SMOKE MANAGEMENT: TOWARD A DATA BASE TO VALIDATE PB-PIEDMONT - NUMERICAL SIMULATION OF SMOKE ON TEE GROUND AT NIGHT

Gary L. Achtemeier
USDA Forestry Sciences Laboratory
320 Green Street
Athens, GA 30602

ABSTRACT

The use of fire for controlled burning to meet objectives for silviculture or for ecosystem management carries the risk of liability for smoke. Near-ground smoke can degrade air quality, reduce visibility, aggravate health problems, and create a general nuisance. At night, smoke can locally limit visibility over roadways creating serious hazards to transportation.

PB-Piedmont, a numerical model designed to simulate smoke movement at night over irregular terrain similar to that of the Piedmont of the Southeastern United States, is becoming available for use by land managers. PB-Piedmont has the potential to significantly influence management decisions and therefore must be subject to thorough validation. Decisions based on an incompletely validated model can be worse than decisions made with no model at all.

This paper summarizes a project designed to acquire the necessary validation data - remote measurements of smoke on the ground taken from the air with an intensified multi-spectral video camera capable of amplifying light up to 15.000 times. The project tested the hypothesis that smoke trapped near ground at night scatters sufficient moonlight to be observed from an aircraft. Smoke movement was recorded on Super VHS tape for two nighttime prescribed fires timed to coincide with moonlight and clear sky and near calm weather conditions. Selected images for the first night. 20 March 1997. demonstrate the complexity of near-ground smoke plumes. Image data were transferred to U.S. Geological Survey elevation maps. Small variations in elevation such as gaps in ridges are critical to smoke movement. PB-Piedmont must accurately simulate smoke movement at night on terrain scales that smoke "sees".

INTRODUCTION

Continued supply of the nation's paper and other wood products increasingly depends upon wood fiber produced from Southern forests. Approximately 200 million acres of forest land are found within the thirteen states that make up the South - states roughly south of the Ohio River and from Texas eastward. Though these states have about 24 percent of the land area. they comprise JO percent of the forest land in the United States. These Southern forests are dynamic ecosystems. capable of supply. in perpetuity with good stewardship. the myriad of goods and services we have come to rely on as the mainstay of the economy [1].

The region's potential productivity of forests is about 80 cu A per acre which is the highest in the country. This strong productivity reflects the favorable soil and climate features of the region that allow stands of southern pines to reach financial maturity in 30-50 years. optimal rotation ages are 1/2 to 1/3 of the length of timber stands in other parts of the United States. In combination with the decline in productivity of forests elsewhere in the country, this productivity ranks the forest industry among the largest employers in several states (USDA).

Continued high forest productivity requires good forest management practices. Southern land managers have found that prescribed fire is economically the best means to reduce fuels, remove species that compete for nutrients, and lower danger of wildfires that can destroy commercial fiber and threaten urbanized areas. From 6-8 million acres of forest and agricultural lands per year are being treated with prescribed fire.

Problem:Smoke,ParticularlyatNight

The effects of prescribed fire on air quality are a serious concern. The mild, mostly snow and ice free winters make the Southern climate ideal for the development of retirement communities. Thousands of older people, many with respiratory problems, have relocated into Southern communities. Because many of these retirees have little or no experience with forestry practices, they may not be receptive to frequent intrusions of smoke into their communities.

The Environmental Protection Agency (EPA) has the responsibility under the Clean Air Act to propose. revise. and promulgate National Air Quality Standards (NAAQS) for airborne pollutants. New NAAQS for particulate matter have been proposed. The revised standard focuses on particulate matter which are PM-IO and PM-2.5. Most forestry smoke falls within this size range. The EPA claims the added standards for PM-2.5 will provide better health protection. Those with heart and lung problems, including asthma sufferers, particularly among children and the elderly, have been statistically correlated to more health problems than people living in areas with lower PM-2.5 concentrations.

