# 8 Prescribed Fire and Air Quality in the American South: A Review of Conflicting Interests and a Technique for Incorporating the Land Manager into Regional Air Quality Modeling

Gary L. Achtemeier
Center for Forest Disturbance Science, USDA Forest Service,
320 Green Street, Athens, GA 30602
Email: gachtemeier@fs.fed.us

**Abstract** In this paper, conflicting interests in prescribed burn practice and improving air quality in the South are reviewed. Conflicting societal interests and legislative actions threaten to curtail the use of prescribed fire to manage for endangered species and for other land management objectives in the South. This comes at a time when efforts are being made to increase prescribed burning on existing forest land and to initiate prescribed burning on tracts of old agricultural land that are being restored to forest land. Regulatory interests regarding impacts of regional haze on visibility and impacts of fine particulate matter on health are increasingly in conflict with management objectives driven by natural resource management. The air quality community is increasingly relying on computer air quality models for understanding the movement of pollutants across regions and for the chemical interactions of airborne materials. The success of air quality/air chemistry models depends on the availability of accurate source inventories. Wildland burning in the South is considered a significant contributor to the organics inventory. Because prescribed fires are managed, the timing and locations of burns and where in the atmosphere fire products are distributed must be taken into account. Therefore land managers become active players in local and regional air quality.

A technique for incorporating the land manager into regional air quality modeling is described. The core of the technique is two modeling tools for dealing with the conflicting interests, that is, a dynamical-stochastic smoke model, Daysmoke, and a "modeling framework", the SHRMC-4S. Daysmoke distributes smoke in the atmosphere after the manner the burns are "engineered" by land managers. SHRMC-4S is constructed by linking an atmospheric chemical model, CMAQ, with Daysmoke. Applications of the two modeling tools to a prescribed burn case are illustrated. Daysmoke produces a ground

PM level close to the measured value if complex plume structures are correctly modeled. CMAQ simulations of ground-level PM for a single prescribed fire suffer from grid resolution.

**Keywords** Prescribed burning, smoke, air quality, modeling, daysmoke, SHRMC-4S

## 8.1 Introduction

The American South comprises one of the most productive forested areas in the United States with approximately 200 million acres (81 million ha) or 40% of the nation's forests in an area occupying only 24% of the U.S. land area (SRFRR, 1996). Furthermore, Southern forests are dynamic ecosystems characterized by rapid growth and hence rapid deposition of fuels within a favorable climate, and a high fire-return rate of every 3 – 5 years (Stanturf et al., 2002).

Research efforts in investigating the air quality effects of prescribed fires in the South have been made in the Southern high-resolution modeling consortium (SHRMC). SHRMC was established as one of the USDA forest service fire consortia for advanced modeling of meteorology and smoke (FCAMMS) centers funded by the national fire plan (NFP).

As the air quality community relies more on high-resolution air quality/air chemistry models such as CMAQ, it is critical that emissions inventories from prescribed burns supplied to these models are accurate. The timing and locations of burns and where in the atmosphere fire products are distributed must be taken into account.

Prescribed burns are managed fires. Land managers choose the day and time to conduct their burns under favorable dispersion conditions. Land managers determine how much fire to place on the landscape and how the fire is to be distributed. Therefore, land managers are active players in local and regional scale air quality.

Our objective is to design a regional scale air quality "modeling framework" that gives land managers a "say" in how their land management practices are incorporated into air quality/air chemistry models. The framework is called Southern High-Resolution Modeling Consortium Southern Smoke Simulation System SHRMC-4S (Achtemeier et al., 2003; Liu et al., 2004). SHRMC-4S includes models to simulate fire emissions, local smoke movement (including plume rise), high-resolution meteorological processes (MM5) and air chemistry (CMAQ). SHRMC-4S, in comparison with the modeling framework, Bluesky (O'Neill et al., 2003), is designed specifically for assessing air quality impacts from prescribed burning in the South through CMAQ.

The impact of prescribed burn "engineering" by the land manager is modeled through plume rise—how high the plume goes and the vertical distribution of smoke particles. The plume model determines the fraction of smoke left in the atmospheric boundary layer (mixed layer) that can be transported to the ground locally and the fraction of smoke partitioned at higher altitudes. Smoke carried to higher altitudes will be transported regionally or beyond by prevailing winds. The national ambient air quality standards (NAAQS) apply to the ground-level pollutant concentrations. When more smoke is injected at higher altitudes and dispersed to remote areas, the chances for exceeding the NAAQS standards locally and regionally are reduced. Specification of plume rise is thus crucial for evaluating the air quality effects of prescribed burning. Many efforts have made to develop smoke plume rise schemes (e.g. Pouliot et al., 2005).

In this Chapter, issues on the air quality effects of prescribed fire are discussed. The development of the modeling tools and their applications to simulating the air quality effects are described.

## 8.2 Conflicts over the Airshed of the American South

One of the adverse consequences of prescribed burning is degradation of air quality (Ward and Hardy, 1991; Sandberg et al., 1999; Riebau and Fox, 2001). Air pollution from smoke has led to conflicts between interest groups involved with clean air and forest management. Issues of human health, nuisance smoke, visibility, and transportation hazard often stand against issues of forest health and safety, wildlife management, ecosystem restoration, timber production, and carbon sequestration. In some instances, the clean air act conflicts with the threatened and endangered species act.

Prescribed burning is extensively used, treating 6 – 8 million acres (2 – 3 million ha) of forest and agricultural lands each year (Wade et al., 2000). Prescribed fire has long been recognized as the most economical means for managing timberlands for fiber production. Prescribed fire eliminates species that compete for nutrients and reduces buildup of dead and live fuels that increase the hazard of destructive wildfire.

The mild, mostly snow and ice free winters make the Southern climate ideal for the development of retirement communities. Thousands of older people, some with respiratory problems, have relocated into these communities. Many of these retirees have little or no experience with forestry practices and therefore may not be receptive to frequent incursions of smoke into their communities. Human health concerns and issues of nuisance have created a need for regulation of smoke.

