

Project Title: Does Prescribed Burning in Southern Forests Release Significant Amounts of Mercury to the Atmosphere?

Final Report: JFSP Project Number 05-2-1-45

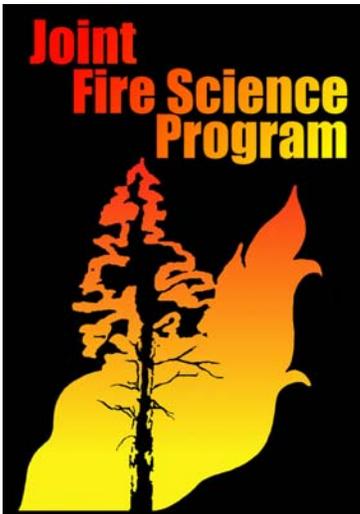
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I. Abstract

Mercury (Hg) emissions from prescribed fire present a potential impact on air quality that could motivate regulators to further restrict prescribed burning. Atmospheric deposition of Hg (originating from industrial sources) to forests is well documented, and the prescribed burning of two to four million acres per year in the South recycles an unknown (but potentially significant) amount of Hg into the atmosphere and surface waters by volatilization and post-fire runoff. This and other environmental concerns present a significant challenge to local land managers who use prescribed fire. Our objectives were (1) to estimate local and South-wide emission of Hg due to prescribed fire, and (2) to test the hypothesis that Hg in ashen fire debris is leached into and subsequently retained in mineral soil. Increased retention of Hg in mineral soils as a result of fire may mitigate the environmental impact of fire-related emissions because Hg volatilization during future fires would be reduced and the retained Hg would be less likely to enter surface waters as runoff. We estimated emissions by measuring Hg amounts in the forest floor and surface mineral soil soon before and immediately after individual prescribed fires. We assessed the influence of fire on Hg storage in mineral soil by determining Hg in the mineral soil and forest floor of paired areas that have been managed with or without prescribed fires for many years.

II. Background and purpose

Mercury (Hg) emissions from prescribed fire present a potential impact on air quality that could motivate regulators to further restrict prescribed burning. Such restrictions would pose a significant challenge to local land managers in the South who use prescribed fire. Although the regulatory focus of the United States Environmental Protection Agency (USEPA) is currently directed toward curbing Hg emissions from electric utilities, the sources of atmospheric Hg are controversial. As evidence, USEPA received a record number of public comments on its proposed rule to reduce Hg emissions from electric utilities (540,000 comments according to Christen (2004)). Further, a recent article in the Lufkin Daily News (East Texas) included a debate between spokespersons for an electric utility and the US Forest Service concerning the relative importance of Hg emissions from power plants and prescribed forest fires (Diamond, 2004). Whatever the source of the emissions, data indicate that Hg deposition is relatively high in the South (Figure 1).

In light of the elevated levels of Hg deposition in the South (Figure 1) and the large acreage of Southern forests that are prescription-burned each year (2-4 million acres per year; Southern Area Coordinating Group, 2003; Haines et al., 2001), the re-emission of atmospherically deposited Hg by Southern prescribed fire should be quantified. However, only limited data on Hg emissions from forest fires (prescribed or wild) in the US are available. Most of these data originate from regions outside the South. Estimates of Hg emissions from US wildfires in the lower 48 states vary from 3-14% of the total US anthropogenic emissions, and are based on extrapolation of data from the Western and Great Lake states (Friedli et al., 2003; Cannon, 2004; USEPA, 1997, p. 5-2). Extrapolating our preliminary data from the Osceola National Forest (Florida) suggested that South-wide emission of Hg from prescribed fire was small (0.2% of total US

anthropogenic emissions). These data further suggested, although trends were not statistically significant, that prescribed fire may lead to the buildup of Hg in subsoil due to the post-fire leaching of Hg from ashen fire debris. This retention of Hg in subsoil may reduce Hg volatilization during future fires and reduce the transport of Hg to surface waters as runoff.

