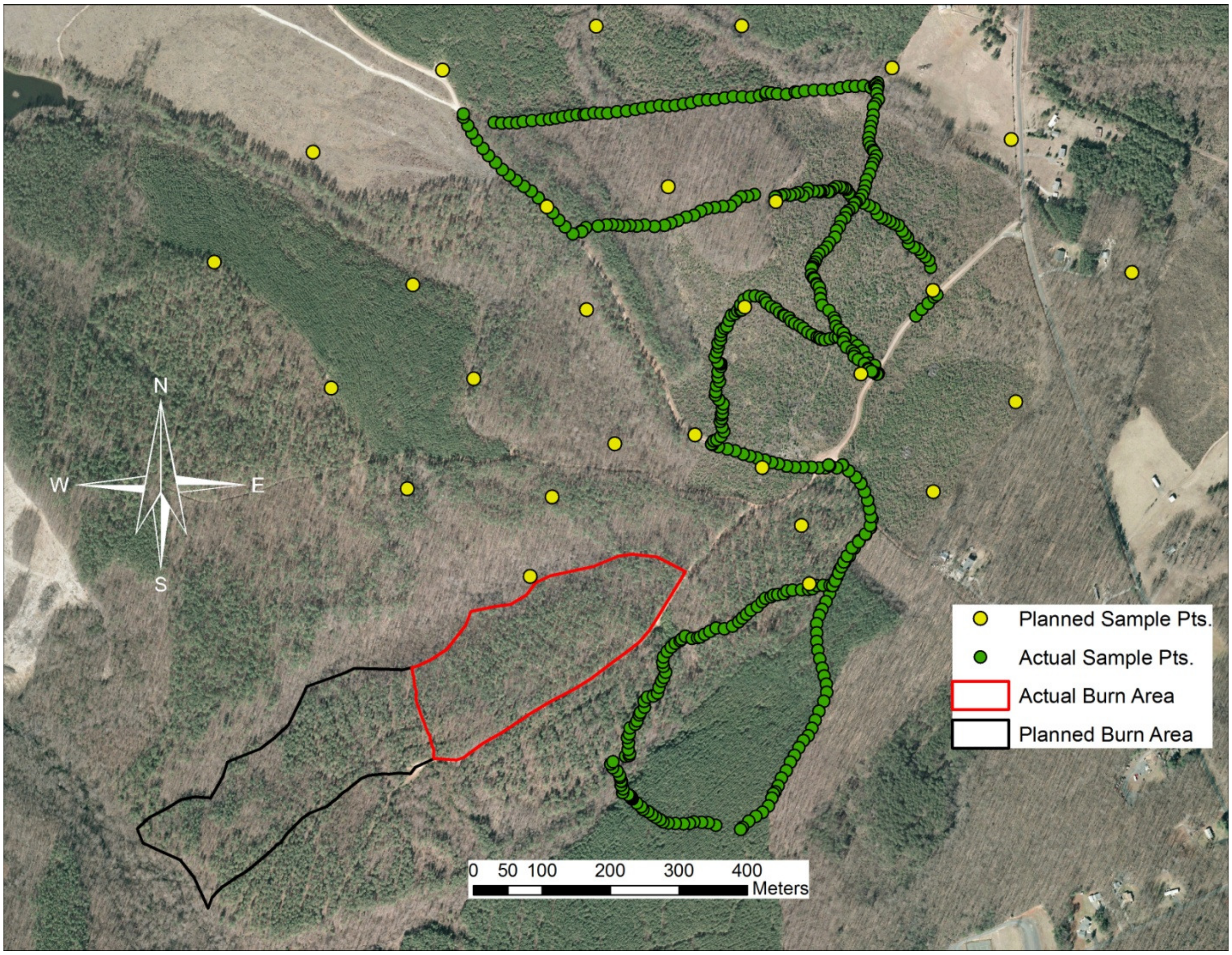


Figure 2.8. Map of the Kennedy burn showing the sampling points we planned to go to before the burn based on the predicted wind direction. The actual wind direction shifted to a more westerly wind and the actual mobile DT readings are shown after we made adjustments to our particulate matter sampling locations.

As a planning tool it would be more useful for a model to project a plume from a digitized polygon. For validation purposes on smaller burns it was much harder to project a plume from a single point. A more feasible way would be to digitize the prescribed burn for each hour of simulation based on the area of the stand that was burning. A model could then project multiple plumes, one for each hour based on the digitized area with the plume starting from the entire digitized area for the given hour. The digitized areas could then be programmed with ArcGIS and a emission simulator model to combine emission predictions based on the acres burning during the hour of simulation and those acres already burned yet still smoldering. This would project plumes from a polygon simulating the area burning, and would produce better plume predictions closer to the burn versus projecting them from a single point.

We have identified many recommendations for future smoke emission model validation. While there are probably many more, it is important that future studies take into account the equipment and models they will be using, the time allotted for the research, and the funds available. We saw most of our limitations stem from the costs of equipment, available burn crew members, and time constraints. While this study was not a full scale validation of the smoke plume model VSMOKE. We believe the insights gained from this research could lead to future full scale validation efforts of prescribed burning smoke emission.

Chapter 3
SMOKE MANAGEMENT

3.0 – Background

Prescribed burning has been well accepted by professional forest managers as a valuable silvicultural tool to reduce the damage to the environment from wildfires and meet management objectives (Haines et al., 2001). However, despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints such as those associated with the increasing residential developments and wildland fires becoming in contact with the Wildland-Urban Interface (WUI), air quality and other environmental regulations, and liability issues relating to smoke intrusions (Haines et al., 2001). The most important constraints that limit the effective use of prescriptive fires on private woodlands are regulatory requirements associated with smoke management.

In order to maintain prescribed burning as a viable silvicultural tool, we needed to understand the regulatory environment for prescribed burning. In Virginia open burning is regulated at the state level by the State Air Pollution Control Board (SAPCB) and the Virginia Department of Forestry (VDOF) is involved in the smoke management aspect (VDOF, 1998). The problem is that there are few statewide regulations promoting and encouraging the use of prescriptive fire as a silvicultural tool and the responsibility of enforcing is left to the local governments. This has created a patchwork of prescribed burning-related ordinances (Mortimer et al., 2006). The concern for forest managers is the possibility that these ordinances have produced unmanageable and unneeded regulation of prescribed fire. The regulation of private forestland raises the fundamental question of how far the public may go in restricting the rights of private landowners to use their land (Cubbage, 1995). While other states may be taking regulatory steps to protect the continued use of prescribed burning and burn manager's liability, Virginia has yet to follow suit.

The ***objective*** of Chapter Three of this study ***focused on identifying the various smoke management guidelines or regulations used by states in the southeast***. To achieve the objective of Chapter Three of this study, we first: (1) identified the various smoke management criteria states require or recommend in their prescribed burning smoke management plans and then, (2) identified the characteristics of prescribed fire programs and their implications on the ability of private landowners to use prescriptive burning.

3.1 – Literature Review

Prescribed Burning

McNabb (1995) defined prescribed burning as fire applied in a skillful manner to an area, under a particular set of weather conditions for a specific purpose to achieve certain results. Prescribed burning is accepted by professional forest managers as a valuable silvicultural tool to reduce the wildfire damage to the environment (Haines et al., 2001). When used properly, low-intensity fires like prescribed burns have been shown to have little adverse effect on the chemical and physical properties of soil or stand composition. Fewer emissions on a per acre basis are released into the atmosphere compared to wildfires (Wiedinmyer and Hurteau, 2010). However, despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints such as air quality and other environmental regulations, and liability issues relating to smoke intrusions and escaped fires (Haines et al., 2001). When fire is excluded from an ecosystem, it can have a profound effect on the structure of those ecosystems and their economic productivity (McNabb, 1995).

The application of prescribed fire is determined by its objective – a desired outcome or future condition (Vose, 2000). Prescribed fire can have many management objectives. One prevalent objective is to reduce fuel loads and the possibility of threats from wildfires. Other objectives include site preparation, improvement of wildlife habitat, disease control, increase fodder production, appearance, and access (McNabb, 1995). These objectives are used to achieve short term and/or long term ecosystem conditions. For example, returning the forest conditions to those prior to human influence or pre-European settlement, altering the structure and function of the ecosystem, creating and maintaining unique habitats, and increasing the value of commercial species (Vose, 2000).

Prescribed burning is an integral part of silviculture in the United States for forest management and is recognized as one of the most cost effective silvicultural tools for pine management (McNabb, 1995). When prescribed fire is applied correctly, it does not adversely affect the environment. Ecosystems have evolved mechanisms to handle repeated burning. Trees resist the overall impacts of burning by developing thick bark, recovering/sprouting quickly, and cone serotiny (Vose, 2000). Although these mechanisms help deal with the effects of prescribed burning, it depends greatly on the intensity and severity of the prescribed burn.

Although prescribed burning is recognized as a viable silvicultural tool, it produces smoke and harmful emissions that can degrade air quality and reduce visibility. Haines et al. (2001) conducted a study in which they mailed a questionnaire to the forest supervisor of each national forest in the south and one representative from each of the 12 southern states' forestry agencies. The questionnaire asked them to characterize their respective prescribed burning programs and identify the trends, purpose, and barriers to prescribed burning. They found that two barriers, air quality and smoke management laws and risk of liability, were the most highly rated barriers for both national forests and state fuels managers. Negative public opinion was the primary barrier on private forests (Haines et al., 2001). The public's concern over the use of prescribed fire is largely due to the smoke released from the burn. An unsightly landscape can be ignored by the public, but the reduced visibility and choking smoke (particulate matter) are too apparent (Crow, 1973). Social constraints force fire managers to take precautions that increase the costs of prescribed burning operations (Gonzalez-Caban, 1997). The use of prescriptive burning decreases substantially with higher costs. Existing air control regulations could seriously curtail the use of prescriptive fire (Crow, 1973).

Regulatory barriers present huge problems to fire managers using prescribed fire effectively and are among the top concerns limiting its use for private landowners (Haines et al., 2001). Smoke is the primary adverse impact from prescribed burns (Dennis, 2002) and is the focus of the majority of regulations concerning prescribed burns. These regulations are most concerned with "sensitive targets": airports, hospitals, schools, nursing homes, and major highways. The increasing use of regulation to achieve environmental protection goals, and the litigious nature of American society are increasing voluntary compliance with smoke management guidelines and Best Management Practices (BMP) to stave off the public's negative opinion and stricter regulation of prescribed fire (Haines and Cleaves, 1999).

Smoke Management

Due to the smoke and emissions released during prescribed burning operations, smoke management must be considered in every prescribed burning plan (Turck, 2009). Achtemeier (2009) defined smoke management as the action taken by a land manager to minimize the environmental impact of smoke. According to the VDOF's Guide to Prescribed Burning in Virginia (Turck, 2009) the three main objectives of smoke management are avoidance, dilution, and emission reduction. A prescribed burn manager wants to avoid smoke-sensitive areas, disperse and dilute the smoke before it reaches the smoke-sensitive areas and reduce the smoke (emissions) produced from the burn site. As the use of prescribed burning continues to increase, the need for better smoke management is evident. This is compounded by the increase in the populations living within the WUI and has resulted in more people being exposed to smoke (Robison, 2007). The combination of increased burning and public smoke exposure has created a need for improved predictive tools for smoke production, dispersion, and weather (Robison, 2007, Lahm, 2006).

Smoke from prescribed burns can adversely impact air quality, visibility, and can cause health problems for sensitive individuals. Prescribed burns produce smoke that is composed primarily of water vapor, however it produces pollutants that can harm the public (Turck, 2009). Pollutants that are released during burning include particulate matter, hydrocarbons, carbon monoxide, nitrogen dioxide, and sulfur dioxide. With respect to public health, particulate matter is the pollutant of concern. The other pollutants are released in negligible amounts or are diluted in the open air (Turck, 2009). Particulate matter can greatly reduce visibility. With respect to visibility the major concern for burn managers is the possibility of degrading the visibility in a Class I Air Shed – EPA designation of a pristine area, where little deterioration of visibility is allowed (Wark et al., 1998). Class I Air Sheds include wilderness areas and some national parks. The Grand Canyon Visibility Transport Commission (GCVTC) found that emissions from wildland fire and prescribed fire are likely to be the single greatest impact on visibility in a Class I Air Shed (Sandberg et al., 2002). The GCVTC also stated that during intense fire activity, smoke from wildland fires is likely to make visibility days for the Grand Canyon in the lowest 20 percent.

Particulate matter not only affects visibility, it can also affect the health of certain individuals. The particulate matter of concern are those particles smaller than 2.5 microns in diameter ($PM_{2.5}$). These particles are small enough in diameter to be breathed in and can cause respiratory problems (CDPH, 2008). Wildfire smoke also contains significant quantities of other respiratory irritants (formaldehyde and acrolein) which compound the effects of $PM_{2.5}$. It also causes eye irritation and can aggravate the breathing of sensitive individuals (VDOF, 1998, CDPH, 2008). Healthy individuals are usually not affected by the smoke from prescribed burns due to the generally short exposure. Sensitive individuals are affected most – those with asthma or respiratory disease, cardiovascular disease, elderly, children, pregnant women, and smokers (CDPH, 2008).

Smoke Management – Regulation

Regulations concerning prescribed burns originate from air quality laws, forest fire control laws, laws concerning property damage and personal injury from escaped fires, and environmental laws such as the Endangered Species Act and the Clean Water Act (Haines and Cleaves, 1999). Of these regulations air quality laws affect prescriptive burning the most. As more people move into the WUI, tighter regulations have been enacted for prescribed burning. An increased interest has developed in forestry burning as an air pollution source and has forced governments to regulate prescribed burning within their jurisdiction. These air quality regulations, though often not severe, are usually only enforced upon complaint (Hauenstein and Siegel, 1980). Examples of air quality regulations that pertain to prescribe burning include obtaining a permit, prohibiting burns near roads and inhabited areas, restrictions on windrow burning, prohibiting the use of heavy, oil based starter fluids, restrictions on time of day and season of burn, and prohibiting activities that impair visibility (Haines and Cleaves, 1999).

Throughout the United States prescribed fire is increasingly scrutinized and regulated (Cubbage, 1995). The hazards associated with prescribed fire are a result of the increasing residential development and wildland fires becoming in contact with the WUI and the threat of having smoke impacts on these areas and the individuals there. Regulations for these hazards can be attributed to the increasing social conflicts between urban and rural residents in rapidly urbanizing communities (Martus, 1995). The most prominent hazards that arouse conflicts between urban and rural residents are: human health hazards, highway accidents associated with smoke, probability of an escaped fire resulting in personal injury or property loss (Haines and Cleaves, 1999). These hazards are the driving force behind prescribed fire regulation. Coupled with the potential liability associated with prescribed fire smoke and escape, hazards are the primary factor for litigation (Sun, 2007).