The South has some of the highest levels of PM and ozone in the nation. Fires have been found to be an important contributor (Zheng et al., 2002). Smog, regional haze, and visibility impairment are air quality issues addressed by the U.S. EPA. Prescribed burning releases $PM_{2.5}$ and $PM_{10}$ (particulate matter (PM) with a size not greater than 2.5 μm and 10 μm, respectively), $NO_2$ and volatile organic compounds (VOC), which are either direct contributor or precursors of $O_3$. Prescribed burning also emits CO, $SO_2$, which together with PM, $NO_2$, and $O_3$ are the criteria air pollutants subject to the U.S. NAAQS (EPA, 2003).

The EPA has issued the interim air quality policy on wildland and prescribed fire to protect public health and welfare by mitigating the impacts of air pollutant emissions from wildland fires on air quality (EPA, 1998). Among various issues of concern in the South is the contribution of burning to $PM_{2.5}$ concentrations. $PM_{2.5}$ is a risk to both human health and the environment. It is able to penetrate to the deepest parts of the lungs. It is also a major cause of visibility impairment and a contributing factor for acid rain. EPA established NAAQS for $PM_{2.5}$ in 1997 and Biomass burning is one of the major sources for the atmospheric $PM_{2.5}$.

These air quality regulatory concerns conflict with growth in the need for prescribed burning of Southern forest lands. The Endangered Species Act, requires land managers to manage habitat to preserve or increase populations of threatened and endangered species. For example, prescribed fire is used in the coastal plains and Piedmont regions of the Southeast to improve habitat for the red-cockaded woodpecker (Picoides borealis Vieillot)—a species listed as endangered under the endangered species act (Achtemeier et al., 1998).

An example of conflicting legislation is to be found in the Southern Appalachians. There, a low-growing shrub species called Hudsonia montana Nuttall is listed as a threatened species under the endangered species act. H. montana is dependent upon fire for survival. Including prescribed burning in a recovery plan would be straightforward except that the largest populations of H. montana are found within and adjacent to the Linville Gorge Wilderness, a Class I area, governed by clean air regulations (Achtemeier et al., 1998).

The conflict between managing for natural resources and managing for air quality has placed Southern land managers in the difficult position of "getting it right all of the time." Through careful monitoring of fuel moisture and weather conditions land managers have learned to "engineer" prescribed burns to accomplish natural resource objectives while minimizing (though not eliminating) impacts on local air quality. Although the vast majority of prescribed burns are done without incident, there are occasions when weather conditions are not as expected and local and regional air quality is compromised.

## 8.3 Daysmoke

The southern burn program is threatened by nuisance complaints, litigation, and lowering of 24 hour fine particulate ($PM_{2.5}$) air quality standards. Land managers need to have accurate downwind fine particulate predictions if they are to continue burning at the same levels as they have in the past or increase their burning programs. The daysmoke plume model incorporates a human factor—how burns are engineered by land managers through burning techniques/ignition methods—in modeling smoke from prescribed burns. Therefore daysmoke may provide land managers with a tool that will assist in achieving their burn programs.

Daysmoke (Achtemeier et al., 2006) is a dynamical-stochastic plume model designed to simulate smoke from prescribed burns in a manner consistent with how the burns are engineered by land managers. It is an extension of ASHFALL, a plume model developed to simulate deposition of ash from sugar cane fires (Achtemeier, 1998). Daysmoke consists of four models (Fig. 8.1): ① Entraining turret plume model. The plume is assumed to be a succession of rising turrets. The rate of rise of each turret is a function of its initial temperature, vertical velocity, effective diameter, and entrainment. ② Detraining particle trajectory model. Movement within the plume is described by the horizontal and vertical wind velocity within the plume, turbulent horizontal and vertical velocity within the plume, and particle terminal velocity. Detrainment occurs when stochastic plume turbulence places particles beyond plume boundaries, plume rise rate falls below a threshold vertical velocity, or absolute value of large eddy velocity exceeds plume rise rate. ③ A large eddy parameterization. Eddies are 2D and oriented normal to the axis of the mean layer flow. Eddy size and strength are proportional to depth of the planetary boundary-layer (PBL). Eddy growth and dissipation are time-dependent and are independent of growth rates of neighboring eddies. Eddy structure is vertical. Eddies are transported by the mean wind in the PBL. ④ Relative emissions production model. Particles passing a "wall" three miles downwind from a burn are counted for each hour during the burning period.

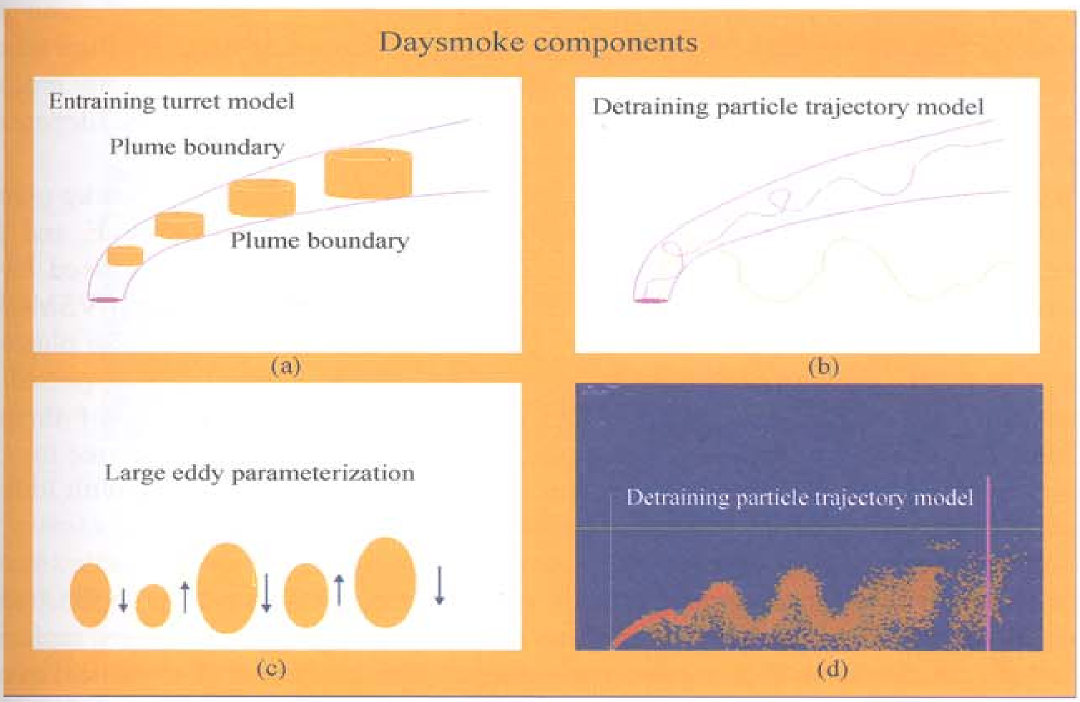


**Figure 8.1** An overview of daysmoke, including Entraining turret plume model (a), Detraining particle trajectory model (b), Large eddy parameterization (c), and Relative emissions production model (d)