There exists an extensive road network that connects the many cities, towns, and villages that grew up in the old agricultural South. As population increases and the numbers of tourists driving to resort areas increases. the number of highway accidents related to smoke and smoke/fog could also increase. Visibility reductions caused by smoke or a combination of smoke and fog already have been implicated in multiple-car pileups. numerous physical injuries. heavy property damage. and fatalities.

Most of the serious accidents have occurred at night or around sunrise as smoke trapped in stream valleys and basins is carried across roadways, Several attempts to compile records of smoke-implicated highway accidents have been made. The available accident data is admittedly incomplete. The most comprehensive study was *undertaken* by Mobley for the 10-year period from 1979-1988 [2]. He reported 28 fatalities. over 60 serious injuries, numerous minor injuries and millions of dollars in lawsuits. Using less complete data from 1989-March 199 1, Mobley recorded 5 additional fatalities.

During the period from October 1996 through June 1997, eight smoke on the highway incidents that ranged from minor accidents to road closures were reported in South Carolina. The record was admittedly incomplete. Based on South Carolina, similar smoke incident frequencies can be estimated for other southern states. If the South Carolina data are modified for area devoted to forestry and agriculture in other states, the number of smoke/highway incidents throughout the South can be conservatively estimated to be more than 150 annually [3].

Solution: Numerical Modeling Smoke Movement at Night

Existing information on smoke, especially the behavior of smoke at night. is largely anecdotal. The body of scientific information necessary to serve as a base for wise management decisions and sound regulatory guidelines is lacking. Mistakes made at one location can lead to unnecessary penalties imposed on prescribed burning at other locations.

Smoke in the daytime can be a nuisance when it moves into sensitive areas and a hazard to transportation when it drifts across roadways. However. the most severe impacts of smoke can occur at night when small amounts of smoke from smoldering heavy fuels are more likely to be trapped near the ground and carried several miles in slow moving air without much dispersion. In addition. smoke entrapped within moist shallow valleys at night can initiate or enhance local fog. Smoke or smoke and fog can impair visibility and create serious hazards to transportation.

The Southern Research Station Smoke Management Team of the USDA Forest Service has constructed a smoke movement model for near-ground smoke at night. The model can be used to monitor smoke as it moves •

information that can be used to alert authorities or to display smoke warning signs on roads, if necessary. Future versions of PB-Piedmont will predict smoke movement. Land managers may choose not to burn or implement ignition strategies.

Tests with the model show that the combination of large scale wind systems with weak drainage winds that form over terrain typical of the Piedmont of the Southeast can create complex plume structures. Whether these patterns exist is a subject for model validation. The best way to observe a smoke plume moving near the ground at night is from aloft. It was hypothesized that if smoke scatters headlights from vehicles to create visibility hazards smoke will also scatter moonlight and thus be visible from the air. The following describes the Talladega Project designed to test the hypothesis and to collect data to validate PB-Piedmont.

THE TALLADEGA PROJECT

During January-March 1997, a project was conducted to test if smoke can be observed from an aircraft equipped with a light-enhanced video imaging system. The project included representatives from the USFS Remote Sensing Applications Group (RSAG). Region 8 Fire and Aviation and the Southern Research Station Smoke Management Team. The project was held at the Oakmulgee Wildlife Management Area located on the Talladega National Forest in western Alabama. The site was selected because:

(1) Valley to ridge elevation differences were typical of the Piedmont (200-300 A: 60-100 m).

(2) Major stream valleys extended 10 mi (16 km) without crossing heavily traveled roadways.

(3) A major highway located 8 mi (13 km) from the site was separated from all drainages by a system of ridges.

(4) Few alien light sources (yard lights, lights from homes or automobiles) were present to interfere with the light-sensitive equipment

To test the hypothesis, a Xybion intensified multispectral video camera capable of amplifying moonlight up to 15,000 times was mounted in a Beech Craft King Air aircraft and flown at approximately 1,500m agl. Video imagerywasstoredviaa Super VHS data recorder. Geopositioning System (GPS) tracking information was incorporated on each frame of the recording tape [4].