Federal Government and $PM_{2.5}$ – Laws pertaining to smoke from prescribed fire in Virginia are enacted by both the state and federal government. The federal government has previously taken a minor role in its approach to prescribed fire, leaving much of the regulation of nonfederal forests to the state (Ellefson, 2006). However, federal involvement regarding the use of prescribed fire is increasing, as they recognize the benefits of prescribed fire. The U.S. Congress is increasing its role in prescribed fire policy. This was indicated in the CRS Report for Congress on Forest Fire/Wildfire Protection on January 18, 2006. The report also states the concerns associated with prescribed fire, in particular the emissions of particulate matter and its effect on the Clean Air Act. However, they state that an aggressive prescribed burning program would reduce the total emissions of particulate matter from prescribed fires and wildfires (Gorte, 2006).

The greatest involvement by the federal government in regulating prescribed burning is through the Environmental Protection Agency (EPA). The EPA is in charge of enforcing the 1970 federal Clean Air Act (CAA) and its amendments. Congress passed the CAA in 1970 and its subsequent amendments with the intent to limit atmospheric concentrations of pollutant emissions (Paulson et al., 1980). The CAA also established the responsibility to the EPA to develop National Ambient Air Quality Standards (NAAQS). There are two types of NAAQS: primary, which are designed to ensure public health, and secondary, which are designed to protect public welfare (Paulson et al., 1980). The EPA has established NAAQS for six criteria pollutants and atmospheric concentration levels: particulate matter (PM), Ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO), lead (Pb), and nitrogen dioxide (NO_2). With respect to prescribed fire emissions PM is the biggest threat to violation of NAAQS. The NAAQS for PM are: PM_{10}: 24-hour – 150 ug/m^3, annual – revoked, $PM_{2.5}$: 24-hour – 35 ug/m^3, annual – 15.0 ug/m^3 (Arithmetic Mean). The CAA also established attainment areas which meet NAAQS and nonattainment areas which violate NAAQS. The CAA does not give the federal government control over air pollution; rather, it provides the legal framework for state control of air pollution (Hauenstein and Siegel, 1981).

Prescribed fire has two major impacts that relate to the CAA – visibility impairment and particulate emissions. The EPA, under the CAA's authority, has established programs that affect forest management burning activities either directly or indirectly. These include setting of national primary and secondary ambient air quality standards (PM), and the requirement that each state must draft and enforce an EPA-approved air quality state implementation plan (SIP) which must include a section on open burning (prescribed burning) (Hauenstein and Siegel, 1981). A SIP is a comprehensive plan identifying a strategy that a state will follow in order to maintain and achieve NAAQS for both primary and secondary standards. Virginia's SIP has a section on the development of smoke management guidelines for forestry management purposes.

Hauenstein and Siegel wrote in 1981 referring to the CAA and its subsequent amendments, "…there is nothing in the act itself or in the accompanying legislative history to suggest that Congress considered smoke from prescribed fire as a significant source of visibility impairment." The problem of the CAA not addressing prescribed burning was corrected in 1998 when the EPA issued its *Interim Air Quality Policy on Wildland and Prescribed Fires*. This Interim Air Quality Policy transcended in 2007 to EPA's *Treatment of Data Influenced by Exceptional Events* (EPA, 2007). EPA defines an exceptional event as events for which the normal planning and regulatory process established by the CAA are not appropriate. The event (1) must affect air quality, (2) is not reasonably controllable or preventable, (3) is an event caused by human activity that is unlikely to recur at a particular location or a natural event, and (4) is determined by EPA through the process established by 40 C.F.R. parts 50 and 51 to be an exceptional event (EPA, 2007). This allows states to exclude air quality data related to exceedances or violations of the NAAQS and avoid classifying an area as nonattainment, or redesignating an area as nonattainment if the state adequately demonstrates that an exceptional event caused the violation of a NAAQS (EPA, 2007).

At present, exceptional events only apply to NAAQS for ozone and particulate matter. The EPA has specifically classified prescribed fire as an exceptional event. The only stipulation for prescribed fire to be an exceptional event is contingent on the guidance contained in the *Interim Air Quality Policy on Wildland and Prescribed Fires*, requiring that states have adopted and implemented a Smoke Management Program (SMP) (EPA, 2007). SMPs provide the basic framework of procedures and requirements and objectives for planning and managing smoke from prescribed fires (VDOF, 1998). In Virginia SMPs are required by law to accompany a prescription for a prescribed burn (Code of Virginia, § 10.1-1142), but prescriptions are not required. The goal of an SMP is to minimize ambient air quality impairment, prevent smoke from being carried to "sensitive areas," and recommend burning guidelines to supplement the regulations established by the State Air Pollution Control Board (VDOF, 1998).

Virginia Regulations – Virginia's state laws that affect prescribed fire smoke management can be divided into two areas: administrative law and statutory law. Virginia's Administrative Code governs the activities of administrative agencies in Virginia. Open burning in Virginia is regulated by the Virginia Department of Environmental Quality (DEQ) and the Virginia Department of Forestry (VDOF) is involved with the smoke management aspect. The VDOF does not have any Administrative Codes that regulate directly or indirectly the use of prescribed fire or smoke management. The DEQ regulates open burning and its associated emissions through its Division of Air Quality and Air Pollution Control Board. The DEQ has two Administrative Codes under the State Air Pollution Control Board's Regulations for the Control and Abatement of Air Pollution that regulate the use of prescribed fire. Indirectly, the Air

Pollution Episode Prevention (9VAC5-70) can affect prescribed burning when there is a stage of an air pollution episode, and the governor can ban all open burning. Directly affecting prescribed burning is the Regulation for Open Burning (9VAC5-130).

The VAC for Regulation for Open Burning (section 5-130) permits open burning for forest management and agriculture practices approved by the Air Pollution Control Board, provided that the burning is conducted in accordance with the VDOF's smoke management plan (VCC, 1999). Section 5-130 also allows the governing body of any locality to adopt an ordinance relating to air pollution and govern its open burning within its jurisdiction, provided that the board has approved the ordinance. The ordinance for any locality must be at least as strict as the state regulation. Allowing localities to adopt their own ordinances on open burning creates a patchwork of local ordinances on prescribed fire. Differences in permits, exemptions and restrictions from various localities create a confusing regulatory situation for landowners (Mortimer, 2006).

The statutory laws that pertain to prescribed burning smoke management are enforced by DEQ's Air Pollution Control Board (APCB) under Title 10.1 – Conservation. The APCB is affected by Chapter 13 – Air Pollution Control Board. The APCB is controlled indirectly by the EPA. The EPA sets the NAAQS and delegates its enforcement and regulation to the states. The state is, therefore, in charge of enforcing emission standards that are at least as stringent as the NAAQS. The statutory authority given to the APCB regarding prescribed burning are § 10.1-1307 – Further Powers and Duties of the Board and § 10.1-1308 – Regulations (Code of Virginia, § 10.1-1307, Code of Virginia, § 10.1-1308). The Further Powers and Duties of the Board explicitly states what the APCB can do and must do. The APCB must implement emission standards pursuant with the NAAQS and enforce them (Code of Virginia, § 10.1-1307). § 10.1-1308 further defines the role of the APCB in regulating air pollution. The APCB has the power to promulgate regulations, including emergency regulations, abating, controlling and prohibiting air pollution throughout any part of the Commonwealth in accordance with the provisions of the Administrative Process Act (Code of Virginia, § 2.2-4000 et seq., Code of Virginia, § 10.1-1308). This gives complete discretionary authority to the APCB in regulating prescribed fires with respect to emissions (smoke management) classified in the NAAQS.

There are two statutory laws that pertain to prescribed burning in general that are enforced by the VDOF under Title 10.1 – Conservation. The VDOF is affected by Chapter 11 – Forest Resources and the Department of Forestry. The two laws are § 10.1-1158 – Prohibition of all Open Burning Where Serious Fire Hazards Exist and § 10.1-1142. Regulating the Burning of Woods, Brush, etc. § 10.1-1158 gives the State Forester the right to curtail all open burning when serious fire hazard exists through recommendation to the Governor of Virginia. § 10.1-1142 contains the 4:00 p.m. Burning Law. The 4:00 p.m. Burning Law prohibits open burning during the period of February 15 through April 30 except for the hours between 4:00 p.m. and 12:00 midnight. A burn can be exempted from this law if the fire is a prescribed burn conducted in accordance with a prescription and managed by a prescribed burn manager. The burn must be conducted in accordance with Virginia's Prescribed Burn Elements (§ 10.1-1150.4), and the State Forester must approve of the burn prior to February 1.

Local ordinances play a major role in limiting the use of prescribed fire in Virginia. As stated earlier the Virginia Administrative Code allows localities to implement ordinances that regulate open burning. This creates a patchwork of prescribed fire ordinances and a confusing regulatory situation (Mortimer et al., 2006). The dispersed regulatory landscape produces many problems to prescribed burners and smoke managers: (i) regulatory responsibilities are assigned to too many agencies; (ii) limited funds and staff are spread over many programs and agencies; (iii) effects of multiagency resistance to comprehensive monitoring of regulatory programs; and (iv) public reluctance to accept regulatory initiatives emanating from many different state agencies (Ellefson, 2006).

3.2 – Research Methods

The research in Chapter Three was separated into two phases. Objective 3.1 consisted of reviewing the smoke management guidelines and recommendations for prescribed burning in the states of: Virginia, North Carolina, South Carolina, Georgia, Arkansas, and Florida. Initial efforts were focused on reviewing the required or recommended smoke management criteria employed by the various states. The second phase focused on identifying the characteristics of the states' prescribed fire programs and their smoke management regulations that either foster or hinder a private landowner's ability to use prescriptive fire.

3.2.0 –Phase 1: Smoke Management Criteria

3.2.0.0 – Introduction- Our ***approach*** focused on reviewing the criteria the states require in their smoke management plans and how they employ the criteria in mitigating smoke impacts downwind. This data allowed us to group the criteria required into three main categories that included: geographic location, available fuel loads, and atmospheric conditions. This phase of the project consisted of one main task – identifying which criteria or combination of criteria each states employs.

3.2.0.1 – Task I, Identifying States' Smoke Management Criteria- Smoke management plans are used to reduce the downwind impacts of smoke released from prescribed burning operations. Smoke management plans can be mandatory and required by law or they can be recommendations that are used as guidelines for burn managers to reduce emissions, but they all have the objective of minimizing the impacts downwind.

Preliminary research identified three main criteria that the states of Virginia, North Carolina, South Carolina, Georgia, Arkansas, and Florida use: the geographic location of the prescribed fire – its proximity to sensitive sites; available fuel loads – the specified/available fuel to be burned; and atmospheric conditions the day of the burn. The first step was to obtain the smoke management plans or guidelines from each state and determine if their guidelines or regulations are mandatory or just mere recommendations. Then, we identified what criteria or combination of criteria each state's smoke management plan used.

We also identified techniques to manage smoke from prescribed fires that complement the criteria we were looking for. The techniques to reduce smoke came from Virginia's Smoke Management Guidelines and included: avoidance, dilution, and emission reductions. Avoidance takes into account the geographic location of the burn and its proximity to sensitive sites. Emission reduction involves changing the conditions at the burn site, for example, altering firing techniques, reducing the acres to be burned, or reducing the total fuel load to be consumed. Dilution reduces the smoke concentration in the atmosphere. This is achieved by burning during favorable dispersion conditions, when the smoke can be diluted through a greater volume of air.

After we had identified the criteria and techniques used to reduce emissions from prescribed burning for the six southeastern states we compared and investigated the way each state employs them. We were then able to investigate each criteria and its effect on private landowners' ability to use prescribed fire. This enabled us to identify the states with more advanced prescribed burning smoke management plans and how they employ their smoke management plan or guidelines. This data was then used in the second phase and helped us to narrow the scope of the characteristics we were looking for that foster or hinder the continued use of prescribed burning as a silvicultural tool.

3.2.1 – Phase 2: Characteristics of Prescribed Fire Programs

3.2.1.0 – Introduction- The ***goal*** of phase two of this research was to synthesize southeastern states' prescribed fire programs to identify what characteristics foster the continued use of prescribed burning and what characteristics hinder its use. We examined the same six southeastern states as phase one. Our ***approach*** continued from phase one with the smoke management programs but we extended the scope to include the entire prescribed fire regulatory environment. Phase two was carried out with two main tasks: (1) Identifying the characteristics that either foster or hinder prescribed fire and (2) and the implications of these characteristics.

3.2.1.1 – Task I, Characteristics of prescribed fire programs- Prescribed burning can often be regulated to reduce harmful emissions. Therefore, we looked closely at not only forestry-related ordinances but air quality ordinances as well. Initially, we determined if the states have any statutory laws that govern prescribed burning or open burning. Next, we focused our efforts on the Administrative Code – the rules and regulations that govern the various administrative departments. We identified what agencies regulate prescribed burning and what administrative code these states have that pertain to open burning or prescribed burning. Then we determined if these state laws are holistic in nature to the entire state, or if they are deregulated to the individual municipalities to enforce.

We grouped the characteristics that foster prescribed fire's use into laws and agency involvement. With respect to laws that foster prescribed fire we looked mainly at prescribed fire laws and regulations. Air quality laws were not considered in this section because they normally inhibit prescribed fire. For agency involvement, we looked at how involved each state's forestry agency is in their prescribed fire program and the various programs employed by each agency that increases the public's awareness and education of prescribed fire. The characteristics that hinder prescribed fire's use were grouped into social constraints, prescribed fire costs, and lack of non industrial private forests (NIPF) services. Social costs of prescribed fire can often be shifted back to the burner through regulations, liability, and insurance costs (Haines and Cleaves, 1999) and were all include in the group social costs. Once, we had identified the characteristics of prescribed fire programs we were able to describe their potential impacts whether good or bad and initiate the last step in phase two.

The last task conducted in phase two was to determine the implications of these characteristics. We assessed their potential effect on using prescribed fire and identified those characteristics that are most important for prescribed burning to remain a viable land management tool. This enabled us to evaluate the success of the various prescribed burning programs and their respective smoke management program with respect to allowing the continued use of prescribed burning. The knowledge gained from this part of our research can help facilitate the development of more advanced prescribed fire programs, smoke management plans, and the respective regulations and laws. Some states have taken the steps to produce these more advanced programs and regulations, while other states take a simplistic approach. The insights gained in this study could help those states that are lacking, develop programs and regulations that are based on the science behind prescribed burning and smoke management.

3.3 – Results and Discussion

Again, the main goal of this chapter of our research was to review six south eastern states' smoke management programs and asses what criteria was used in their smoke management plans when determining whether or not to burn. The six states we looked at included: Virginia, North Carolina, South Carolina, Georgia, Arkansas, and Florida. We investigated what criteria were used in their smoke management plans and what characteristics help or hinder a private landowners' ability to prescribe a burn.