Daysmoke has many unique features in comparison with some existing smoke transport tools used by land and fire managers in determining downwind transport of $PM_{2.5}$. The ventilation index (VI) is the product of the depth of the atmospheric boundary layer (mixing layer) with the transport wind speed (the mean wind speed within the mixing layer). The VI is used to regulate the amount of fuel consumed on a given day according to ambient weather conditions. However, the VI is limited by the inherent assumptions that the horizontal dimension of the burn site normal to the wind speed is of infinite length and that all smoke remains within the mixed layer. The dispersion index (Lavdas, 1986) modified the VI for an ensemble of finite burn areas and explicitly incorporates atmospheric stability; although the dispersion index also maintains the assumption that all smoke remains within the mixed layer. Lavdas (1996) linked fuels information with meteorological data through VSMOKE, a smoke "screening" model for local smoke dispersion. The Florida fire management information system (Goodrick and Brenner, 1999; Brenner and Goodrick, 2005) merges the cross flow Gaussian horizontal dispersion properties of VSMOKE with 3D trajectories produced by HYSPLIT (Draxler and Hess, 1997) to estimate smoke plume movement and the ground-level impact of $PM_{2.5}$ concentrations on potentially hazardous visibility reductions.

However, none of the existing tools includes the "human element"—how the burns are engineered by land managers. By the choice of firing method—head fire, back fire, mass ignition (where, when, and how much fire is dropped from helicopters)—land managers can influence the timing of heat production and how much heat is produced over the course of the burn. Thus fire ignition timing and pattern can be a major contributor to how high smoke rises and how much is released during a period of evolving mixing layer height within a time-dependent wind field.

Daysmoke includes theory for particulate detrainment from the smoke plume. Daysmoke removes a restrictive assumption inherent in VSMOKE and the Ventilation Index namely that all smoke is contained within the mixed layer. Daysmoke also removes the imposed vertical distribution of smoke in VSMOKE and the instantaneous even distribution of VI. If the convective smoke plume is relatively weak, all or part of it may be captured, torn apart, and dispersed by turbulence within the mixed layer before it rises to an altitude of thermal equilibrium. If the convective smoke plume is strong, most of the smoke may be ejected into the free atmosphere far above the top of the mixed layer with little or no smoke remaining to be dispersed within the mixed layer.

The primary application of daysmoke is simulating local scale smoke concentrations for planning and regulatory purposes. A secondary application is acting as a "smoke-injector" for regional scale air quality models by replacing current plume rise formulations and providing a more representative vertical smoke distribution for wildland fires. Daysmoke is also intended as a training tool to increase our understanding of how ground-level concentrations of $PM_{2.5}$ can be manipulated by burn technique/ignition strategies.

## 8.4 SHRMC-4S

An overview of SHRMC-4S is shown in Fig. 8.2. Each box along the blue arrow represents steps needed to accomplish the objective of including emissions from wildland fires in regional scale air quality models. The first box, Fire Data, gets SHRMC-4S started. Information on the size of the tract of land to be burned, the date and time of the burn, the location of the burn, plus pertinent data on the kinds and state of fuels is supplied by the land manager. Fire activity data is processed through combustion models that calculate emissions inventories for the burns (the Emissions Calculation box). The outputs are hourly productions of heat and the masses of gases and particulate compounds—fire products. The sparse matrix operator kernel emissions modeling system (SMOKE) (Houyoux et al., 2002) processes emission data and provides initial and boundary chemical conditions for the community multiscale air quality (CMAQ) model (Byun and Ching, 1999) for chemical modeling (fourth box). Then a visualization for illustrating modeling results is the last step. The NCAR/Penn State mesoscale model (MM5) (Grell et al., 1994) is used for providing meteorological conditions for emission calculation and SMOKE and CMAQ simulation.

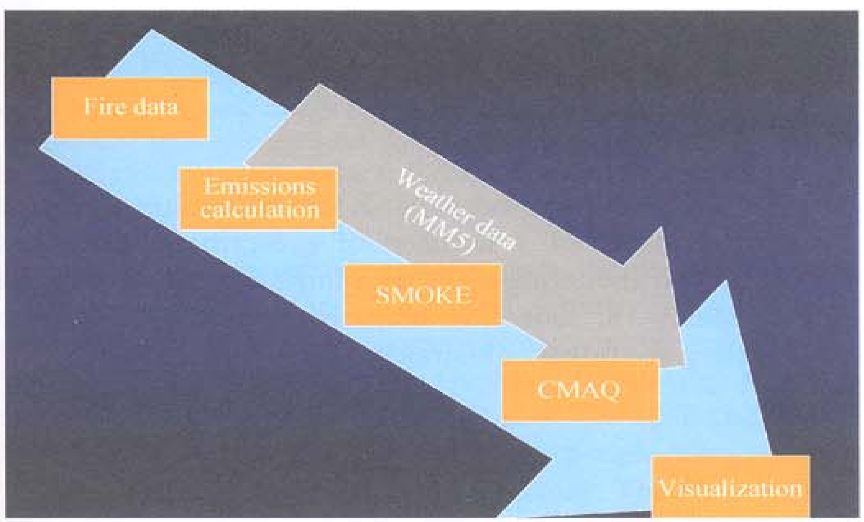


**Figure 8.2** An overview of the SHRMC-4S framework

Several modifications were made to SMOKE for prescribed burning applications (Liu et al., 2006a). Area and point sources are among the various emission categories in SMOKE. Area source emissions are annual amounts (or converted to daily averages) from counties, and are put only at the lowest model level, whereas point source emissions are emitted daily or hourly amounts from certain locations like power plants, and are partitioned to multiple levels. Fires have been traditionally regarded as an area source, but they are more likely a point source because they occur as individual events geographically with hourly and daily variability, and smoke may be partitioned through a depth of a few kilometers. To include fire emissions as a point source in SHRMC-4S, fire emission files for SMOKE were created. A fire is identified through its latitude and longitude in an emission file in the inventory data analyzer (IDA) format. All fire properties (height, diameter, exit temperature, exit velocity, and flow rate) are included in this file. Day- or hour-specific emissions of various chemical species are stored in separate files in the emissions modeling system'95 (EMS-95) format.