The field operations were restricted to clear skies and near calm winds during three 8-night windows timed to coincide with the full moon in January, February, and March 1997. This approach insured data collection during maximum moonlight. However, only four nights, one in January, one in February, and two in March met the meteorological criteria. During the January window a 40 acre night burn was started at approximately 2 100 CST. The heat column generated by this fire lofted smoke above the surrounding ridges and it was carried off by prevailing winds.

Though unsuccessful at remote sensing of smoke trapped near the ground, the January mission provided some useful lessons. The prescribed fire generated too much heat. Alternative methods to generate much smoke without inversion-penetrating heat would have to be found. Furthermore, near infrared radiation reflecting from the ground and passing through the smoke exceeded moonlight reflected from the smoke. Smoke was rendered nearly invisible.

A new smoke-generating method was designed using smoke bombs and hay bales soaked with diesel fuel. A visible light bandpass filter (hot mirror) was employed to cut off near infrared light and improve spectral contrast between smoke and background terrain features. Then, during the February operations window. the equipment was mounted and tested in a 100 ft tower located on the Oconee National Forest in Georgia. The smoke source was a single bale of hay soaked with diesel fuel and ignited. Once burning vigorously, the fire was estinguished. The smoldering hay produced copious amounts of smoke with minimal heat production.

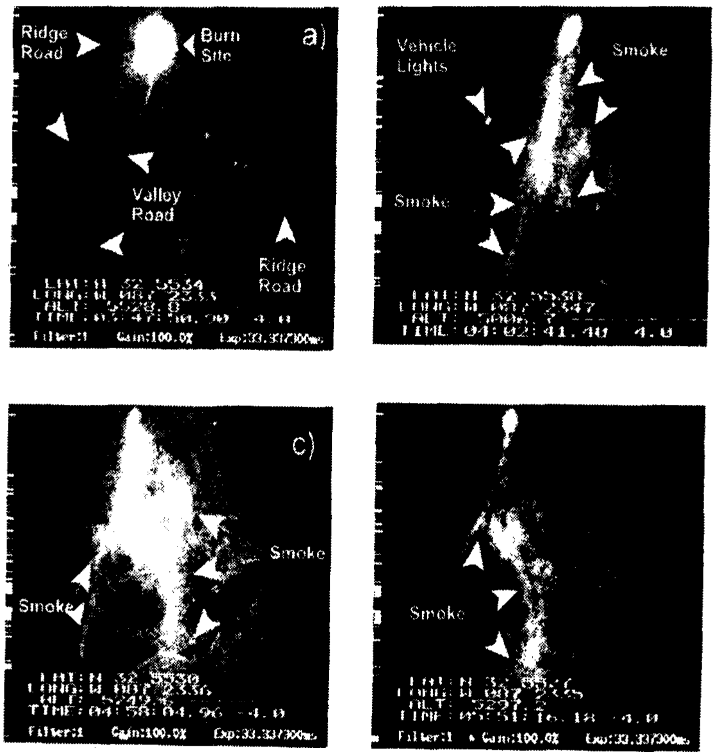
During 20-2 1 March 1997. the project returned to the Oalanulgee National Wildlife Refuge where Forest Service ground personnel burned 50 bales of hay soaked in diesel fuel. In addition. they detonated 60 smoke bombs that had a burn lifetime of approximately 2 minutes each. The fire was started at 2145 CST along a road that followed a NE-SW oriented stream basin (Fig. 1). Aircraft overflights at approximately 1,500 m agl commenced at the bum start time (2 118 CST) and continued at 7 minute intervals for two hours.

Winds blew lightly from the north during the day and became variable at dusk. Ground personnel reported calm conditions at the burn site. Project forecasts called for drainage winds to form along the slopes of steep 30-50 m ridges and to drive smoke northward downstream. Obsencrs were positioned downstream to record smoke upon its arrival.

RESULTS OF TALLADEGA EXPERIMENT

Video Imagery

Figure 1 shows enhanced images of the first successful remote imaging of smoke near the ground at night done on 20 March 1997. The field of view is 1400 m in the horizontal and is compressed to 1050 m in the vertical with an aspect ratio for analog video of 1.335.