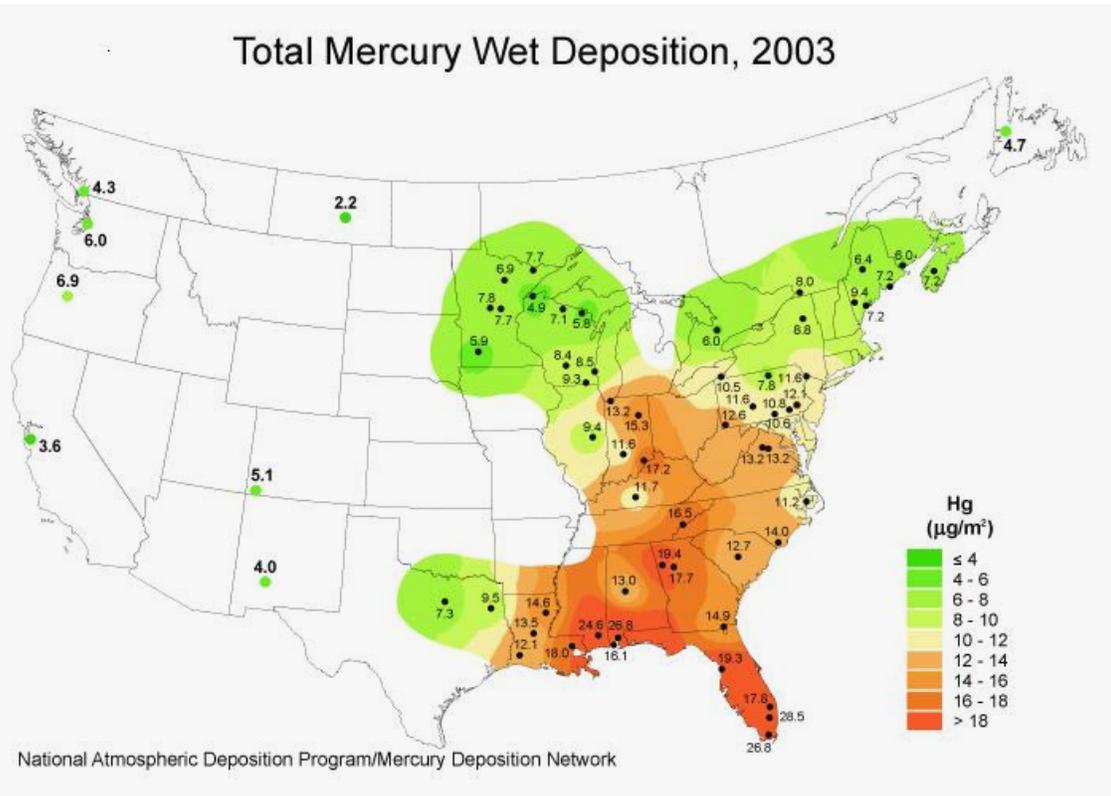


Figure 1. Mercury wet deposition in 2003 in the Eastern United States. (Source: National Atmospheric Deposition Program, <http://nadp.sws.uiuc.edu/mdn/maps/map.asp?imgFile=2003/03MDNdepo.gif>)

The objectives of this study were:

1. To estimate local and South-wide emissions of Hg due to prescribed fire.
2. To develop location-specific predictive relationships that will allow policy makers or managers to estimate Hg emissions from prescribed fire based on percent forest floor consumption and time since last fire.
3. To test the hypothesis that Hg in ashen fire debris is leached into and subsequently retained in mineral soil. If the hypothesis is verified, relate subsoil Hg retention to local variables, such as rainfall, fire regime, and soil type.

III. Study description and location

The study sites and sampling activities are shown in Table 1.

Table 1. Study sites and sampling activities.

Site	Evaluate Hg emissions by pre- and post-burn sampling	Evaluate Hg retention in mineral soil in areas with different fire history	Remarks
Coastal Plain			
Osceola National Forest, FL	X	X	Prescribed fire frequency experiment in place – 1958 to present. Operational burns ongoing.
Francis Marion National Forest, SC	X	X	Prescribed fire frequency experiment in place – 1958 to present. Operational burns ongoing.
Santee Fire Plots, SC		X	Prescribed fire frequency experiment in place – 1946 to 1989, no burning since 1989
Piedmont			
Enoree Ranger District, Sumter National Forest	X	X	Operational burns ongoing.
Hitchiti Experimental Forest, Oconee National Forest		X	Prescribed fire frequency experiment in place – 1958 to present. Operational burns ongoing.
Clemson Experimental Forest, SC	X	X	Site is part of National Fire and Fire Surrogate Study.
Mountains			
Green River Game Land, NC	X		Site is part of National Fire and Fire Surrogate Study.
Tallulah Ranger District, Chattahoochee National Forest, GA	X	X	Operational burns ongoing.
Andrew Pickens Ranger District, Sumter National Forest	X	X	Operational burns ongoing.