3.3.0 – Phase 1: Smoke Management Criteria

3.3.0.0 – Introduction- We identified three key aspects of prescribed burning smoke management guidelines. The criteria that burn managers look at when minimizing smoke impacts are: *atmospheric conditions* – the ability of the smoke to dilute and disperse in the atmosphere; *available fuel loads* – size of the fire and available fuel to be burned; and *geographic location*– location of the burn in reference to sensitive sites and the amount of fuel allowed to burn for a given airshed or tract of land.

The recommended or required techniques burn managers employ varies by states' smoke management criteria. While most states incorporate some variation of all three techniques, avoidance, emission reduction, and dilution, there are still some states that only incorporate one or two of the techniques in their smoke management criteria.

3.3.0.1 – Task I, Geographic Location- The geographic location of the prescribed fire and it's relation to sensitive sites is the simplest and most straight forward approach of the smoke management techniques. One of the main objectives for any states' Smoke Management Guidelines is to identify and avoid smoke sensitive sites. Avoidance of sensitive sites was incorporated into all of the six states' smoke management guidelines and is generally the first step burn managers take when prescribing a burn. The proximity of sensitive sites can greatly impact the decision burn managers make it minimizing smoke impacts and to determine if a prescribed fire is the suitable silvicultural tool.

Geographic location and the prescribed burn's proximity to sensitive sites is the most obvious way to avoid impacting sensitive sites for smoke management criteria (VDOF, 1998). Avoidance involves identifying the smoke sensitive sites and burning when the wind is blowing away. The geographic locations of the burn and sensitive sites that could be impacted are mapped to identify the wind direction that will avoid impacting sensitive sites. While most states incorporate this method in their smoke management guidelines, Virginia relies heavily on this method in their smoke management. Although, this method has been shown to avoid smoke sensitive sites, it can force land managers and landowners to find alternatives to prescribed fire for fear of having a smoke intrusion on sensitive sites. Other states have employed more complex screening methods with respect to the geographic location. In addition to the simple avoidance strategy they take into account the fuel to be burned and how it is allocated to a given airshed or amount of land.

The simple screening model for avoidance (geographically) of sensitive sites is used in two of the states' smoke management guidelines, Arkansas and Virginia. Where both states have adopted it from "A Guide for Prescribed Fire in Southern Forests." It involves four steps: (1) locate the burn and sensitive sites on map, (2) determine wind direction and plot centerline, (3) draw two other lines from the fire at an angle of 30 degrees to allow for horizontal dispersion of the smoke, as well as shifts in wind direction, (4) determine distance to closest sensitive sites within double 30 degree angle. In addition, Virginia's guidelines require you draw a 10 and 20 mile arc with special recommendations if sensitive targets are found between 10 and 20 miles from the burn, and they recommend finding a different wind direction or an alternative to prescribed burning if sensitive sites are found within 10 miles. Although, Virginia uses this screening procedure for the basis of their smoke management guidelines, Arkansas incorporates it along with other procedures to reduce the smoke impact. While, the other states we looked at do not explicitly ask for a map of the screening for sensitive sites, they do ask for the identity, location, and distance to the nearest sensitive sites.

Stepping up in complexity from the simple screening procedure of avoidance, we identified other geographic location criteria. While still assuming the geographic proximity of sensitive sites to a prescribed fire some states have incorporated the total amount of fuel allowed to be burned based on how it is dispersed into the air as particulate matter for given geographic location. States have set threshold values on the amount of fuel that can be burned in a given air shed or tract of land. These threshold values are determined by the atmospheric conditions and distance to nearest downwind sensitive site. The most common procedure we identified was the use of Category Day – "a scale from one to five based on transport wind speed and mixing height. For smoke dispersal one is poor and 5 is excellent." (AFC, 2007) The Category Day for a given day is determined by the ventilation rate, transport wind speed multiplied by the mixing height. Once the category day is determined, the distance to the closest downwind smoke sensitive site dictates the maximum tons of fuel that may be burned per day for an airshed or 16,000 acres.

The states that have incorporated Category Days into their Smoke Management Guidelines are North Carolina, South Carolina and Arkansas (Table 3.1). North Carolina and South Carolina use Category Days to determine if the tonnage from a burn will exceed the tonnage for a 16,000 acre permissible limit. Whereas Arkansas assess whether the fuel tonnage for a burn will exceed the tons allotted for the airshed. Arkansas also based their acceptable fuel loads for Category Days based on the model VSMOKE when it predicted 159 to 175 $\mu g/m^3$ at the sensitive site. The Category Days although different have many similarities. They recommend that no burning be conducted on a Category Day of 1 or when sensitive sites are within 1,000 feet. They all have limitations on the time of day or night burning can be done with respect to the Category Day and the smoke dispersion forecast. The main difference between these states' Category Days are the threshold values they use for the distance to the nearest downwind smoke sensitive site to determine the maximum amount of fuel that can be burned.

Avoidance is simply making sure the prescribed fire smoke does not impact sensitive sites geographically. Using the Category Day, the goal is still to minimize smoke impacts on sensitive targets; however it takes into account the ability of the atmosphere to disperse particulate matter concentrations geographically over the landscape. It does not force the burn manager to choose a wind direction that avoids all sensitive sites. For example, sensitive sites may have been located downwind from a burn determined to be impacted by the smoke from the burn under the geometric screening procedure, and the burn is canceled. However, with the use of Category Days, a burn manager may reduce the maximum tons of fuel to be consumed, either by firing technique or reducing the acreage until they are within the threshold value for maximum fuel to be burned for the given Category Day. Category Days take into account the science behind smoke development and dispersion, and afford burn managers and private landowners more options with when to burn.

Table 3.1. Criteria employed by states when managing smoke from prescribed fires. A check mark indicates that state assess that criteria in their smoke management guidelines.

State	Geographic Location		Available Fuel to Burn	Atmospheric Conditions	Comments
	Proximity to Sensitive Sites	Emissions Allocated to an Airshed			
Arkansas[a]	✔	✔	✔	✔	Category Day System
Florida[b]	✔	✔	✔	✔	Online Mapping Tools
Georgia[c]	✔	✔	✔	✔	Online Mapping Tools
North Carolina[d]	✔	✔	✔	✔	Category Day System
South Carolina[e]	✔	✔	✔	✔	Category Day System
Virginia[f]	✔			✔	Atmospheric Conditions: sensitive sites 10-20 miles ventilation factor recommended

[a] Source: AFC, 2007.
[b] Source: FDOF, 2006; FDOF, 2004a.
[c] Source: GDNR, 2008.
[d] Source: NCDOF, 2009a.
[e] Source: SCFC, 2006.
[f] Source: VDOF, 1998.

We identified Georgia and Florida to have the more advance smoke management plans. The annual amount of acres prescribed burned or authorized to be prescribed burned annually indicates that (Table 3.2) as these two states had on average at least twice as much acres compared to any other state we looked at. Both states still take into account the geographic location of the burn and avoiding smoke sensitive areas. However, they do not use Category Days or the simple geometric screening process identified earlier. The Georgia Forestry Commission (GFC) requires burn managers to obtain authorizations for burning. The GFC employees who issue burn authorizations are trained to follow published guidelines for smoke dispersion (GDNR, 2008). Georgia has locations throughout the state where burn authorizations can be obtain and at each of these locations there is an area map showing smoke sensitive locations with the current wind direction of the day. GFC plots all burn authorizations of one acre or more on the map. They then analyze the burn permits in relation to wind direction, smoke sensitive receptors, and other burn permits already granted for the day to ensure there are no serious smoke intrusions (GDNR, 2008). GFC has an online Fire Weather System that offers a web-based VSMOKE application that allows burn managers and the public to predict the projected smoke plume from a prescribed fire using the location of the fire, weather, fire information, and fuel information.

Table 3.2. Yearly average amount of prescribed burn acres (silvicultural and wildlife purposes only) by state for the last five years of data available compared to the total amount of forested acres in each state.

State	5-yr Avg. of Rx acres	Total Forested Acres[a]
Arkansas[b]	283,631	18,830,000
Florida[c,g]	1,396,889	16,147,000
Georgia[d]	1,111,117	24,784,000
South Carolina[e,g]	439,543	12,746,000
Virginia[f]	20,522	15,766,000

[a] Source: Smith et al., 2009
[b] Source: Scott Reed, AFC, Malvern, AR, 2010, pers. comm., for the years from 2006-2010.
[c] Source: John Sadler, FDOF, Tallahassee, FL, 2010, pers. comm., for the years from 2006-2010.
[d] Source: Neal Edmondson, GFC, Macon, GA, 2010, pers. comm., for the years from 2006-2010.
[e] Source: Darryl Jones, SCFC, Columbia, SC, 2011, pers. comm., for the years from 2005-2009.
[f] Source: Fred Turck, VDOF, Waverly, VA, 2011, pers. comm., for the years from 2004-2008. Data is for private and federal land prescribed burned.
[g] Data is for the number of authorized acres (not acres burned) by fiscal year (July-June).

Florida is similar to Georgia in that a burn manager must get authorization from the Division of Forestry (DOF) to burn. The DOF's burn authorizations rely on a state-of-the-art weather forecasting model that predicts smoke dispersion conditions (Monroe et al., 2009). The weather forecasting model is combined with Florida's Fire Management Information System that relies on GIS technology to record and map smoke sensitive sites, weather, and prescribed fires. This allows the DOF to forecast the size and directions of the smoke plume with the GIS model and helps the DOF to predict the impacts on smoke sensitive areas. The Fire Management

Information System Mapping Tool along with their online Smoke Screening Tool used by the DOF is available to burn managers and the public online and is one of the first in the nation. Burn managers are able to see all existing or active wildfires in Florida and all open burn authorizations that are planned for any particular day and are able to screen for potential sensitive sites all via online (Monroe et al., 2009).

3.3.0.2 – Task II, Available Fuel Loads- Most of the smoke management guidelines incorporate the amount or available fuel to be consumed for the proposed burn. Available fuel conditions that can affect the resulting smoke plume, its location, duration, and concentration include the size of the burn or acres to be burned and the fuel loading or total amount of fuel to be consumed by prescribed burn. Prescribed fires produce fine particulates into the atmosphere through the combustion of fuels. With respect to the fuel available to be burned the technique employed in a smoke management plan is emission reduction. To reduce the total amount of emissions released from a prescribed fire, a burn manager must reduce the total amount of fuel available to burn. The most common emission reduction technique is to reduce the total amount of fuel to be burned. For example, dividing a larger tract of land planned to be burned into smaller individual prescribed fires. Other techniques to reduce the fuel consumed by a prescribed fire are altering the firing techniques and burning under certain moisture conditions.

The available fuel criterion that every state acknowledges in their smoke management plan is the total number of acres that are planned to be burned. However, Virginia does not correlate this in their smoke management criteria (Table 3.1), but only requests it in a prescribed fire plan. However, they do offer recommendations in their Smoke Management Guidelines. In VSMG to reduce emissions they recommend utilizing backing fires to cause a higher fraction of the fuel to be consumed in the flaming stage thus minimize the smoldering phase and reducing total smoke production. VSMG also recommend burning in smaller blocks when appropriate and under favorable moisture conditions for the objectives of the burns.

As discussed in the previous section many of the states we looked at used Category Days. Category Days take into account all three criteria we identified in smoke management plans (Table 3.1). States that use Category Days have the objective of reducing emissions for that airshed or tract of land by reducing the total fuel available for consumption. The use of Category Days allows states to control the emissions released by prescribed fires for an airshed or 16,000 acre tract of land. This gives burn managers more options by allowing them to reduce the tonnage of fuels to be consumed if their burn or nearby burns in the same airshed (Arkansas) or 16,000 acres (South and North Carolina) may exceed permissible limits. In Arkansas, the law requires burn managers to notify their Dispatch Center the day of a prescribed fire. The Dispatch Center informs the burn manager of the Category Day. This will determine the range of tons that can be allocated to the airshed based upon the downwind distance to the nearest sensitive site. If the tonnages exceed the allowed limits, the AFC Dispatch Center will recommend to the burn manager that the prescribed fire plan should be altered (AFC, 2007). The prescribed fire plan can be altered by delaying the burn or reducing the acreage. North Carolina and South Carolina incorporate similar structure in their Category Days. However, these states use 16,000 acre tracts to determine the limits of available fuel for consumption and in North Carolina a permit is required and South Carolina requires the burn manager to obtain authorization from the Forestry Commission.

The states that use Category Days give burn managers and landowners more options when using prescribed fire. If sensitive sites have been identified downwind and cannot be avoided, they have the option to reduce the fuel loads until they are within permissible limits for the downwind distance to the sensitive site. Unlike, Virginia where a landowner may be advised not to burn, Category Days give a landowner the option to possibly burn the proposed stand in smaller sections and still accomplish their management goals. Since, Category Days take into account an entire airshed or 16,000 acres; they are not always dealing with one prescribed fire. There could be multiple prescribed burns in 16,000 acres, and once a burn is completed or canceled it can make it possible for someone else in the vicinity to ignite additional fuels that day or carry out their prescribed burn.

Florida and Georgia do not rely specifically on the fuel available for consumption to reduce emissions. Instead, both these states require permits from their Forestry Commission or Division and employ state-of-the-art prescribed fire modeling and smoke management. Their state forestry departments are trained in prescribed fire and weather, and issue permits based on their knowledge and forecasting conditions. The online tools available to model prescribed fires and smoke production make it easier for landowners to see the impacts of their smoke plumes and visualize the effects. These models rely on many model inputs from forecasted weather to burn site conditions and indirectly take into account the techniques to reduce emissions at the location of the burn.

3.3.0.3 – Task III, Atmospheric Conditions- Smoke management plans must take into account the ability of the atmosphere to disperse and dilute smoke. Dispersion is defined as “the decrease in concentration of airborne pollutants as they spread throughout an increasing volume of atmosphere.” (Wade and Lundsford, 1989) The lower atmosphere’s ability to disperse and dilute smoke factors into the decision to use prescribed fire. If dispersion is poor, smoke intrusions can be associated with prescribed burns. If dispersion is too good, there is the potential for the fire to get out of control. All the smoke management guidelines and programs whether voluntary or mandatory use some form of indices to estimate the ability of the atmosphere to disperse and dilute smoke. From the six states’ smoke management plans we reviewed, we identified two common indices used to determine if the atmosphere has the potential to dilute and disperse smoke well enough to prescribe a fire. The indices we identified were the ventilation Rate and dispersion Index.