The other modification was to link daysmoke to SMOKE as an addition to the laypoint algorithm for estimating plume rise and specification of plume vertical profiles. The fourth component of daysmoke, the relative emissions production model, counts particles passing a "wall" three miles downwind from a burn for each hour during the burn period. A percent of particle number at each layer at each hour relative to the total particle number is assigned to SMOKE/CMAQ simulations.

Prescribed fire data is obtained from the existing systems or those to be developed. The portion of this total fuel load consumed by the fire is determined using the single parameter regression equations of CONSUME 3.0 (Ottmar et al., 1993). Fire emissions are calculated by multiplying the consumed fuel by an emission factor appropriate for the fuel type and ignition plan (Mobley et al., 1976). These total emission values are transformed into hourly values using equations provided in Sandberg and Peterson (1984).

## 8.5 Application

Daysmoke and SHRMC-4S have been used for simulating smoke movements and the air quality impacts of a number of prescribed burns in the South. Simulations with the two modeling tools of a burn case at the Tennessee /North Carolina border on March 18, 2006 have been conducted (Achtemeier et al., 2006; Liu et al., 2006b). They are briefly illustrated here.

### 8.5.1 Burn

The Cherokee national forest conducted the Brush Creek prescribed burn on 743 ha of woodland near the Tennessee/North Carolina State line (upper left hand corner of Fig. 8.3) approximately 50 km northwest of Asheville, NC on 18 March 2006. Approximately 670 ha or 90% of the land area was expected to be burned. The site had never had a prescribed fire nor had a wildfire occurred recently. The district staff estimated 26.9 metric tons of fuel would be consumed for each hectare burned. Aerial ignition at Brush Creek began along the main and spur ridges between 1,220 and 1,400 EST then further ignition was done between 1,620 and 1,710 EST. During the active burning phase, fire would have spread down the side slopes until no fuels were available to ignite. Hourly estimates of area consumed were used by the REM to model the history of the burn.

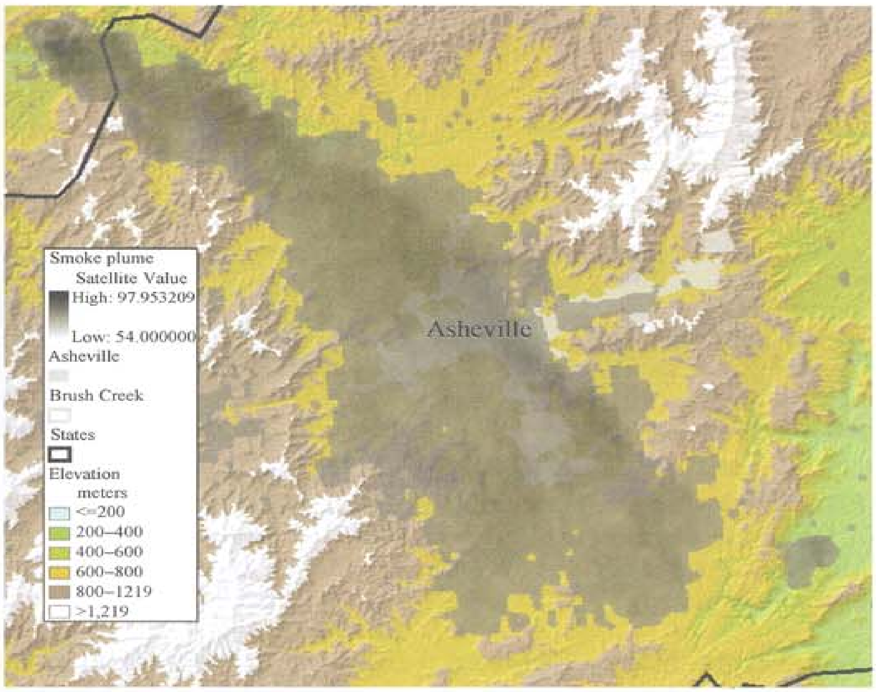


**Figure 8.3** Smoke plume image processed from the Polar satellite (received from National Oceanic and Atmospheric Administration) showing the cloud of smoke from the Brush Creek prescribed fire at 1,715 EST (Provided by William A. Jackson, Air Resource Specialist, Cherokee National Forest)

The leading edge of the smoke plume from the Brush Creek burn passed Asheville, NC, between 1,515 and 1,530 EST. Shortly after 1,600, elevated fine PM concentrations were measured at a particulate monitor in Asheville operated by the Western North Carolina Regional Air Quality Agency (Fig. 8.4). Concentrations of $PM_{2.5}$ rose from near zero to 106 $\mu g{\cdot}m^{-3}$ at 1,700 EST and to 130 $\mu g{\cdot}m^{-3}$ by 1,800 EST. These PM levels could cause some people who are sensitive to air pollutants to experience short-term health problems. The concentrations fell back to 30 $\mu g{\cdot}m^{-3}$ by 2,100 EST.

## 8.5.2 Daysmoke Simulation

Even though the smoke plume shown in Fig. 8.3 is a simple plume, with the implication of a simple plume updraft, the plume structures can be complex. Many smoke plumes are supported by multiple-core updrafts—subplumes rising from the flaming areas and merging into a single plume. Daysmoke allows for the simulation of multiple-core updraft plumes.