For estimating the Hg emissions due to individual prescribed fires, we sampled the forest floor and the 0-2 and 2-5 cm depths of mineral soil soon before and immediately after prescribed fire. The differences in Hg between the pre- and post-fire samples for the three layers (as well as the sum of the layers) were used to assess the source and amount of Hg

emissions due to the fire. Pre-fire samples were taken from ten random points within the burn area, with the time between this initial sampling and the burn not to exceed eight weeks. Post-fire samples were taken as soon after the prescribed burn as safety considerations permit (within about 24 hours), using a second set of ten random points. The pre-fire points were not revisited because of fuel disturbance associated with sampling.

To test our hypothesis that prescribed fire causes a long-term increase of Hg in the mineral soil, we sampled comparable areas with different fire histories (Table 1). These areas included established experimental areas as well as paired operational sites identified by local land managers. Based on our preliminary data, we sampled to 60 cm depth. In established experimental areas, we composited samples (by layer) from each combination of block and treatment. In paired operational areas, we sampled approximately ten random locations within each area.

Forest floor samples were obtained by cutting through the forest floor and into the mineral soil with a square (10 cm x 10 cm) metal cutting device. The mineral soil samples were taken immediately adjacent to the forest floor samples, after manually and carefully clearing away forest floor material. Mineral soil samples were collected with a slide-hammer-driven steel corer fitted with butyrate inner liners (two-inch diameter) or with a standard stainless steel slotted soil corer (0.7 inch diameter). Soil corers were cleaned as necessary by driving them into soil near the next sampling location, removing, and cleaning walls with a putty knife.

In the field, soils were stored in glass, pre-weighed, pre-cleaned (certified clean for Hg) environmental sampling bottles with Teflon-lined plastic caps. The bottles were transferred to an ice chest within about one hour of collection, and stored at 4 °C upon return to the laboratory. Cold storage minimized loss of gaseous Hg. Samples were pre-processed by the procedures below.

Forest floor samples were oven-dried at 40 °C in a non-convection oven, in the presence of an open beaker of activated carbon. (The activated carbon serves to take up potentially contaminating Hg vapor from the atmosphere.) Drying was hastened by capping and shaking the sample once per day in order to minimize the time the samples are exposed to laboratory air. The dried forest floor samples were ground in a stainless steel Wiley mill (1-mm screen opening), transferred back to the glass bottles, and returned to 4° C storage until Hg analysis. The field-moist mineral soil samples were pushed through a 2-mm sieve with the aid of a solid wooden cylinder. The mineral soil samples were transferred back to the glass bottles, returned to 4° C storage until Hg analysis, and analyzed moist.

A subsample of each forest floor and soil was analyzed for organic carbon, as Hg is often chemically bound to soil organic matter. We dried, sieved (2 mm), and finely ground (ball-mill) subsamples for this analysis.

Within one month of collection, the forest floor and mineral soil samples were analyzed at the Forest Service's laboratory in Athens, GA. Mercury was determined using a

Tekran Model 2600 CVAFS Mercury Analyzer. Organic carbon was determined by dry combustion using a Perkin Elmer Series II 2400 CHNS/O Analyzer. Soils at all of our sites are acidic and thus do not contain interfering inorganic carbon (carbonate). Because the Osceola samples were collected before our laboratory was operational, Hg in these samples was analyzed at the University of Georgia by microwave-assisted nitric acid digestion (USEPA, 1994) followed by inductively coupled plasma mass spectrometry.

At this time, the laboratory analyses are complete only for the long-term burning sites (Hitchiti, Osceola, and Clemson). Full data will be posted when the analyses for all sites and samples are complete.

Quality Control

Quality of analytical results were assured by running duplicate analyses of outlying data points (Dixon, 1986) and running standard reference materials (e.g. soils and plant matter) from the National Institute of Standards and Technology through both the pre-processing and analytical steps. Analysis of Hg in samples remote from point sources of Hg is difficult because of low concentrations and ease of contamination. Accordingly, some samples were analyzed more than once. Means were used as the final data for duplicate analyses and medians were used for triplicate analyses.