The ventilation rate (factor) is defined as the mixing height multiplied by the transport wind speed and gives a rate that indicates the ability of the lower atmosphere to disperse and dilute smoke (AFC, 2007). In Virginia’s SMG they reference the ventilation factor only if sensitive sites are between 10 and 20 miles downwind. They recommend a ventilation factor (mixing height in meters; transport wind speed in meters per second) of at least 2,000. For those states which use Category Days, Arkansas, North Carolina and South Carolina they use the ventilation rate (mixing height in feet; by transport wind speed in miles per hour) as a predecessor to the Category Day. When planning a prescribed fire the predicted Category Day will be determined on the calculated ventilation rate. This means that the ventilation rate will determine the total amount of fuel available for consumption for a particular prescribed fire based on the prescribed fire's distance to the nearest downwind smoke sensitive site. With the ventilation rate as predecessor for the Category Day, burn managers are relying on the ability of the lower atmosphere disperse and dilute the smoke for determining when to burn and how much to burn.

The dispersion index is a numerical index that estimates the ability of the atmosphere to disperse smoke from prescribed burns for a 1,000 square mile area. It takes into account the mixing height, transport wind speed, and stability near the ground (AFC, 2007). It was developed by Lee Lavdas and is related to the ventilation rate but also considers the rate of pollutant dispersion. Both Georgia and Florida incorporate the dispersion index into their Smoke Management Plans as a basis for smoke mitigation. Arkansas also lists the dispersion index as an index to ensure optimum dispersal of smoke.

The use of indices to estimate the dispersion potential in the atmosphere is one of most important components of a smoke management plan. It forces burn managers to take into account the science behind smoke development and how it is dispersed and can be mitigated. Of all the smoke management criteria states require or recommend, the ability of the atmosphere to disperse smoke can have the biggest impact smoke management. We are not saying that dispersion is the single factor that should be considered when burning because, if dispersion is too good, or the numerical index is on the high end it can make prescribed burns difficult to control. When burn managers consider all the criteria in a smoke management plan (Table 3.1) when deciding to burn or not, it appears, it does not cause a decrease in the use of prescribed fire (Table 3.2).

3.3.1 – Phase 2: Characteristics of Prescribed Fire Programs

3.3.1.0 – Introduction- We identified the main characteristics of the six states and their prescribed fire programs to determine what key aspects of their programs foster or hinder a private landowners' ability to use prescribed fire. We then assessed their implications on private landowners' and the continued use of prescribed fire.

3.3.1.1 – Task I, Characteristics that Foster Prescribed Fire's Use-To ensure prescribed fire's use in the future we identified two main characteristics of the states we looked at. They included prescribed fire laws and regulations and agency involvement – public awareness, education, and the available tools for burn managers.

Laws- With respect to laws that help foster prescribed burning we looked mainly at laws that deal directly with prescribed fire. Laws that indirectly affect prescribed burning like air quality laws were not considered in this section as they mostly limit or put certain restrictions on the use of prescribed fire. We identified five general laws that help promote prescribed fire and its use (Table 3.3). The first law we identified was a "prescribed burning" law. Which we identified as legislation specifically promoting and authorizing the continued use of prescribed fire. Also called "certified burner" laws, these statutes limit civil liability and provide a more favorable legal environment for prescribed burning (Haines and Cleaves, 1999). A "prescribed burning" law can be broad in scope and encompass some of the other laws identified in its sub-sections. Four out of the six states we looked at had a "prescribed burning" law. They included Florida (1990), Georgia (1992), South Carolina (1994), and North Carolina (1999) (Fla. Stat. § 35-590-125, Ga. Code. § 12-6-146, S.C. Code. § 48-34-30, N.C. Gen. Stat. § 113-60-40). These states' laws define prescribed burning legally, the ecological benefits, and state that it does not constitute a public or private nuisance. Having these provisions in a law is important for the continued use of prescribed burning. Whereas states' without a "prescribed burning" law can have citizens' nuisance complaints and/or local ordinances identifying prescribed burning as a nuisance, which in turn can limit the use of prescribed burning (Haines and Cleaves, 1999).

Table 3.3. The laws we identified that help foster the use of prescribed burning separated by state identifying which state has a version of a particular law.

State	Rx Law[f]	Defined Property right of owner	Considered in the public interest	Local Ordinances Prohibited in Statutes	Liability Protection Standard
Arkansas	No	No	No	No	Negligence
Florida[a]	Yes	Yes	Yes	No	Gross Negligence
Georgia[b]	Yes	Yes	Yes	Yes	Gross Negligence
North Carolina[c]	Yes	No	Yes	No	Negligence
South Carolina[d]	Yes	Yes	Yes	Yes	Negligence
Virginia[e]	no	no	Yes	No	Negligence

[a] Source: Fla. Stat. § 35-590-125.

[b] Source: Ga. Code. § 12-6-146, Ga. Code. § 12-6-148, Ga. Code. § 12-6-90.

[c] Source: N.C. Gen. Stat. § 113-60-40, N.C. Gen. Stat. § 113-60-42.

[d] Source: S.C. Code. § 48-34-30, S.C. Code. § 48-34-40, S.C. Code. § 50-2-50, S.C. Code. § 48-34-50.

[e] Source: VA Code . § 10.1-1150.

[f] Rx Law is a "prescribed fire" law that explicitly states in the legislation the ecological benefits and promotes and authorizes prescribed fire's use.

Other laws considered in this research included whether prescribed burning was considered in the public interest, a property right of the owner, and if they explicitly void local ordinances that prohibit prescribed fire. All the states examined in this research except Arkansas, considered it in the public interest (S.C. Code. § 48-34-40, N.C. Gen. Stat. § 113-60-42, Ga. Code. § 12-6-148, Fla. Stat. § 35-590-125, VA Code . § 10.1-1150). When prescribed burning is considered in the public interest it does not constitute a public or private nuisance. This gives some protection to the continued use of prescribed burning, but this statue alone cannot ensure its use. Rather, it is generally combined along with the "prescribed burning" law to give it more legal backing. Prescribed burning was recognized as a property right of landowners in the statutes of Florida, Georgia, and South Carolina (Ga. Code. § 12-6-148, Fla. Stat. § 35-590-125, S.C. Code. § 48-34-40). The legislatures in these states have realized that nonindustrial private landowners (NIPL) own a large portion of the states' woodlands, and have recognized the importance of prescribed burning. Prescribed burning as a property right ensures that private landowners' use of prescribed burning will not diminish, and gives private landowners the ability to use prescribed burning to manage their woodlands. These laws may be seen as making it too easy for anyone to burn, they are under the condition that the burner or landowner are following a prescription or the conditions under their statues to reduce risk to others.

Another statue we identified was if the state prohibited the enactment of local ordinances regulating prescribed burning. South Carolina and Georgia were the only two states that prohibit local ordinances from regulating open burning (Ga. Code. § 12-6-90, S.C. Code. § 50-2-50). Local ordinances can play a major role in limiting the use of prescribed fire. Municipalities may enact these ordinances with intentions to make the public safer. However, they do not always employ a local forester or land manager. These ordinance when created and enacted without the guidance of a person knowledgeable of prescribed burning and its benefits can lead to dangerous fuel build up and wildfires. Allowing localities to adopt their own ordinances on open burning creates a patchwork of local ordinances on prescribed fire (Figure 3.1). Differences in permits, exemptions and restrictions from various localities create a confusing regulatory situation for landowners (Mortimer, 2006). For example, Mortimer et al., (2006) looked at forest-related ordinances for Virginia's 95 counties and 40 incorporated cities. With respect to fire for forest management they found 53 percent of the localities do not address prescribed burning or open burning, it was specifically exempted in seven counties and seven cities (10 percent), and 29 counties and three cities (24 percent) exempt prescribed burning conditioned on certain restrictions. Permits or authorizations are required in six counties and eight cities (10 percent) and in one county and four cities it was prohibited all together. The dispersed regulatory landscape produces many problems to prescribed burners and smoke managers: (i) regulatory responsibilities are assigned to too many agencies; (ii) limited funds and staff are spread over many programs and agencies; (iii) effects of multiagency resistance to comprehensive monitoring of regulatory programs; and (iv) public reluctance to accept regulatory initiatives emanating from many different state agencies (Ellefson, 2006).

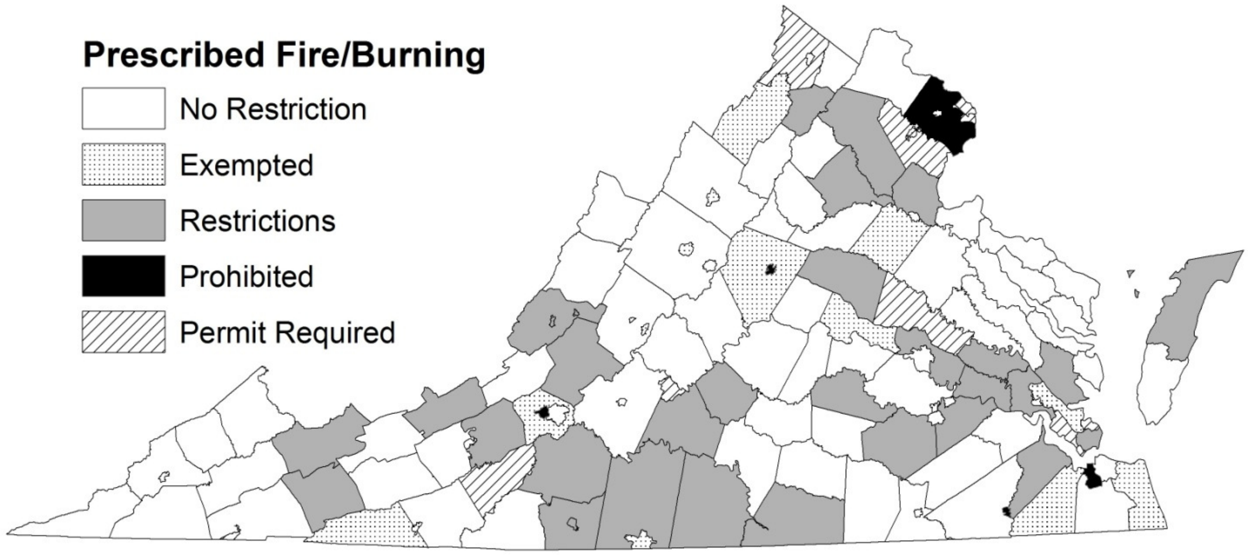


Figure 3.1 Map of Virginia showing the prevalence and type of prescribed burning ordinances by counties and incorporated cities. Adapted from Mortimer et al., (2006).

The last law affecting prescribed burning operations we identified was the liability given to a prescribed burner resulting from escaped fires, smoke intrusions, and smoke-related highway accidents. For most states we studied, the burner or landowner are only liable if the damages resulted from improperly conducted prescribed burning, and the burner or landowner acted negligently – failure to use "due care". Virginia, South Carolina, and North Carolina all require negligence as the burden of proof for being held liable (S.C. Code. § 48-34-50, N.C. Gen. Stat. § 113-60-42, Code of Virginia § 10.1-1150). In Arkansas, they do not explicitly identify the liability protection for prescribed burners. In the absence of statutory law liability the burden of proof is based on common law. The common law for prescribed fire is generally based on negligence (Yoder et al., 2004). Therefore, Arkansas can be classified with the previous states as having to prove the prescribed burner acted negligently. The states considered to have prescribed burning programs at the forefront of the southeast – Florida and Georgia both require the gross negligence standard (Ga. Code. § 12-6-148, Fla. Stat. § 35-590-125). Gross negligence as the burden of proof differs from simple negligence in that the burner must have failed to even use the slightest amount of care (Yoder et al., 2004). Gross negligence requires a lower standard of care and is much harder to prove compared to simple negligence and provides burn managers and landowners more protection with respect to prescribed burning. Although, the states we examined all had some form of negligence protection for the prescribed burner or landowner for proving liability, they all rely on compliance with the smoke management plan and/or prescription for liability protection.

"Liability is consistently listed as a major concern for land managers using prescribed fire, and is often cited as a reason for not using it." (Yoder et al., 2004) This concern comes from the fear of escaped fires, smoke intrusions, and smoke related highway accidents and often drives up the cost for prescribed burning by mitigating these fears. However, a lower standard of negligence can lower the required precautionary costs and expected damage, making prescribed burning more cost effective and worth the risk (Yoder et al., 2004). Lowering the standard of negligence does not necessarily protect the burner all together and allow them to burn at will. Yoder et al., (2004) identified that the lower liability standard is bolstered by regulations and permits which both Georgia and Florida require and is contingent on written prescriptions, sufficient firebreaks, equipment and personnel, and other factors (Yoder et al., 2004). These regulatory requirements could increase the costs at the regulatory level, but not more than a simple negligence rule would. However, the liability costs generally accrued by the burner will be reduced because of the smaller chance of being found negligent (Yoder et al., 2004). States that provide a higher standard of negligence for liability laws can indirectly drive up the costs of prescribed burning and could see a decrease in its use. However, states with a lower standard of negligence like gross negligence are providing their landowners and burn managers with more of an incentive to use prescribed burning as silvicultural tool. This was apparent in Table 3.2 where their annual average of acres prescribed burned or authorized is considerably more compared to the other states with a simple negligence standard.

Agency involvement- Public awareness and education- The contribution and involvement of an individual states' forestry department on prescribed burning can significantly impact the continued use of prescribed burning in an individual state. States' have a vested interest in prescribed burning to protect their citizens from the dangers of wildfires and doing so legislatures have recognized this in some states and have made it clear that their state forestry department has the objective to promote, educate, and assist the public with prescribed burning. States that have had legislature decisions recognizing the importance of prescribed burning and tasking their forestry department to develop programs to educate the public and promote its use include Florida and Georgia (Ga. Code. § 12-6-149, Fla. Stat. § 35-590-125). These states' statues clearly define that their state forestry department is in charge of promoting prescribed burning for hazardous fuel reduction and using it as forest management tool and to educate the public of prescribed burning and its benefits (Table 3.4). These statutes are critical for the continued use of prescribed burning. They show that in these states their ligatures understand the benefits of prescribing burning, conflicts arising from increasing urban areas dangerous fuel build ups in woodlands adjacent, that natural ecosystems require periodic fire, and that conflicts are arising resulting from liability issues and the public misconception of prescribed burning.