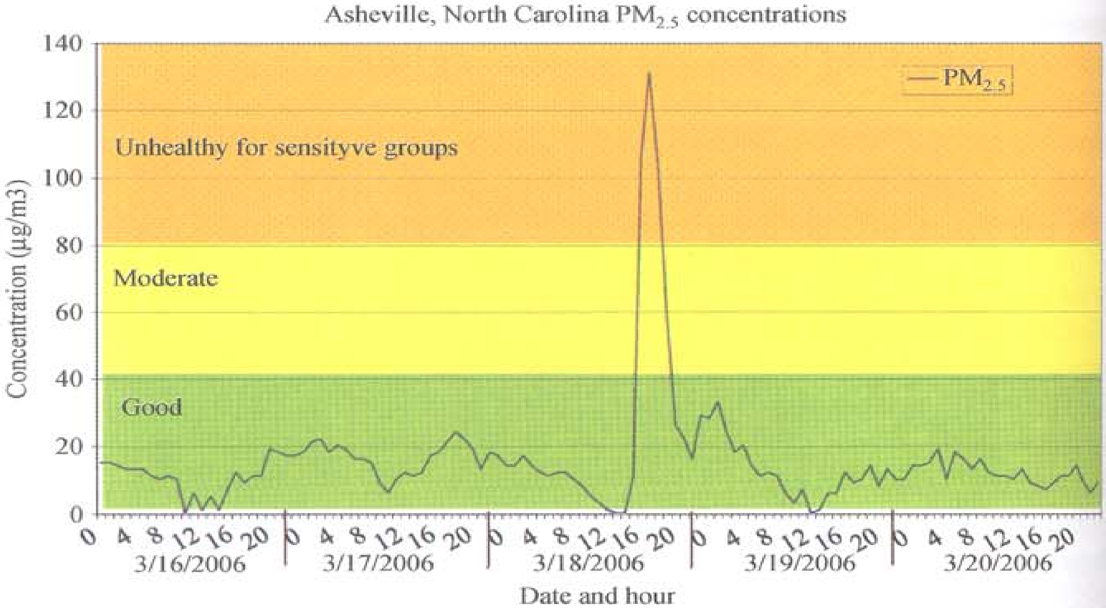


**Figure 8.4** Fine PM concentrations ($\mu g \cdot m^{-3}$) measured at the Buncombe County Board of Education monitoring site in Asheville, North Carolina between March 16 and March 20, 2006 (Provided by William A. Jackson, Air Resource Specialist, Cherokee National Forest)

Figure 8.5 shows the hourly $PM_{2.5}$ concentration at Asheville as calculated by daysmoke. Each line represents a ten-simulation average. Maximum hourly concentrations range from 42 $\mu g \cdot m^{-3}$ for a one-core plume updraft to 244 $\mu g \cdot m^{-3}$ for a ten-core plume updraft.

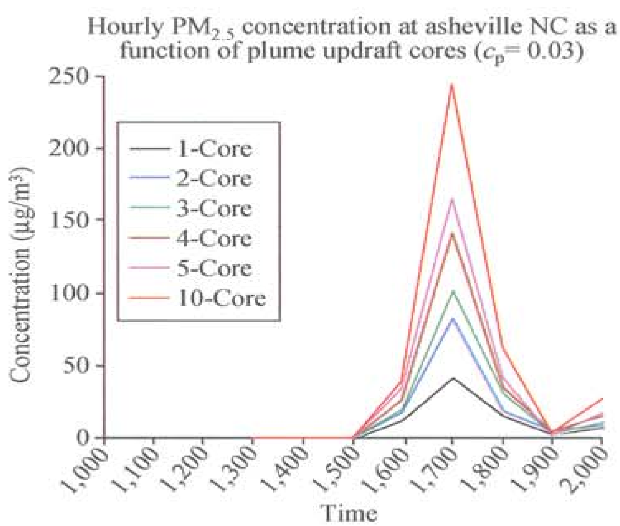


**Figure 8.5** Hourly $PM_{2.5}$ smoke concentrations for Asheville, NC, for six multiple-core updraft simulations by daysmoke. (from Achtemeier et al., 2006)

Daysmoke is a combined dynamic-stochastic model. Stochastic terms control small scale turbulence within the plume and within the ambient atmosphere. The large eddy parameterization model is linked to clock-time so that large eddy magnitudes and distributions will be different each time daysmoke is executed (averages of ten simulations for each updraft core were used to calculate the concentrations shown in Fig. 8.5). Therefore, individual simulations by daysmoke vary according to the stochastic terms. The average peak concentration for the one-core updraft is 42 $\mu g \cdot m^{-3}$ but varies between 30 – 60 $\mu g \cdot m^{-3}$. The ensemble average for the 10-core updraft is 244 $\mu g \cdot m^{-3}$ with a range between 211 – 279 $\mu g \cdot m^{-3}$.

Figure 8.6 compares the means and distributions of daysmoke-predicted ground-level $PM_{2.5}$ concentrations at 1,700 hours as a function of the number of updraft cores in a prescribed burn plume. $PM_{2.5}$ concentrations from the 1-core solutions were all under-predictions of observed levels at Asheville (130 $\mu g \cdot m^{-3}$—dashed line). Furthermore, concentrations from the 10-core solutions were all over-predictions of observed levels. Although the mean of the 4-core solution (141 $\mu g \cdot m^{-3}$) was closest to the Asheville observation, some results from the 3-core and 5-core solutions also bracketed the 130 $\mu g \cdot m^{-3}$ concentration.

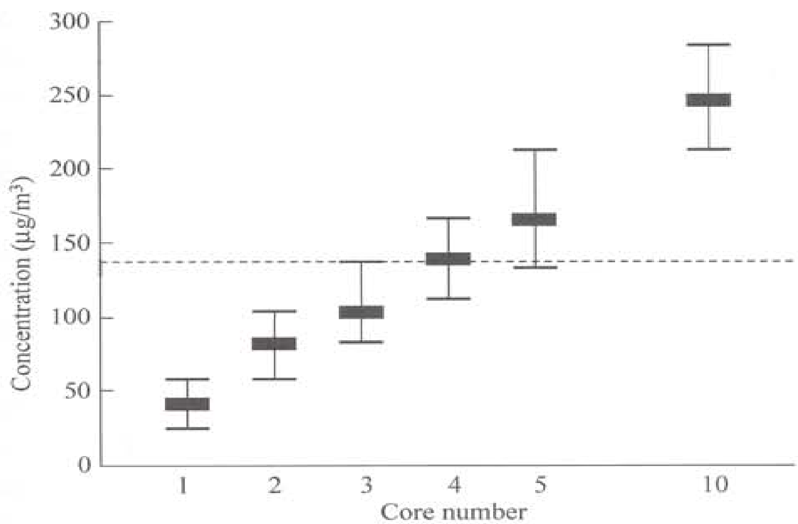


**Figure 8.6** The means and distributions for each updraft core number compared with the maximum hourly $PM_{2.5}$ concentration (dashed line) observed at Asheville, NC (from Achtemeier et al., 2006)

### 8.5.3 CMAQ Simulation

The model domain is configured with a 40×30 horizontal grid with 21 vertical layers. The horizontal resolution is 12 km. This resolution is too low to accurately simulate smoke concentration from a single burn with a size of approximately

1 km. The emission intensity for the grid box that includes the burn site is about two-orders of magnitude smaller than that at the burn site. This simulation provides an example of application of daysmoke in CMAQ. The Carbon Bond-IV (CB-IV) chemical mechanism is used to simulate gas-phase chemistry in CMAQ. Daysmoke is used to estimate plume rise and vertical distribution.