IV. Key findings

Mercury (Hg) emissions from US wildfires (lower 48 states only) have been estimated as 3.2 to 20 metric tons per year, or 3-14% of the US emissions of 144 metric tons per year (Friedli et al., 2003a; Cannon, 2004; USEPA, 1997, p. 5-2). These estimates rely heavily on extrapolated data from the West and Great Lakes and may not represent the Hg emissions from low-intensity prescribed fires such as are common in the South. We sampled three locations where paired burn versus non-burned conditions existed. For the non-burned plots, fire had been excluded for more than 20 years. Of the three sites, one is located in the Coastal Plain in an area of relatively high Hg-deposition, on the Osceola National Forest in Florida. At this site, our data were collected from the forest floor, topsoil (A), leached subsoil (E), and organic-enriched subsoil (B) horizons in a 46-year old prescription-burn experiment. The forest canopy was not sampled because the vast majority of Hg in forests resides in the soil (Grigal, 2003).

An independent estimate of Hg deposition at this site was available and aided in the interpretation of Hg-cycling. Wet deposition to the Osceola site was based on the two nearest sites in the US National Atmospheric Deposition Program's Mercury Deposition Network (NADP, 2005), Okefenokee National Wildlife Refuge, Georgia and the Chassahowitzka National Wildlife Refuge, Florida (Figure 1). These monitoring sites are approximately collinear with the Osceola study site and wet deposition was computed as the distance-weighted mean of the values at the two monitoring sites. These means were computed for each year of data availability (1998-2003) and averaged across years, yielding a figure of $0.136 \text{ g Hg ha}^{-1} \text{ yr}^{-1}$. Dry deposition was estimated as $0.035 \text{ g Hg ha}^{-1} \text{ yr}^{-1}$, based on a national-scale map of dry deposition presented by Seigneur et al. (2004).

The sum of wet and dry deposition, $0.171 \text{ g Hg ha}^{-1} \text{ yr}^{-1}$, was taken as the total deposition to the site. For simplicity and lack of further data, the total wet plus dry deposition was assumed to be constant over the 46-year period of the prescribed burn study.

Osceola National Forest

The only statistically significant differences due to fire regime at the Osceola NF occurred in the forest floor (Figure 2). The *annualized* amount of Hg accumulated in the unburned forest floor over the 46-year experiment ($0.180 \text{ g Hg ha}^{-1} \text{ yr}^{-1}$) matches the wet and dry deposition rate estimated from other sources ($0.171 \text{ g Hg ha}^{-1} \text{ yr}^{-1}$). This suggests that the atmosphere is the source of the Hg retained in the forest floor. The resulting interpretation is that all inputs of soil Hg were emitted each year from the O horizon of the annually burned plots of the 46-year study period. The relatively small amount of Hg in the annually burned forest floor (Figure 2) suggests that atmospherically deposited Hg is removed by re-emission or translocation. Assuming that the differences in the burned versus unburned forest floors are due only to Hg volatilization during fire over the 46-year old experiment, and extrapolating our results to the maximum 4 million acres per year burned South-wide, the four- and one-year burn cycles emit approximately 0.1-0.3 metric tons of Hg per year. These emissions correspond to only 0.07–0.21 % of the 144 metric tons emitted annually in the US.