In these states the forestry department tends to be more encouraging for using prescribed fire to manage private woodlands and have developed programs to ease the process of one trying to prescribe burn their land. Georgia and Florida on average burn or authorize more acres per year compared to the others reviewed (Table 3.2). These states have developed programs/initiatives for prescribed burners or landowners and programs to make aware and educate the public. For prescribed burners and private landowners considering burning, forestry departments have developed dispatch centers, offer prescribed burning services, memorandum of understanding (MOU) with other departments or divisions, strategic plans for the future of prescribed burning, programs to train, educate, and certify prescribed burners, and made available tools for prescribed burners. All the states we looked at with the exception of Virginia have developed in one form or another, centralized dispatch centers for prescribed burners (AFC, 2007; GDNR, 2008; SCFC, 2006) or incorporate required authorizations or permits to burn by contacting their forestry agency (Fla. Stat. § 35-590-125, N.C. Gen. Stat. § 113-60-40). Dispatch centers provide burn managers with a centralized location to receive authorization and notify the forestry department of possible burns and obtain fire weather forecasts for a certain area. These states with dispatch centers ease the process for burn managers in obtaining permits, if needed, and fire weather forecasts. Limiting many of the barriers burn managers in Virginia might have in notifying the respectable authorities and obtaining on site fire weather conditions. All the states we studied have some form of training and certifying prescribed burners rather voluntary or mandatory. These programs help ensure that educated and experienced individuals are the ones carrying out burning operations. Certification when mandatory could reduce the adverse consequences of prescribed burning operations. Mandatory certification for prescribed burners can safeguard the public as burners are more knowledgeable of the science behind smoke production and fire ecology.

In all the states except in Virginia, the forestry department offers assistance with carrying out prescribed burning operations (Table 3.4) (FDOF, 2004b; AFC, n.d.; SCFC, 2010.; NCDOF, 2009b). Although, some states will not ignite the fire they will still assist with the burn (GFC, 2011). This greatly eases the process for private landowners wishing to use prescribed burning as a management tool. Even though in Virginia the DOF will not prescribe a burn for private landowners, they still offer services for fireline construction (Gwenn Tyler, VDOF, Buckingham, VA, 2010, personal communication). Most private landowners do not have the knowledge or physical capability to carry out prescribed burning operations. States that offer prescribed burning as a service to its citizens can significantly reduce the critical fuel build up and return fire to private lands that have been fire exclusion over the past decades. This limits the barriers to private landowners wanting to use and incorporate fire on to their woodlands.

Other achievements identified by state forestry agencies include MOUs and strategic plans for the future of prescribed burning. MOUs are critical if prescribed fire is to be incorporated as a states' best management practices (BMP) option. Prescribed burning not only deals with the forest ecology but can have externalities resulting in degradation of air quality. Therefore, it is imperative, that if prescribed burning remains a viable silvicultural tool that agreements, ease of communication, and MOUs be made between state forestry and air quality agencies. MOUs can reduce the misunderstandings, promote cooperation between agencies, and streamline the processes for smoke management from prescribed burns. Agency cooperation should not be just in the form of MOUs. State agencies should also combine their knowledge and staff when considering the future of prescribed burning. For example, Georgia in 2008 convened a "Fire Summit" to draft "Prescribed Fire in Georgia, A Strategic Plan 2008-2020," where they identified their goals and objectives for the future of prescribed fire in Georgia. The "Fire Summit" was composed of professionals from the natural resource private sector, inter-state and intra-state agencies both forestry and air quality, and federal employees. This cooperation between state agencies, private industries, state and federal governments, and with other states exemplifies the complexity of prescribed burning operations and smoke management and how it should be addressed in the future.

Table 3.4. Private landowner assistance provided by the respective state agencies.

State	Rx Assistance	Fireline Construction	Provides List of Rx Contractors via Website	Statute Tasking the Forestry Agency[g]
Arkansas[a]	Yes	Yes	Forestry Commission	No
Florida[b]	Yes	Yes	Division of Forestry	Yes
Georgia[c]	Yes	Yes	Forestry Commission	Yes
North Carolina[d]	Yes	Yes	Department of Natural Resources	No
South Carolina[e]	Yes	Yes	Prescribed Fire Council	No
Virginia[f]	No	Yes	Department of Game and Inland Fisheries	No

[a] Source: AFC, n.d..
[b] Source: FDOF, 2004b; Fla. Stat. § 35-590-125.
[c] Source: GFC, 2011; Ga. Code. § 12-6-149.
[d] Source: NCDOF, 2009b.
[e] Source: SCFC, 2010.
[f] Source: Gwenn Tyler, VDOF, Buckingham, VA, 2010, pers. comm.,
[g] Statute that tasks the state's forestry agency to educate the public (Georgia) or maximize prescribed burning (Florida).

As states and their forestry agency develop more advance prescribed burning programs, some states have accepted the role of providing their burn managers, private landowners, and citizens online tools to assist in development of the their prescribed fire plan and smoke management plan. Florida and Georgia have developed advance prescribed fire and smoke modeling online tools (GA: http://vsmoke.gfc.state.ga.us/Vsmoke/index.aspx, FL: http://flame.fl-dof.com/wildfire/tools_sst.html). In both these states these tools are made available online to the public and burn managers. Having these tools readily available to burn managers and private landowners quickly assess if prescribed burning is a viable silvicultural tool for treatment of an individual's land. It allows burn managers and private landowners to visually and geographically see the impact of a prescribed burn on their land. These same tools available publically are the ones the state agencies use in determining authorization or approving permits. This could greatly reduce the submission of non-practical prescribed burn plans due to the proximity of downwind sensitive sites and streamline the process for prescribed burn authorizations and approvals.

The final type of agency involvement identified in this research was public awareness and education of prescribed fire's benefits. Prescribed fire can be controversial when it is misunderstood. All the states identified in this research have incorporated public awareness and education into their prescribed fire programs. Having the public aware of the benefits of prescribed burning and educated as to good fire, bad fire is critical for the continued use of prescribed burning. If the public does not support prescribed fire, it'll likely see resistance for its use in managing woodlands. Georgia, has a one of the most advance prescribed fire programs and Georgia's extensive public awareness campaign for prescribed fire use and benefits could be directly tied to it. The Georgia Forestry Commission (GFC) provides door hangers, educational brochures, posters, and videos to help burn managers in notifying and educating the public. They make public appearances at landowner meetings, civic clubs, schools and fairs with the intentions to educate the public of the benefits of prescribed fire (GDNR and GFC, n.d.). They have implemented a school oriented program for 4^{th} and 5^{th} grade students with a Fire Prevention CD that introduces the students to the concept of good fire, bad fire. Along with all the educational material the GFC provides they have also implemented a Prescribed Fire Awareness Week to promote and educate the public and to recognize land managers who conserve the states' natural resources (GDNR, 2008). Steps taken to educate the public like Georgia have shown is imperative to continue using prescribed fire to manage forests. As urban areas grow and more conflicts arouse from the WUI, public acceptance of prescribe fire and support are important characteristics forestry agencies should considered to maintain prescribed burning for future generations.

3.3.1.2 – Task II, Characteristics that Hinder Prescribed Fire's Use- Even though prescribed fire programs are growing and it is being used in many states across the U.S. it's important to identify those constraints that limit private landowners' ability to apply prescribed fire to their woodlands. It has been well accepted in the literature of the ecological benefits of prescribed fire and the social costs of harmful emissions and degraded air quality that can result from burning operations. These social costs are what drive the development of regulations, increased insurance costs, and fear of liability. Regulations have been increasing to restrict the downwind impacts of smoke from prescribed burning at the federal, state, and local level. Smoke management regulation has become one of the most important barriers to prescribed burning. Most of these regulations are dealing with prescribed fire as a source of air pollutants and hazards as a result of the constraints that arise when forest areas are in close proximity to residential, commercial, or industrial developments. Although, some legislatures have recognized the benefits of prescribed fire, there are still some states that think more regulation of smoke management from prescribed burns is needed. Although air quality regulations can prevent the application of prescribed fire, it is important to realize that legislatures are trying to minimize the social costs borne from prescribed burning. However, it can have inadvertently increase the notion of liability.

Prescribed burners are exposed to two types of liability that include escaped burns and smoke impacts. These events, generally rare, but can result in catastrophic losses and costly litigation. The notion of liability becomes even more complex when added with the uncertainty associated with common law from judicial decisions regarding prescribed fire liability. The potential of the fire jumping the control line and becoming an uncontrolled wildfire would bring threats to human life and property. The litigation that would follow is what constrains the use of prescribed fire. The potential for these events to occur is what drives up the cost of prescribed burning insurance for forestry consultants. Private forestry consultants and businesses generally accept the fact that they must pay their insurance premiums. However, most insurance companies have lower premiums for those companies that do not offer services for prescribed burning operations. Therefore, private forestry consultants have an incentive not to offer services for prescribed burning operations to lower their operating costs as a company. For those companies that carry out prescribed burning operations, they are forced to pay higher insurance premiums. These increased operating costs are generally borne by the private landowner paying for the service.

The social costs of prescribed burning through litigation and liability claims is what drive the cost of prescribed burning and produces and the lack of NIPF burning services. The monetary costs of prescribed burning services as a result of the social costs associated are not just a result of higher insurance. Prescribed burners must take the necessary steps and procedures to ensure their prescribed burn does not escape or have smoke impacts. This means longer times and more attention to detail in planning the burn, preparing the burn and control lines, and carrying out the burn. Undoubtedly leading to increased help and having to hire and pay more employees. These increased costs in prescribed burning operations will be passed down to the private landowners often deterring the use of prescribed burning for private landowners even when the services for prescribed burning are present. The monetary costs of prescribed burning not only deter private landowners from wanting to use prescribed fire but also make it more favorable financially, for forestry consultants not to offer prescribed burning services. Forestry consultants that do not offer services for prescribed burning operations are not only able to lower their insurance premiums but are able to operate their company with fewer employees and equipment and lower their overall operating costs, thus, giving them the incentive not to offer prescribed burning services.

3.3.1.3 – Task III, Implications- The implications of these programs, whether they help or hinder the ability to prescribe a fire, can have long lasting effects on private landowners. Prescribed burning must remain a viable silvicultural tool, so that dangerous fuel build ups and wildland fires are reduced and the ecological benefits of its use remain available. When those characteristics that hinder prescribed burning outweigh its benefits, private landowners may be forced to find alternative treatments. As residential development increases and wildland fires are becoming in contact with the WUI the prescribed burning environment is becoming more complex. States' legislatures and their forestry agencies must address prescribed burning legally and increase agency involvement if prescribed burning is to remain a viable silvicultural tool.

To ensure prescribed burning remains a tool for land managers and private landowners to manage their woodlands, the regulatory and legal environment needs to remain favorable for its use and provide protection for burners and landowners who wish to use it. Prescribed fire is scrutinized and regulated to manage the air pollutants associated and to minimize the hazards that could result. To continue applying prescribed fire, air resource managers and legislatures must realize that the emissions associated with burning are a onetime occurrence and can be mitigated by burning with the atmospheric conditions are optimal. As legislatures become aware of the benefits and regulations are developed recognizing and promoting the importance of prescribed burning, it is imperative that the public acceptance of its use as an ecological treatment is present. Legislatures should recognize the role that forestry agencies should have in educating and promoting prescribed burning. Agencies should accept the role, and increase their involvement by providing materials, information, and making public appearances discussing the benefits of prescribed burning. Not only should agencies assist in making the public more knowledgeable of prescribed burning, but should provide tools and information for burn managers and private landowners assisting them with planning and carrying out prescribed burns.

The complex prescribed burning environment will likely continue to amplify and the liability issues associated with escaped fires and particular smoke impacts will see increases if they are not addressed. Smoke impacts from prescribed burning operations were identified as the main liability constraint to electively using prescribed fire. Smoke is influenced by factors which the burner has no control over (i.e. weather). However, it can be minimized through prediction services offered by various meteorological companies and the National Weather Service. With predicted weather parameters, there is still the possibility of having smoke intrusions on sensitive targets; this notion of liability is the main reason landowners look to alternatives to prescribed fire. The liability issues regarding smoke intrusions have yet to be challenged in many states' court systems, making it difficult to consider how the court might handle the situation. It is likely the court will not consider the broad social benefits of prescribed fire in the application of liability law, thereby discouraging its use (Yoder et al., 2004). On the same concept of overcoming the screening of sensitive targets the notion of liability associated with smoke impacts can be mitigated by applying a model based on fuel characteristics, spatial data, and meteorological data for predicting smoke plumes. In the southern states there has been a demand by private landowners to reduce the liability burden placed on burn managers (Sun, 2006). This demand is conflicted with the increasing residential development in forested areas that may exacerbate liability risks and increase public pressure against burning (Haines and

Cleaves, 1999). Educating landowners of the ecological, wildlife and social benefits of prescribe fire would alleviate the pressure against burning and could possibly lead to lighter liability rules.

Knowledge of the constraints and incentives for prescribed burning will facilitate the development of better regulations. Better regulations in some states are needed and the natural resource management community must work with legislatures and the public to ensure prescribed burning will remain a forest management tool for private landowners. The future prescribed burning environment will likely see some resistance, and there is a need for interdisciplinary research projects to include not only the ecological effects but the broad social and legal implications of prescribed burning for private landowners.

Chapter Four
GEOGRAPHIC ANALYSIS AND CASE STUDY

4.0 – Background

Smoke management regulation has become one of the most important barriers to prescribed burning on private woodlands. Compliance with smoke management regulations and the intimidating process of managing smoke from prescribed burns can make it difficult for private landowners to manage their forests with prescribed fire (Gass, 2009). Prescribed fire's use has decreased substantially on private lands in Virginia, yet is still recognized as a viable silvicultural tool and is increasing on federal lands and conservation lands like The Nature Conservancy (Yoder, 2002; TNC, 2010). A U.S. Forest Service survey for the south in 1985 on the economic benefit of prescribed fire identified that for every dollar spent in prescribed fire fuel management, $2.14 in suppression and damage costs for wildfires was saved (FDOF, 2004c). The benefits of prescribed fire for wildfire mitigation are evident, yet private lands in some states are still not receiving its application.

In order to maintain prescribed burning as a viable silvicultural tool for private landowners, we needed to understand the regulatory environment for prescribed burning. In Virginia the state smoke management barriers are a generic, one-size-fits-all guideline with respect to how much smoke might be produced and may be confusing to a private landowner not familiar with prescribed burning or managing smoke. According to the Virginia Administrative Code 9VAC5-130-50, open burning is permitted for forest management practices provided that the burning is conducted in accordance with Department of Forestry smoke management plan (SMP). However, Virginia's SMP and burn manager certification is voluntary. Thus, if one wishes to prescribed burn under 9VAC50130-50 with the benefits of certification (liability protection) they must be follow a SMP and be certified (Fred Turck, VDOF, Waverly, VA, 2011, personal communication). The problem is that this creates a confusing situation with regulatory compliance when managing smoke from prescribed burns. Private landowners may not be familiar with these regulations and guidelines. In Virginia, alternative methods to prescribed burning for site preparation and fuel reduction are being utilized more (Fred Turck, VDOF, Waverly, VA, 2011, personal communication). This confusing situation for regulatory compliance may be leading to the decreasing use of prescribed burning on private land in Virginia even though prescribed fire's use is increasing on national forests lands in Virginia (Figure 4.1).