Fiie 1. Images of smoke moving along the **ground at** night. a) 2 147 CST -plume shortly **after** ignition, b) 2202 CST **- plume drifting** up **valley** along road, c) 2258 CST **-** plume **diverting into** adjacent valley, and d) **235** 1 CST -dissipating plume at end of burn

The burn site is **identified** by the bright area near the top of Figure la. The bright area was smoke illuminated by a combination of scattered moonlight and diffused light **from** flaming material. The valley road leading from the lower **left** of the image to the burn site is clearly visible. Other roads follow ridge lines; one to the west of the burn site and the other barely visible to the southeast near the right edge of the image. These roads connect south of the burn site thus enclosing the drainage area. The drainage area exits past the burn site toward the top of the figure.

The origin of the secondary sources of reflected light surrounding the burn site and extending toward the bottom right of the figure are not known for certain. The sources **could** be bare ground beneath hardwood trees that had not yet leafed-out. Roads are visible as strips of bare ground. In addition, dogwood trees were in **full** bloom. Dogwood blossoms reflect in visible light. Ground observers reported that flowering dogwoods could be easily seen in moonlight.

By 2202 CST (Figure lb). the smoke plume moved up the valley along the valley road. Although the brightest areas extended from the burn site toward the center of the image, dense smoke was observed all along the road to where it ascended the southern ridge of the valley near the bottom of the image.

After 22 15 CST, the smoke turned up a side valley and crossed the southern perimeter road. An example is the image for 2258 CST (Figure Ic).

The pattern of smoke movement continued through 2300 CST. Figure 1d (2351 CST) shows smoke shortly after the burn was concluded. The bright areas at the burn site were vehicle headlights. The dissipating smoke plume continued to flow up the side valley. The image shows no evidence of smoke along the lower half of the valley road. Ground crews reported dense smoke along that stretch of road however

Mapping Smoke Images

The next step in the analysis was to overlay the video images on an elevation map to isolate the reason why smoke persistently moved up a side valley and crossed the ridge that enclosed the southern perimeter of the basin. An image analysis method to map smoke images from video imagery into smoke polygons is described by Achtemeier [4]. The smoke polygons were overlaid on an elevation map of the valley and surrounding ridges. The elevation map was constructed from 30-meter digital elevation model (DEM) data acquired from the U.S. Geological survey.

Figure 2 shows the evolution of the smoke movement relative to the surrounding elevation. Elevations range from 100 m in the bottom lands to around 150 m along the ridge tops with a few high points near 170 m. Elevations greater than 130 m (430 ft) are shaded to better identify the drainage basin. Elevations above 135 m are shaded darker. This choice for shading clearly identifies a gap in the ridge system that surroundedthebasinin which the burn was conducted. Elevations surrounding the drainage basin were above 145 m (480 A) except at one location where they were 130 m (430 ft). It was at this location where smoke exited the valley.

Smoke generated at the burn site (Fig. 2a) moved southwestward along the natural extension of the stream valley (Fig. 2b). Then the plume shifted to impinge directly upon a protruding ridge. The plume split around the ridge (Fig. 2c). flowed up the side valley and crossed the ridge through the gap at the southern end of the valley. Smoke diversion through the side valley continued throughout the remainder of the burn (Fig. 2d).