Figure 8.7 shows the height of smoke plume (plume rise) and vertical profile of the smoke particle simulated with Daysmoke for 1-core and 10-core updrafts. For the 1-core updraft (Fig. 8.7(a)), plume rise is about 1.5 km from 1,200 to 1,600 LST and increases to 2.1 km at 1,700. For the 10-core updraft (Fig. 8.7(b)), plume rise is about 0.75 km at 1,200 LST with the largest percentage occurring at about 0.6 km. Plume rise gradually increases to 1.1 km at next hour and remains there until 1,700. It reduces to 0.92 km at 1,800. These results indicate two differences between 1- and 10-core updrafts. First, plume rise is usually smaller for multiple-core. Thus, more smoke particles are distributed at lower levels in the atmosphere. Second, plume rise simulations for 1-core updrafts place most smoke high above the PBL, while simulations for 10-core updrafts place smoke close to or slightly higher than the PBL. This results in significant impacts on the ground concentrations when daysmoke smoke profiles are linked to CMAQ.

Figure 8.8 shows the geographic distribution of ground-level $PM_{2.5}$ at 1,700, when largest concentrations were observed at Asheville. The smoke plume spreads from the burn site south-southeastward to the North Carolina-South Carolina border. The transport track is close to what shows in the satellite image (Fig. 8.3) but with too much lateral spread. For both simulations, the magnitudes of concentrations are too small in comparison with the measurements at Asheville. The underprediction by CMAQ is primarily due to the 12 km resolution of the model domain which causes a laterally wider spread of the plume. In comparison, the magnitudes of the concentrations for the 10-core updraft are about 2 – 3 times of that for the 1-core updraft.

Figure 8.9 shows time-height cross sections of $PM_{2.5}$ concentrations over Asheville as simulated by daysmoke/CMAQ. The plume reaches Asheville after 1,500. Both simulations show two peaks in concentrations (an outcome of a 1-hour lapse in aerial ignition) the first arriving at 1,600 and the second arriving at 1,800. This result compares with the PM measurements at Asheville which show a general peak between 1,700 and 1,900. The main difference between the 1- and 10-core updraft simulations is in the vertical distributions of smoke. Large concentrations are found between 1.1 km and 1.5 km above ground for 1-core updraft, and within about 1 km above ground for 10-core updraft. The one-core simulation placed most smoke far enough above the PBL that few particles were transported to the ground (Fig. 8.9(a)). As Fig. 8.9(b) shows, most particles are found within the PBL for the 10-core updraft simulation and these are nearly uniformly distributed from the ground to the top of PBL by strong turbulent mixing.