When managing smoke to reduce the impacts on sensitive sites it is recommended that if sensitive sites are within 10 miles downwind an alternative to prescribed burning be done (VDOF, 1998). This can give the perception that one should do something else, when the actual science behind smoke production and dispersion could indicate that the distance to sensitive sites affected would be much less. Misleading SMG coupled with the confusing regulatory situation with smoke management could be leading to use of alternatives to prescribed burning. SMG based on the science of smoke production and dispersion, and regulations that favor prescribed burning in an ecologically beneficial and legally responsible manner are needed.

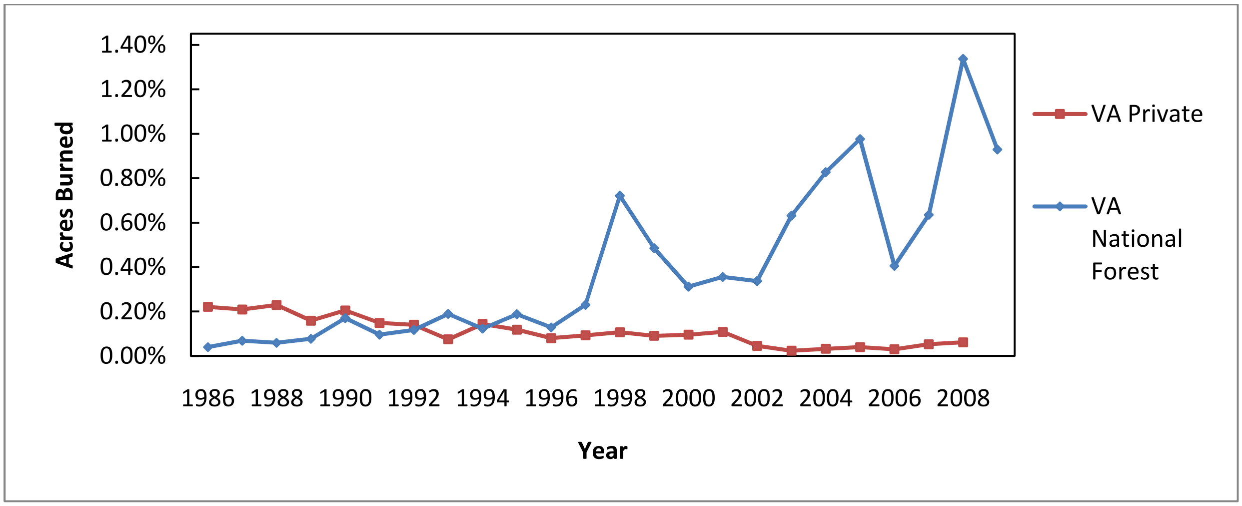


Figure 4.1. Percent of Virginia private land and Virginia National Forests prescribed burned annually. Percentages are of Virginia's total forested private land[a,b] and total forested acres of national forests in Virginia[a,c].

[a] Source: Created from data obtained from Fred Turck, VDOF, Waverly, VA, 2011, personal communication.

[b] Source: Created from data obtained from Smith et al., 2009.

[c] Source: Created from data obtained from USDA, n.d..

New methods and models developed over the past decade for predicting smoke impacts from fires have provided a means to overcome the regulatory barriers limiting the use of controlled burns (Lahm, 2006). Geospatial models combined with GIS technology make it possible to predict downwind smoke concentrations, as well as provide insights into locations that have regulations that prohibit or limit controlled burning. Identifying the localities in Virginia that prohibit or limit controlled burning has helped uncover the regulatory barriers to prescribed burning in the state.

The objective of Chapter Four of the study was limited to Virginia and ***consisted of a geographic analysis of Virginia's current methods and involved a case study approach to demonstrate, quantitatively, how much area may be impacted in Virginia with minimal apparent benefit***. This included applying the screening systems for sensitive sites with Virginia's Smoke Management Guidelines (VSMG) and the model VSMOKE-GIS throughout Virginia. We quantified how much forest land is potentially available and favorable for burning in Virginia given a hypothetical burn scenario by two alternate ways to screen for sensitive sites. We wanted to assess the extent to which VSMG limit burning compared to one alternative based on VSMOKE and ***our working hypothesis was that VSMG are far more restrictive than they need to be***.

Results of the geographic analysis provided a clearer spatial picture of the barriers associated with prescriptive burning on private woodlands in Virginia. The geographic analysis and case study could help promote a regulatory environment where scientific tools and knowledge are used to prohibit only activities for which the evidence suggests there will be adverse consequences. The results from the model tests could be a useful tool in developing more defined management strategies for prescriptive burning in Virginia. Model results combined spatially with smoke sensitive targets and weather information have indicated how much forest in Virginia is potentially available to be prescribed burned.

4.1 – Literature Review

Prescribed Burning

McNabb (1995) defined prescribed burning as fire applied in a skillful manner to an area, under a particular set of weather conditions for a specific purpose to achieve certain results. Prescribed burning is accepted by professional forest managers as a valuable silvicultural tool to reduce the wildfire damage to the environment (Haines et al., 2001). When used properly, low-intensity fires like prescribed burns have been shown to have little adverse effect on the chemical and physical properties of soil or stand composition. Fewer emissions on a per acre basis are released into the atmosphere compared to wildfires (Wiedinmyer and Hurteau, 2010). However, despite its ecological and protection importance to silvicultural practices, it has become increasingly subject to constraints such as air quality and other environmental regulations, and liability issues relating to smoke intrusions and escaped fires (Haines et al., 2001). When fire is excluded from an ecosystem, it can have a profound effect on the structure of those ecosystems and their economic productivity (McNabb, 1995).

The application of prescribed fire is determined by its objective – a desired outcome or future condition (Vose, 2000). Prescribed fire can have many management objectives. One prevalent objective is to reduce fuel loads and the possibility of threats from wildfires. Other objectives include site preparation, improvement of wildlife habitat, disease control, increase fodder production, appearance, and access (McNabb, 1995). These objectives are used to achieve short term and/or long term ecosystem conditions. For example, returning the forest conditions to those prior to human influence or pre-European settlement, altering the structure and function of the ecosystem, creating and maintaining unique habitats, and increasing the value of commercial species (Vose, 2000).

Ecosystems have evolved mechanisms to handle repeated burning. Forests resist the overall impacts of burning by developing thick bark, recovering/sprouting quickly, and cone serotiny (Vose, 2000). Although these mechanisms help deal with the effects of prescribed burning, it depends greatly on the intensity and severity of the prescribed burn (Vose, 2000). Although prescribed burning is recognized as a viable silvicultural tool, it produces smoke and harmful emissions that can degrade air quality and reduce visibility. The smoke and emissions produced from prescribed fires are considered to be the greatest barrier to its effective use. Haines et al. (2001) conducted a study where they mailed a questionnaire to the forest supervisor of each national forest in the south and one representative from each of the 12 southern states' forestry agencies. The questionnaire asked them to characterize their respective prescribed burning programs and identified the trends, purpose, and barriers to prescribed burning. They found that two barriers, air quality and smoke management laws and risk of liability, were the most highly rated barriers for both national forests and state fuels managers. Negative public opinion was the primary barrier on private forests (Haines et al., 2001). An unsightly landscape can be ignored by the public, but the reduced visibility and choking smoke (particulate matter) are too apparent (Crow, 1973). Social constraints force fire managers to take precautions that increase the costs of prescribed burning operations (Gonzalez-Caban, 1997). The use of prescriptive burning decreases substantially with higher costs. Air control regulations could seriously curtail the use of prescriptive fire (Crow, 1973).

Regulatory barriers present huge problems to fire managers using prescribed fire effectively and are among the top concerns limiting its use for private landowners (Haines et al., 2001). Smoke is the primary adverse impact from prescribed burns (Dennis, 2002) and is the focus of the majority of regulations concerning prescribed burns. These regulations are most concerned with "sensitive targets": airports, hospitals, schools, nursing homes, and major highways. The increasing use of regulation to achieve environmental protection goals, and the litigious nature of American society are increasing voluntary compliance with smoke management guidelines and Best Management Practices (BMP) to stave off the public's negative opinion and stricter regulation of prescribed fire (Haines and Cleaves, 1999).

<u>Smoke Management</u>

Due to the smoke and emissions released during prescribed burning operations, smoke management must be considered in every prescribed burning plan (Turck, 2009). Achtemeier (2009) defined smoke management as the action taken by a land manager to minimize the environmental impact of smoke. According to the VDOF's Guide to Prescribed Burning in Virginia (Turck, 2009), the three main objectives of smoke management are avoidance, dilution, and emission reduction. A prescribed burn manager wants to avoid smoke-sensitive areas, disperse and dilute the smoke before it reaches the smoke-sensitive areas, and reduce the smoke (emissions) produced from the burn site. As the use of prescribed burning continues to increase, the need for better smoke management is evident. This is compounded by the increases in the populations living within the WUI and has resulted in more people being exposed to smoke (Robison, 2007). The combination of increased burning and public smoke exposure has created a need for improved predictive tools for smoke production, dispersion, and weather (Robison, 2007, Lahm, 2006).

Smoke from prescribed burns can adversely impact air quality, visibility, and can cause health problems for sensitive individuals. Prescribed burns produce smoke that is composed primarily of water vapor, however it produces pollutants that can harm the public (Turck, 2009). Pollutants that are released during burning include particulate matter, hydrocarbons, carbon monoxide, nitrogen dioxide, and sulfur dioxide. With respect to public health, particulate matter is the pollutant of concern. The other pollutants are released in negligible amounts or are diluted in the open air (Turck, 2009). Particulate matter reduces visibility. The concern for burn managers is the possibility of degrading the visibility in a Class I Air Shed – EPA designation of a pristine area, where little deterioration of visibility is allowed (Wark et al., 1998). Class I Air Sheds include wilderness areas and some national parks. The Grand Canyon Visibility Transport Commission (GCVTC) found that emissions from wildland fire and prescribed fire are likely to be the single greatest impact on visibility in a Class I Air Shed (Sandberg et al., 2002). The GCVTC also stated that during intense fire activity, smoke from wildland fires is likely to produce visibility days for the Grand Canyon in the lowest 20 percent.

Regulations concerning prescribed burns originate from air quality laws, forest fire control laws, laws concerning property damage and personal injury from escaped fires, and environmental laws such as the Endangered Species Act and the Clean Water Act (Haines and Cleaves, 1999). Of these regulations air quality laws affect prescriptive burning the most. As more people move into the WUI, tighter regulations have been enacted for prescribed burning. An increased interest has developed in forestry burning as an air pollution source and has forced governments to regulate prescribed burning within their jurisdiction. These air quality regulations, though often not severe, are usually only enforced upon complaint (Hauenstein and Siegel, 1980). Examples of air quality regulations that pertain to prescribe burning include obtaining a permit, prohibiting burns near roads and inhabited areas, restrictions on windrow burning, prohibiting the use of heavy, oil based starter fluids, restrictions on time of day and season of burn, and prohibiting activities that impair visibility (Haines and Cleaves, 1999).

Throughout the United States prescribed fire is increasingly scrutinized and regulated (Cubbage, 1995). The hazards associated with prescribed fire are a result of the increasing residential developments and wildland fire becoming in contact with the WUI and the threat of having smoke impacts on these areas and the individuals there. Regulations for these hazards can be attributed to the increasing social conflicts between urban and rural residents in rapidly urbanizing communities (Martus, 1995). The most prominent hazards that arouse conflicts between urban and rural residents are: human health hazards, highway accidents associated with smoke, probability of an escaped fire resulting in personal injury or property loss (Haines and Cleaves, 1999). These hazards are the driving force behind prescribed fire regulation. Coupled with the potential liability associated with prescribed fire smoke and the threat of escaped fires, hazards are the primary factor for litigation (Sun, 2007).

Smoke Models

Smoke dispersion models are valuable tools in smoke management, especially for screening and planning (Breyfogle and Ferguson, 1996). Smoke dispersion is considered a second-order fire effect, which occurs over a long time frame – days, months, or years (Reihardt et al., 2001). However, to model smoke dispersion, it is necessary to have estimates of smoke production, a first-order fire effect that occurs at the time of the fire or within seconds or minutes. Smoke production is often modeled at the stand level. However, as smoke disperses, it moves spatially so that smoke dispersion models generally have a broader spatial extent (Reihardt et al., 2001). Spatial extent is used to group the models into local models (day and night) or regional models. Regional models predict the impacts of prescribed fire smoke across large areas (hundreds of miles), whereas local models predict the impacts of smoke locally (generally less than 70 miles). Examples of regional models include BlueSky and Southern Smoke Simulation System (4S). Local daytime models include VSMOKE, CALPUFF, and DaySmoke (Achtemeier, 2009). One of the more deadly smoke impacts, in terms of personal injury, is the movement of smoke at night. There are a few models that have been produced to predict the movement of smoke at night on the local scale; they include PB-Piedmont and Superfog (Achtemeier, 2009).

Of the above models only VSMOKE is complete and operational (Achtemeier, 2009). Although VSMOKE is complete and operational there are no studies to validate it and very few, if any, for other smoke dispersion models (Bill Jackson, U.S. Forest Service, Asheville, NC, 2009, personal communication). This illustrates one of the challenges for all smoke dispersion and impact models – being able to characterize their accuracy of predicting smoke trajectories, concentration of pollutants, and duration of impacts (Lahm, 2006). Long term investment in these models' development and modifications needs to continue to better assess smoke impacts from prescribed burns (Lahm, 2006).

VSMOKE is a smoke screening model developed by the Forest Service for application in the Southeast (Bill Jackson, U.S. Forest Service, Asheville, NC, 2009, personal communication). It is a steady-state, local daytime smoke dispersion model that estimates the effects of prescribed burning on air quality and visibility. It predicts downwind concentrations of particulate matter at 31 fixed distances, and how far and how well a person may see through the smoke plume at each distance (Jackson et al., 2009; Achtemeier, 2009). VSMOKE has an interface with FEPS to get estimates of the amount of fuel consumed and the emissions factors. The emission factor is used along with the amount of land burned, fuel load, and duration of impact to obtain the emission rate. This emission rate can then be combined with meteorological data to obtain estimates of the effects of prescribed burning on air quality.

4.2 – Research Methods

Using the data collected in Chapter Three on Virginia's SMG and the results of VSMOKE-GIS's pilot validation in Chapter Two, the geographic analysis and case study focused on testing our underlying hypothesis that VSMG are far more restrictive than they need to be when screening for sensitive sites. Output plumes from VSMOKE-GIS were used and applied to the whole state along with the current VSMG to screen for sensitive sites. The information collected was compiled in ArcGIS for display and comparisons. These comparisons allowed us to complete the case study in Virginia comparing the current guidelines of screening for sensitive sites versus using VSMOKE-GIS to screen for sensitive sites. This enabled us to gain quantitative data on the amount of land that could be burned.