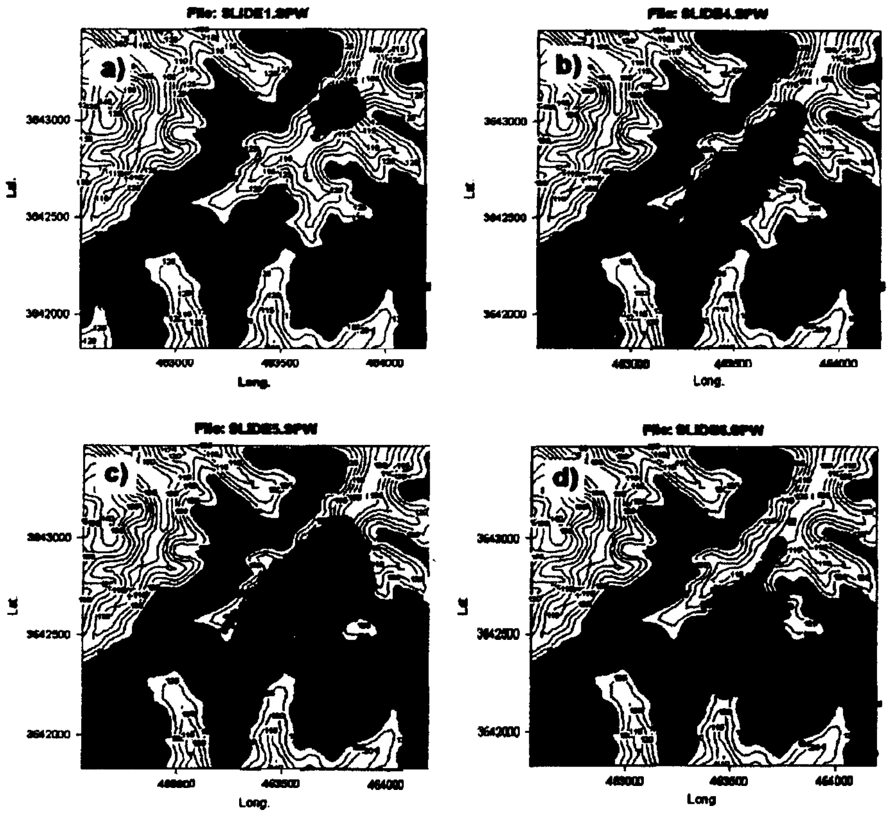


Figure 2. Image analysis of smoke **images** overlain on 30 m **DEM** elevation **data.** a) 2147 CST -**plume shortly after ignition,** b) 2202 CST -**plume drifting** up **valley along road,** c) 2258 CST -**plume diverting into adjacent** valley, and d) 2351 CST-**dissipating plume** at **end of burn.**

DISCUSSION AND CONCLUSIONS

The Talladega Smoke Study has revealed the following:

1. The results verify the hypothesis that smoke can be observed from the air under moonlight if the smoke is sufficiently dense. Thus, a light-intensified video camera can be used for airborne remote sensing of

smoke moving near the ground at night. This technology is critical for smoke management because airborne observation is the only way to observe and understand the movement of an entire smoke plume and to validate numerical models for ground-level nocturnal smoke movement and dispersal.

2. Some shallow layers of dense smoke escaped detection. Some undetected smoke was hidden beneath partially closed vegetation canopies along the valley road. Furthermore, smoke that turned up the side valley vanished from the imagery after crossing the gap in the ridge. This smoke was passing over a clear-cut field and should have been clearly visible.

3 The wind field near the ground at night is extremely complex in both space and time. Winds are channeled by small variations in elevation. In figure 3 smoke channeled up a side valley and crossed a ridge. Elevations surrounding the drainage basin were above 150 m (480 ft) except at one location where they were 130 m (430 ft). Smoke exited the valley through this gap. Therefore, fine details in terrain, such as small gaps in ridges, must be carried in numerical wind models if smoke movement at night is to be successfullysimulated.

As judicious application of prescribed fire reduces the threat of catastrophic wildfire, smoke will become the biggest obstacle to fire-based land management. Successful widespread application of prescribed fire will require knowledge of smoke concentration, location, and movement so appropriate reaction strategies can be implemented. The Talladega experiment shows that smoke moving near the ground at night can be remotely imaged from an aircraft. Thus it may be possible to operationally monitor nocturnal smoke events.

Efforts are underway to collect more data to validate PB-Piedmont. A more powerful light intensifier capable of magnifying light up to 80,000 times has been acquired. Additional projects like the one conducted at the Talladega National Forest are planned

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