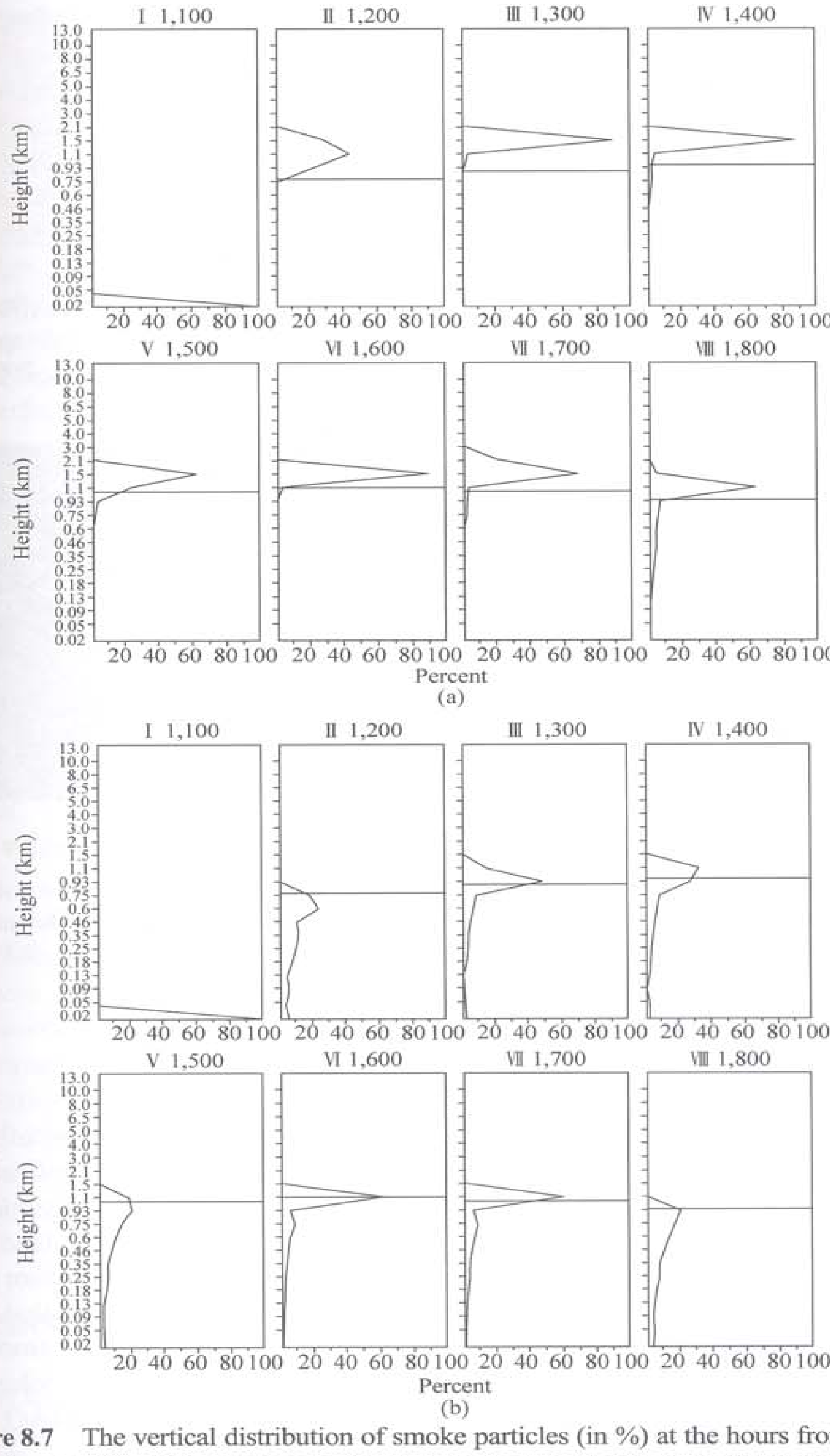


**Figure 8.7** The vertical distribution of smoke particles (in %) at the hours from 1,100 throughout 1,800 LST calculated using Daysmoke. The light horizontal lines indicate the top of planetary boundary layer. (a) one-core updraft. (b) 10-core updraft. (from Liu et al., 2006b). The light horizontal lines indicate the top of planetary boundary layer

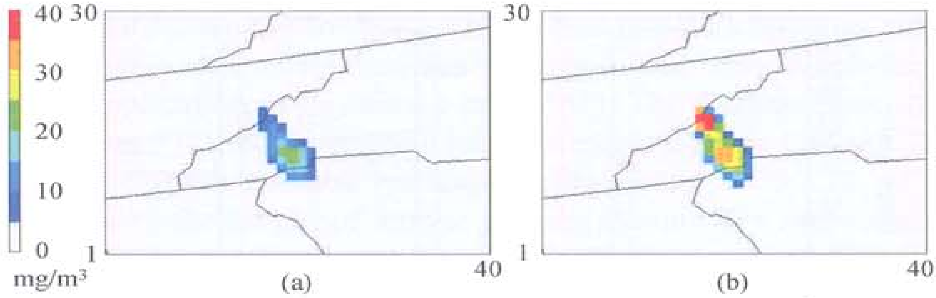


**Figure 8.8** Spatial distribution of ground $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$) at 1,700 LST simulated with CMAQ using plume rise and smoke particle vertical profile specified with daysmoke. (a) one-core updraft. (b) 10-core updraft (from Liu et al., 2006b)

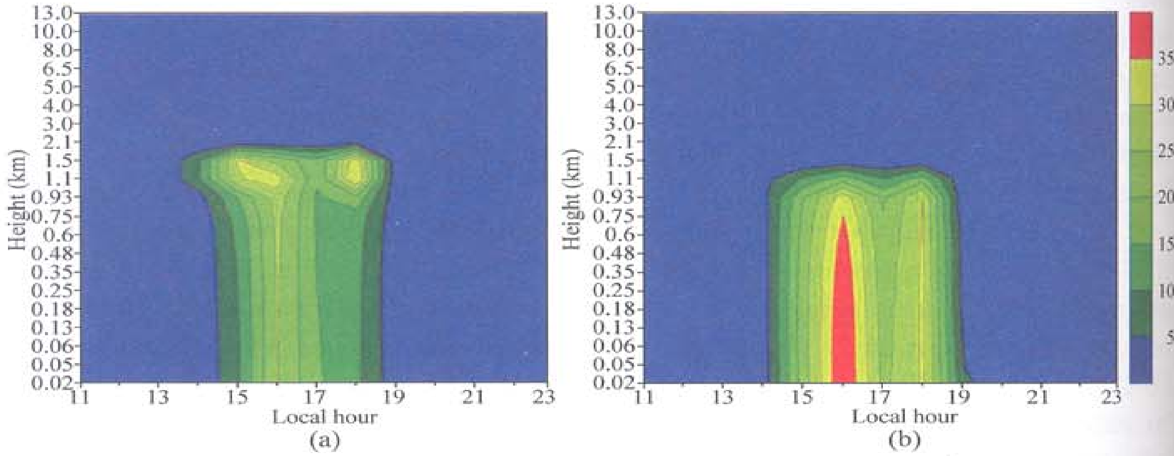


**Figure 8.9** Time-height across section of $PM_{2.5}$ concentration ($\mu g\ m^{-3}$) at Asheville simulated with CMAQ with plume rise and smoke particle vertical profile specified with daysmoke. (a) one-core updraft. (b) 10-core updraft (from Liu et al., 2006b)

## 8.6 Summary and Discussion

Two tools for smoke transport and the regional air quality modeling of prescribed burns, daysmoke and SHRMC-4S, have been described. Their applications have been illustrated by a recent burn case in a National Forest. The daysmoke plume model incorporates a human factor—how burns are engineered by land managers through burning techniques/ignition methods—in modeling smoke from prescribed burns. Therefore daysmoke may provide land managers with a tool that will assist in achieving their burn programs. SHRMC-4S is a framework for smoke and air quality research focused on prescribed fires in the South. daysmoke has been linked as an alternative to the layer fraction method in SMOKE/CMAQ for smoke plume rise calculation and vertical profile specification.

Simulations of a prescribed burn at the Tennessee /North Carolina border on March 18, 2006 indicate that daysmoke and SHRMC-4S are useful modeling tools for understanding smoke transport and the impacts on local and regional air quality. Daysmoke produces a ground PM level that could cause some people who are sensitive to air pollutants to experience short-term health problems. The simulated magnitude is close to the measured one. Daysmoke simulation and the resultant plume rise are dependent on the number of updraft cores. This property has an important impact on CMAQ simulations. The simulated ground PM level with CMAQ is larger for multiple-core updraft than single-core updraft.

Although some measurements were used for the development and validation of daysmoke, more measurements are needed for further validation of this model and comparison with other plume rise schemes. Furthermore, more complete prescribed fire information is needed for improving the performance of SHRMC-4S. Model performance is dependent on accurate specification of burn and other properties such as the number of updraft cores. In addition, the application case of daysmoke to CMAQ simulate presented here was run off-line. The two models need to be coupled to each other to make daysmoke a more practically useful tool for CMAQ simulation.