4.2.0 – Phase 1: Geographic Analysis

4.2.0.0 – Introduction- Our ***approach*** was initially to analyze the two screening systems and then to compare the amount of forest land available to burn under each system. This data enabled us to obtain quantitative estimates for the potential area of Virginia that can be burned.

4.2.0.1 – Task I, Compiling the Data- The first step in this task was to collect geographic data on Virginia's sensitive sites. After the data was collected and represented, we determined the prevailing wind directions at sensitive sites, and determined the prescribed burn conditions that represented small private landowners and used this burn information for input into VSMOKE.

GIS data was obtained from Virginia's Information Technologies Agency (http://gisdata.virginia.gov/Portal/). We obtained a statewide layer of Virginia counties and sensitive sites. Sensitive sites included airports, hospitals, nursing homes, schools (public, private, and universities), correctional facilities, and Class I airsheds. We did not collect data on major highways or urban areas as most of the sensitive sites we had, had overlapping boundaries with those areas. We combined all these layers into one dataset for the analysis. After all the sensitive sites were obtained, the next step was to define the prescribed burn conditions used as inputs for VSMOKE and screening for sensitive sites. The Difficult Creek burn used for validation in Chapter Two represented a typical private landowner prescribed burn. So the same conditions we recorded at that burn were used for inputs. We had a simulated burn that was 54 acres in a mixed forest.

The last step in compiling the data consisted of assigning a prevailing wind direction to each sensitive site. The National Weather Service defines the prevailing wind direction as the direction that the wind blows most frequently. When possible, within topographic and space limitations, airports construct runways based on the prevailing wind at that location and our airport layer had the bearing of its primary runway included in the attribute table. We assigned each airport a prevailing wind direction based on its primary runway. Then we created Thiessen polygons around each airport. A Thiessen polygon is an area around a point such that any location inside that polygon is closer to that point than any other point in that dataset. This created a layer that had a polygon around each airport with the prevailing wind direction. These polygons were used to assign the prevailing wind to all the sensitive sites within the polygon. Thus, every sensitive site then had a prevailing wind direction associated with it, based on the closest airport. Our prevailing winds ranged from 181 to 360 degrees. We then combined the sensitive sites based on a range of degrees for the prevailing wind direction creating four primary wind directions. We created four layers with our sensitive sites, with each layer containing all those sensitive sites with a prevailing wind direction range. The ranges we used were azimuths of 181-230, 231-270, 271-320, and 321-360 degrees. We took the median azimuth for each range and assigned that as the wind direction for the sample burn with the double 30 degree angles added (Table 4.1).

Table 4.1. The four ranges of prevailing winds used for projecting the prevailing winds, with the prevailing wind and double 30 degree angle ranges used for the mask. All numbers are degrees.

Prevailing Wind Range	Centerline Angle for Prevailing Wind	Double 30° Angle Range
181 – 230	205	175 – 235
231 – 270	250	220 – 280
271 – 320	295	265 – 225
321 – 360	340	310 – 10

4.2.0.2 – Task II, VSMG and VSMOKE Analysis- The first step in this task was to represent VSMG geographically and then next VSMOKE-GIS's plumes as used to screen for sensitive sites. According to VSMG, the predominant wind vector for the day of the prescribed burn must be drawn from the burn area. After the wind vector has been drawn, two 30 degree lines need be drawn from the center line to account for horizontal dispersion. Once the three lines are drawn, 10 mile and 20 mile arcs are drawn across the three lines. All the sensitive targets must be accounted for within these 10 and 20 mile buffers, and then the recommended procedures will be followed to reduce smoke to those targets within the buffers (VDOF, 1998). According to VSMG if sensitive targets are found between 10 and 20 miles, the burn manager may burn as prescribed. However, if sensitive targets are found within 10 miles VSMG recommend the burner find an alternative method of treatment. For this reason our analysis of VSMG screening for sensitive sites focused on the area included in the double 30 degree angles within 10 miles of the proposed burn and was referred to as the VSMG mask.

To represent the amount of area covered under the VSMG mask we worked backwards from the sensitive sites. We had the prevailing wind direction at each sensitive site. To determine the area of land each sensitive site prevented one from burning we took the reciprocal heading of the prevailing wind direction (added or subtracted 180 degrees). For example, if the prevailing wind direction was 270 degrees or west the reciprocal heading was 90 degrees or east. We projected the VSMG mask with the reciprocal wind direction for each sensitive site with the double 30 degree angle. Projecting the mask with the reciprocal wind direction created our masks upwind from the sensitive sites. The masks covered all the land upwind from the sensitive sites that may not burn because of the respective sensitive site being downwind.

To represent the VSMG masks we used the Neighborhood Statistics function in ArcGIS to create wedges at each sensitive site. The wedges were created by assigning the reciprocal prevailing wind range in degrees for the double 30 degree angles and setting the calculation out to 10 miles. This created four raster layers, one for each prevailing wind range. We combined these layers to produce one raster layer combining all four prevailing wind ranges and assigned values of zero or one corresponding to whether you cannot burn or can burn, respectively. To satisfy the requirement of no occupied dwellings being within 1,000 feet of prescribed burn, we created 300 meter buffers around each sensitive site. This buffer layer was then converted to a raster and combined with our VSMG mask layer. Once, we had our final VSMG Mask layer, we added a National Land Cover Dataset (NLCD) raster for Virginia. This had all the land in Virginia grouped by land cover. We combined the NLCD layer with VSMG Mask layer to give us all the land in Virginia that can be burned or cannot be burned by land cover. We were then able to get estimates of the amount of forest land in Virginia that can be burned based on the current SMG.

The VSMOKE analysis was conducted much like the VSMG. We used the Difficult Creek burn to produce our VSMOKE-GIS plume used to create our VSMOKE Mask layer. All the same steps followed in creating VSMG Mask layer were used in creating the VSMOKE Mask layer. The only difference was how far out the analysis was undertaken to create the wedges. For the VSMOKE wedges we conducted the analysis out to 0.9 miles. This distance was chosen based on longest distance downwind that VSMOKE-GIS projected concentrations of $PM_{2.5}$ to have an AQI class of three or a concentration of 89-138 $\mu g/m^3$. These concentrations have a level of health concern that is “Unhealthy” for sensitive groups. We then followed the same steps as previously. We included the 300 meter buffer around sensitive sites, because in completing Chapter three of this research – review of other states smoke management guidelines, we found that most states use the 1,000 foot buffer or similar restriction.

4.2.0.3 – Task III, Comparison- Building on the data and insights collected in Task II from the analysis, Task III – comparison of the two screening models was undertaken. We evaluated each screening system with respect to the amount of land that can be burned when the conditions are optimal for the sample burn. We produced quantitative estimates by smoke management program of the amount of land that can be burned, the amount of land that will be affected by the resulting smoke, and the amount of land that cannot be burned. This data allowed us to compare and contrast VSMG and VSMOKE-GIS to determine the most appropriate screening system. This knowledge can help to identify the screening system that allows the greatest amount of forest land to be potentially prescribed burn and amount of area that could be impacted in Virginia with minimal apparent benefit.

4.3 – Results and Discussion

4.3.0 – Phase 1: Analysis and Comparison

To carry out the analysis and comparison of this phase, initial efforts focused on comparing the area within VSMG and VSMOKE's individual masks produced by a single sensitive site. Following this step we carried out the case study. The geographic extent of the case study was Virginia and all layers for comparison were converted to rasters with a cell size of 100 by 100 meters (one hectare).

The first step in this task was to compare the individual masks produced by each method. At first glance it is obvious that VSMG's mask is much larger than VSMOKE's (Figure 4.2). VSMG's mask extended out to a distance of 10 miles compared to VSMOKE's which extended out to 0.9 miles. However, because the shape of the mask is a wedge, the area affected by the VSMG mask was much more than ten times that of the VSMOKE mask.

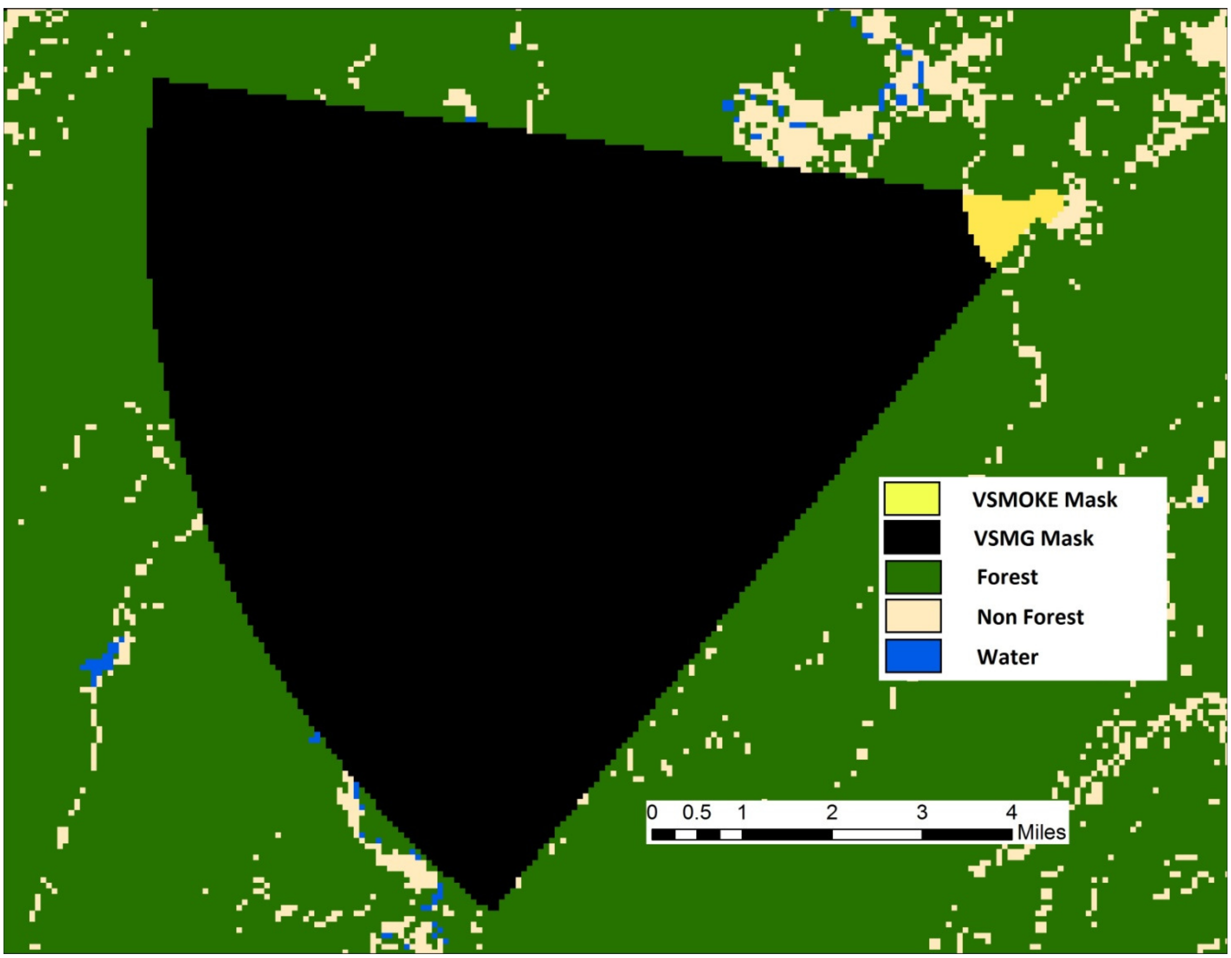


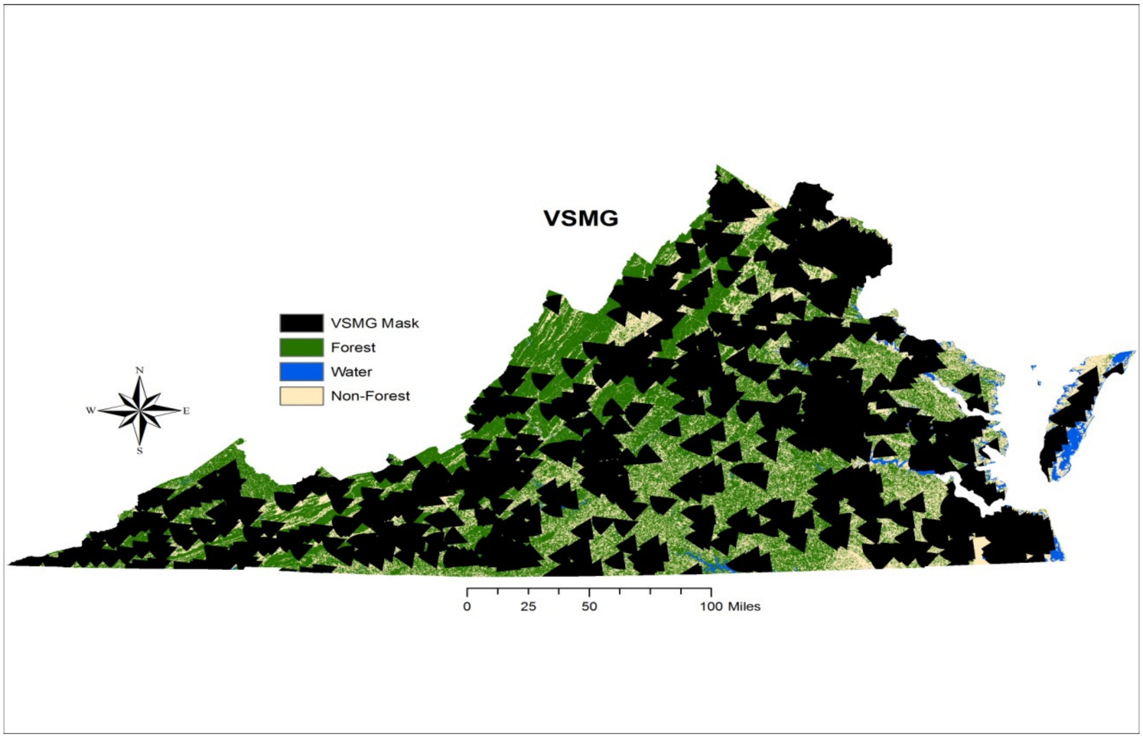
Figure 4.2 Virginia's Smoke Management Guideline's mask compared to VSMOKE's mask.

Considering each raster cell used in the analysis was 100 by 100 meters or one hectare, the VSMG mask had 13,601 cells in each mask. That means 13,601 hectares upwind of a single sensitive site may not be burned given the prevailing wind direction used. VSMOKE's mask covered much less area and contained only 135 cells. VSMOKE's mask was less than one percent of VSMG's mask. VSMOKE's mask covered 334 acres versus VSMG's mask which was 33,609 acres. This substantial increase in area affected by the masks when following VSMGs may be limiting the small private landowners who wish to burn. Small private landowners may not know that VSMG are only recommendations, and may take the guidelines as laws. These consequences could lead to exclusion of prescribed fire in land management decisions.

After comparing the amount of land affected by each mask, the next step was to compare the amount of land affected by each screening system for the entire state. We looked at not only the acres affected, but the amount of forest land affected, and the amount of forest that is potentially available to burn. According to the NLCD layer Virginia has 14,873,021 acres of forest, of which 11,365,266 acres are deciduous, 2,604,446 acres are evergreen, and 903,309 acres are mixed forest. The VSMG Mask layer "blanked" much of the state. That is, when following Virginia's guidelines there is more forested land that cannot be burned than can be burned given the prevailing wind direction. However, when using VSMOKE-GIS to screen for sensitive sites with the given burn conditions in our analysis almost all of Virginia's forested land could be burned. The amount of land covered by each mask varied considerably and is shown in Figure 4.3. Figure 4.3a highlights how much land is affected and cannot be burned when following VSMG. Figure 4.3b shows how much more land could potentially be burned if Virginia was to use VSMOKE-GIS to screen for sensitive sites.

We found that when following Virginia's current guidelines to screen for sensitive targets, the area covered by the masks was 15,624,740 acres (Table 4.2). If VSMOKE-GIS was used in Virginia to screen for sensitive sites there would be 95 percent less land covered by the masks or only 835,624 acres of masked land. That is an increase in 14,789,116 acres of total land available to burn if Virginia was to use VSMOKE-GIS to screen for sensitive sites. Of the total forest land available in Virginia only 43.43 percent may be burned under the current screening system. Almost all the forest land available could be burned following VSMOKE's screening system, where 99.59 percent was available. Using VSMOKE-GIS there was 14,668,198 acres of Virginia's forest available to burn and 6,453,355 acres using the current screening system (Table 4.2). If VSMOKE-GIS were employed in Virginia to screen for sensitive sites there would be 98.63 percent, 98.69 percent, and 98.29 percent of Virginia's deciduous, evergreen, and mixed forest available to burn respectively. Following the current screening system there are only 42.78 percent, 46.40 percent, and 42.40 percent of Virginia's deciduous, evergreen, and mixed forest available to burn respectively (Table 4.2)

(a)



(b)

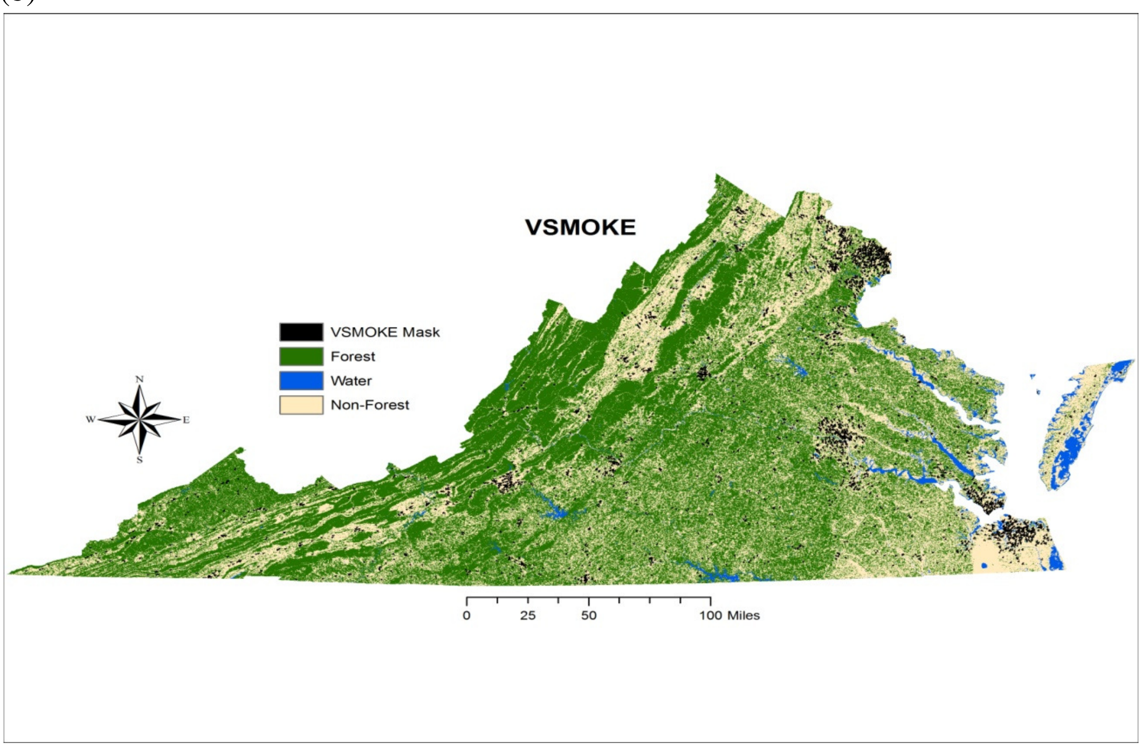


Figure 4.3 Maps of Virginia showing the current guidelines for screening for sensitive sites (a) and using VSMOKE to screen for sensitive sites (b), with the land that cannot be burned because of the masks and the land available to burn by type.

Table 4.2 Total acres available to burn and amount of acres covered by the masks in Virginia by the current system to screen for sensitive sites and by using VSMOKE. Percentages in parenthesis are of the amount of the total land of that type in Virginia. Areas covered by water were left out in the analysis.

	Total Area in VA	Current Guidelines	VSMOKE
Deciduous	11,365,266	4,861,887 (43%)	11,210,079 (99%)
Evergreen	2,604,446	1,208,476 (46%)	2,570,244 (99%)
Mixed	903,309	382,991 (42%)	887,874 (98%)
Total Forest	14,873,021	6,453,355 (43%)	14,668,198 (99%)
Non Forest	11,122,717	3,562,185 (32%)	9,822,686 (88%)
Masks	---------------	15,624,740 (60%)[a]	835,624 (3%)[a]
Total area	25,995,738	---------------	---------------

[a] The masks percentages are the percentage of Virginia's total land.

With the conditions of our hypothetical burn and the prevailing wind direction (most frequent wind direction), Virginia could have the potential to double the amount of land available to burn if they employed VSMOKE to screen for sensitive sites prior to a prescribed burn. This could be a drastic increase, and would reduce one of the biggest barriers to prescribe burning for private landowners. Virginia's current method makes it difficult for someone not familiar with prescribed burning to include prescribed burning as a method to manage their forests. They may see that sensitive sites are within 10 miles and automatically exclude prescribed burning as a silvicultural tool. However, in reality the smoke plume may not even affect any sensitive sites over one mile. VSMOKE-GIS has shown its use as a valuable tool for planning prescribed burns and we have showed that it is a useable and practical model for screening sensitive sites to minimize smoke impacts.

These results were dependent on the selection of our hypothetical burn at Difficult Creek and the prevailing wind direction as an example case; the results will not apply in general. However, the case is reasonable and gives an indication of the magnitude of area affected. We established how much area would be potentially available to burn under VSMG and how much area might really be impacted based on the VSMOKE predictions. The difference in area affected, is the area being regulated or misunderstood to be regulated without tangible benefit.

Chapter Five

Conclusions

The pilot validation of VSMOKE-GIS showed its value as a planning tool for burn managers and was more likely to overpredict $PM_{2.5}$ concentrations then underpredict. During the validation we actively sought out the smoke plume and the concentration readings were instantaneous. With respect to environmental regulations, concentrations are averaged over a few hours or 24-hour period. If we were to record concentrations concurrent with regulatory time intervals it is likely that we would have lower levels of concentration than we recorded, and VSMOKE-GIS's overprediction would be much greater. With VSMOKE-GIS considerably overpredicting, its use in the development of regulations for smoke management is evident and would be conservative concerning making under estimates of $PM_{2.5}$ concentrations and negatively impacting sensitive sites or individuals. This could be considered as an inherent built-in safety factor. To make VSMOKE-GIS a safe recommendation for managing smoke other safety factors could be defined, for example, doubling the length and/or width of the plume. Although the validation showed that VSMOKE-GIS is conservative and could be a safe recommendation, these safety factors could mitigate possible smoke intrusions and litigation.

Although VSMOKE-GIS showed good accuracy in predicting the location of the smoke plume and concentration of $PM_{2.5}$ downwind, we found many difficulties and considerations with validating smoke emission models. We understand now why there is little research in this area of prescribed burning. We hope the difficulties and recommendations highlighted in this research can help in future validation efforts and instill confidence in these models as tools for burn managers. While our study was not a full-scale validation, we have highlighted the difficulties associated with validating smoke emission models and believe the insights gained in our research could lead to full scale validation efforts for other prescribed fire smoke emission models.

In reviewing the SMG most states employed all three criteria: geographic location, burn available fuel loads, and atmospheric conditions. However, Virginia weights the decision to burn or not heavily on the geographic location of the burn and its proximity to downwind sensitive sites. The states that employed all three criteria showed a considerably higher use of prescribed fire. It could be argued that the states with these prescribed fire programs correspond to an increase use of prescribed fire. However, it is difficult to suggest that the increase in acres prescribed burn is a result of the states prescribed burning program. Whereas it could be that the prescribed burning program was a result of the previous high use of prescribed fire or the forest area and characteristics in that state.

The Category Day System was showed to be an effective smoke management tool in this research. Possibly a Category Day System along with online mapping tools to visualize the smoke plume would be a start for a state to advance its prescribed burning program. The pilot validation of VSMOKE-GIS in Chapter Two showed that VSMOKE-GIS was accurate at predicting the geographic extent of the prescribed fire smoke plume. With our assessment of VSMOKE-GIS and its conservative predictions, perhaps more states could employ an online mapping tool incorporating its resulting plume similar to Georgia. With states already incorporating VSMOKE, our validation efforts, and the review of states' SMG, we hope states with less advanced prescribed fire SMGs could improve and offer more prescribed burning services to private landowners and burn managers.

Virginia's SMG are recommendations for burn managers to follow. If burn managers took VSMG as written law or procedures that must be followed, prescribed burning could be very limited in Virginia, as they seem to be. Burn managers in Virginia usually have sensitive sites within 10 miles downwind of their burn however they follow guidelines to minimize smoke from prescribed burning and consider other criteria to reduce smoke impacts. Since, VSMG are recommendations and not law, prescribed burning is actively used in Virginia currently. The problem may be future use of this silvicultural tool. With the VSMG only being recommendations and the litigious nature of American society, Virginia's voluntarily SMG could be in jeopardy in the future. Perhaps more concrete mandatory SMG are needed along with easily-accessible online mapping tools.

This research had the goal of maintaining the ability and increasing the use of prescriptive fire in Virginia and aimed to promote a regulatory environment in which scientific tools and knowledge are used to limit only activities for which the evidence suggests there will be adverse consequences. The results of this research provided a clearer spatial picture of the smoke management barriers associated with prescriptive burning on private woodlands in Virginia. These results should be a useful tool in developing more defined SMG for prescriptive burning in Virginia. Combined spatially with smoke sensitive targets and weather information we have indicated how much forest land is potentially available where prescribed burning can be applied currently and if VSMOKE-GIS was to be employed.

With the review of other states' SMG and the case study of Virginia's current SMG, recommendations have been made for Virginia. While Virginia's current SMG consider the ability of the smoke to disperse in the atmosphere they are only recommendations and do not take into account the full ability of the smoke to rise, mix, and disperse in the atmosphere when screening for sensitive sites. Recommendations from this research include implementing mandatory SMG that must be followed by certified prescribed burners. To streamline the requests for permits and the processes burn managers will need to follow, a Dispatch Center operated by the Virginia Department of Forestry (VDOF) would be advised. This Dispatch Center would authorize permits, provide fire weather information for burn managers, and could map all the prescribed burns in the state to ensure no airsheds exceed their permissible limits of $PM_{2.5}$ concentration. The Dispatch Center could even provide assistance to private landowners in attaining help about possibly using prescribed burning as a silvicultural tool. In addition to a centralized Dispatch Center, the VDOF would have to take an active role in promoting the use prescribed burning and possibly develop a strategic plan for prescribed fire in Virginia in the years to come. All the states reviewed with more advance prescribed burning programs had very active forestry agencies that promoted, educated, and explained the benefits of prescribed fire to the public and woodland owners.

After reviewing the criteria required by the other states in their SMG it would be advised that Virginia requires all three criteria in their SMG: geographic location, burn site conditions, and atmospheric conditions. The Category Day system has been shown to work in North Carolina, South Carolina, and Arkansas and permissible fuel loads could be based on VSMOKE's predictions similar to Arkansas. This would ensure that the decision to prescribe a burn would be based on the actual science of smoke development and its dispersion and not just the geographic proximity of the burn to sensitive sites. If Virginia was to develop a more advanced prescribed fire program similar to Georgia or Florida, Virginia would have to adopt a model for predicting the smoke plume, similar to VSMOKE-GIS. Both Georgia and Florida have a vast array of tools and models available to burn managers online that their agencies use as well when accepting or denying burning permits. They make it easily accessible for burn managers to see the effect of their prescribed burn smoke plume via the internet. If Virginia was to take this route it would require further modification in the current SMG and prescribed burning services, but would promote an environment that encourages prescribed burning under the correct conditions.

Other considerations for Virginia include adopting new regulations and laws identified in Chapter Three of this research. Georgia and Florida were the only two states that had a gross negligence standard for burn manager liability protection. These two states place more protection on burn managers and greatly reduce the fear of liability when conducting a prescribed burn. Other applicable laws identified that help promote the use of prescribed burning include: laws that prohibit local ordinances from enacting restrictions on prescribed burning. It would be better suited if Virginia addressed prescribed burning in a more holistic fashion. Prescribed burning should be a property right of a landowner and Virginia should consider adopting a "prescribed fire law." A law that promotes its use and explicitly defines prescribed burning, its purpose, and benefits, and task the VDOF to promote prescribed burning and educate the public on its ecological and protection benefits.

This research has exposed the problems associated with Virginia's current prescribed burning program and highlighted the strengths of other states' programs. We have verified VSMOKE's accuracy as a tool for burn managers, shown its use as a means to screen for sensitive sites in Virginia, and have made recommendations to make sure prescribed burning remains in use in Virginia. While these recommendations would be a drastic change from the current VDOF way of thinking it would greatly encourage and ensure prescribed burning's use in the future. While all change is not always welcomed, if it is done in small steps with a strategic plan laying out the goals and objectives for the future, it could be achievable, and would be most beneficial to ensure private landowners can burn under conditions that will not compromise public safety and health.

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