Daysmoke has shown us that the dynamics of smoke plumes from prescribed burns are complex, often far more complex than dynamics of plumes from industrial stacks. Application of smoke models designed for industrial stacks should not be expected to yield accurate results for smoke plumes from prescribed burns unless the multiple-core updraft issue is taken into consideration.

## Acknowledgements

Cherokee national forest personnel associated with the Brush Creek prescribed burn are acknowledged for providing reports and photo images of the burn. The project was conducted as part of the Southern regional models for predicting smoke movement project (01.SRS.A.5) and the prediction of fire weather and smoke impacts in the Southeast project (01.SRS.A.1) funded by the USDA forest service national fire plan (NFP). Funding was also provided through the national research initiative air quality program of the cooperative State research, education, and extension service, U.S. Department of agriculture, under agreement No. 2004-05240.

## References

Achtemeier GL, (1998), Predicting dispersion and deposition of ash from burning cane. *Sugar Cane* **1**: 17 – 22

Achtemeier G, Goodrick S, Liu Y-Q, (2003), The Southern High Resolution Modeling Consortium-A source for research and operational collaboration. Proceedings of the 2nd

Int'l Wildland Fire Ecology and Fire Management Congress. Amer. Meteor. Soc. Nov. 16 – 20, 2003, Orlando, FA

Achtemeier G, Goodrick S, Liu Y-Q, Jackson WA, (2006), the Daysmoke plume model for prescribed burns: Model description and application to a multiple-core updraft prescribed burn, *Int'l J. Wildland Fire* (submitted)

Brenner J, Goodrick SL, (2005), Florida's Fire Management Information System. Proceedings of EastFire Conference, Fairfax, VA. May 2005

Byun, DW, Ching J, (1999), Science algorithms of the EPA Model-3 community multiscale air quality (CMAQ) modeling system, Research Triangle Park (NC): EPA/600/R-99/030, National Exposure Research Laboratory

Draxler RR, Hess GD, (1997), Description of the Hysplit_4 modeling system, NOAA Technical Memorandum ERL ARL-224, December, 24

EPA, (1998), Interim Air Quality Policy on Wildland and Prescribed Fire, Office of Air Quality Planning and Standards, Research Triangle Park, NC, USA

EPA, (2003), National Ambient Air Quality Standards (NAAQS), Research Triangle Park, NC, USA (http://www.epa.gov/airs/criteria.html)

Goodrick S, Brenner J, (1999), Florida's Fire management information system. Proceedings of The Joint Fire Science Conference and Workshop, June 15 – 17, 1999 Boise ID. Vol. **1**: 3 – 12

Grell AG, Dudhia J, Stauffer DR, (1994), A Description of the Fifth-Generation Penn State/NCAR mesoscale Model (MM5), NCAR Tech. Note, 398, Boulder, CO, USA, 122

Houyoux M, Vukovich J, Seppanen C, Brandmeyer JE, (2002), SMOKE User Manual, MCNC Environmental Modeling Center

Lavdas LG, (1986), An atmospheric dispersion index for prescribed burning. Research Paper SE-256. Ashville, NC USDA Forest Service Experiment Station. 33

Lavdas LG, (1996), Program VSMOKE–users manual. USDA Forest Service General Technical Report SRS-6. 147

Liu Y-Q, Achtemeier G, Goodrick S, (2004), Air quality effects of prescribed fires simulated with CMAQ, the 2004 CMAQ Workshop, Chapel Hill, NC

Liu YQ, Achtemeier G, Goodrick S, (2006a), Modeling air quality effects of Florida prescribed burning with CMAQ-Daysmoke, *Environ. Pollution* (submitted)

Liu YQ, Achtemeier G, Goodrick S, Jackson WA, (2006b), regional air quality effects of Brush Creek burning simulated with CMAQ-Daysmoke. The Third International Fire Ecology and Management Congress, San Diego, California, USA, 13 – 17 November 2006

Mobley HE, Barden CR, Crow AB, Fender DE, Jay DM, Winkworth RC, (1976), Southern Forestry Smoke Management Guidebook. USDA Forest Service General Technical Report SE-10. Southeastern Forest Experiment Station, Asheville, NC

Ottmar RD, Burns MF, Hall JN, Hanson AD, (1993), CONSUME users guide. USDA Forest Service General Technical Report PNW-GTR-304. Pacific Northwest Research Station, Portland, OR

O'Neill SM, Ferguson SA, Peterson J, Wilson R, (2003), The BlueSky Smoke Modeling Framework. Proceedings of the 5th Symposium on Fire and Forest Meteorology, American Meteorological Society, Orlando, FL, November 2003

Pouliot G, et al., (2005), Wildfire Emission Modeling: Integrating BlueSky and SMOKE. 14th

International. Emission Inventory Conf. "Transforming Emission Inventories Meeting Future Challenges Today", Las Vegas NV

Prins EM, and Menzel WP, (1990), Geostationary satellite detection of biomass burning in South America, *Int. J. Rem. Sens*. **13**: 2783 – 2799

Riebau AR, Fox D, (2001), The new smoke management. *Int'l J. Wildland Fire,* **10**: 415 – 427

Sandberg DV, Hardy CC, Ottmarn RD, Snell JAK, Acheson A, Peterson JL, Seamon P, Lahm P, Wade D, (1999), National strategy plan: Modeling and data systems for wildland fire and air quality. US Forest Service, PNRS, 60

SRFRR, (1996), Southern Region Forest Research Report, 7th American Forest Congress Feb. 1996

Stanturf JA, et al., (2002), Background paper : Fires in southern forest landscapes, in The Southern Forest Resource Assessment, USDA Forest Service, SRS

Wade DD, Brock BL, Brose PH, et al., (2000), Fire in eastern ecosystems. In: Brown JK, Smith, JK (eds) Wildland Fire in Ecosystems: Effects of Fire on Flora. Gen. Tech. Rep. RMRS-42. Ogden, UT: US. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 53 – 96. Chapter 4. Vol. 2.

Ward DE, Hardy CC, (1991), Smoke emissions from wildland fires, *Environ. Int.,* **17**: 117 – 134

Zheng M, Cass GR, Schauer JJ, Edgerton ES, (2002), Source Apportionment of $PM_{2.5}$ in the Southeastern United States Using Solvent-Extractable Organic Compounds as Tracers. *Environ. Sci. Technol.,* **36**: 2361 – 2371