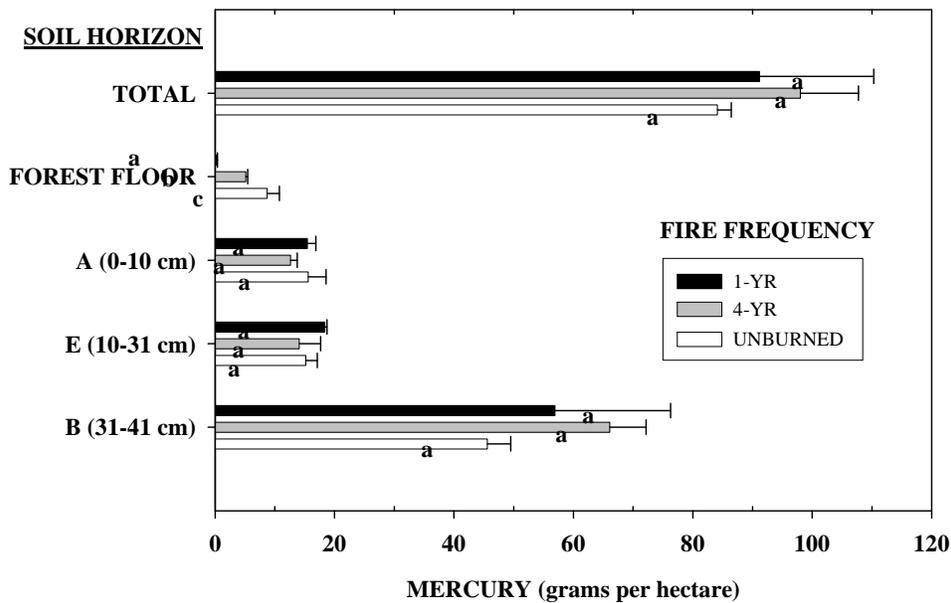


Figure 2. Mercury storage on the Osceola National Forest as a function of burning regime. Burning treatments began in 1958, at which time the entire area was burned. Different lowercase letters within a horizon denote significant differences ($p = 0.1$).

The two other sites long-term burning sites are both located in the Piedmont. The Clemson Forest site in South Carolina receives higher annual Hg deposition than the Hitchiti Experimental Forest site in Georgia (Figure 1).

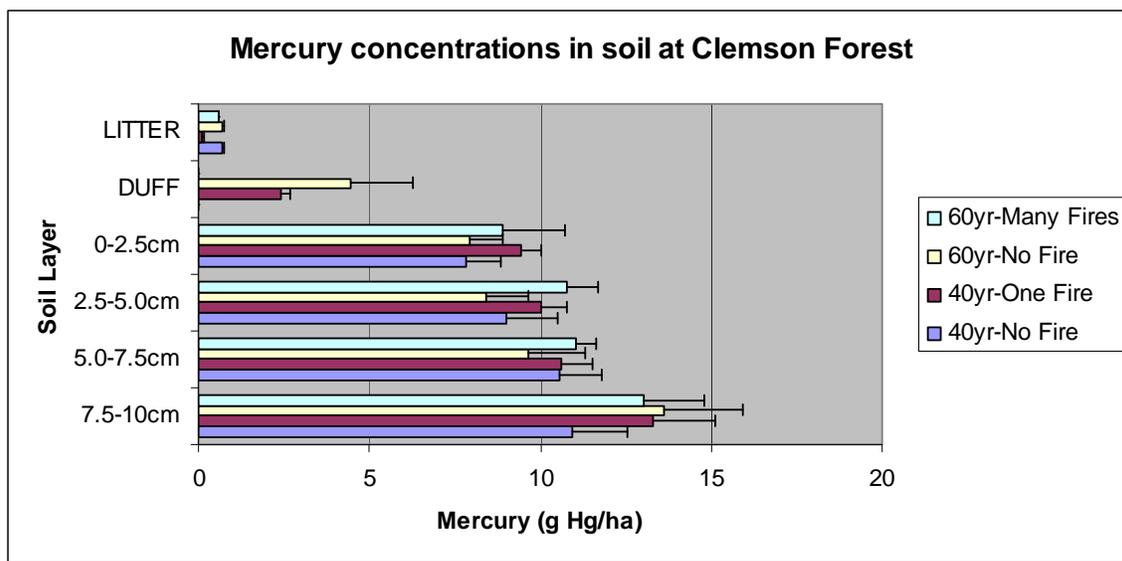


Figure 3.

At the Clemson Forest, the most interesting feature is that for the 60-year-old stand with regular fire, there were higher concentrations of Hg at deeper depths than with any of the other treatment units. This is consistent with our hypothesis (suggested by the Osceola data), that frequent fire results in less complexing of Hg with organic matter (OM) in the litter and duff layer, and thus vertical movement into the mineral horizons of soil (where it is much less likely to be volatilized in fires). We saw insignificant trends in this direction for Osceola soils, but in the Clemson Forest case, the differences in Hg concentrations are significant for the 0-2.5 cm, 2.5-5.0 cm and 5.0-7.5 cm depths.

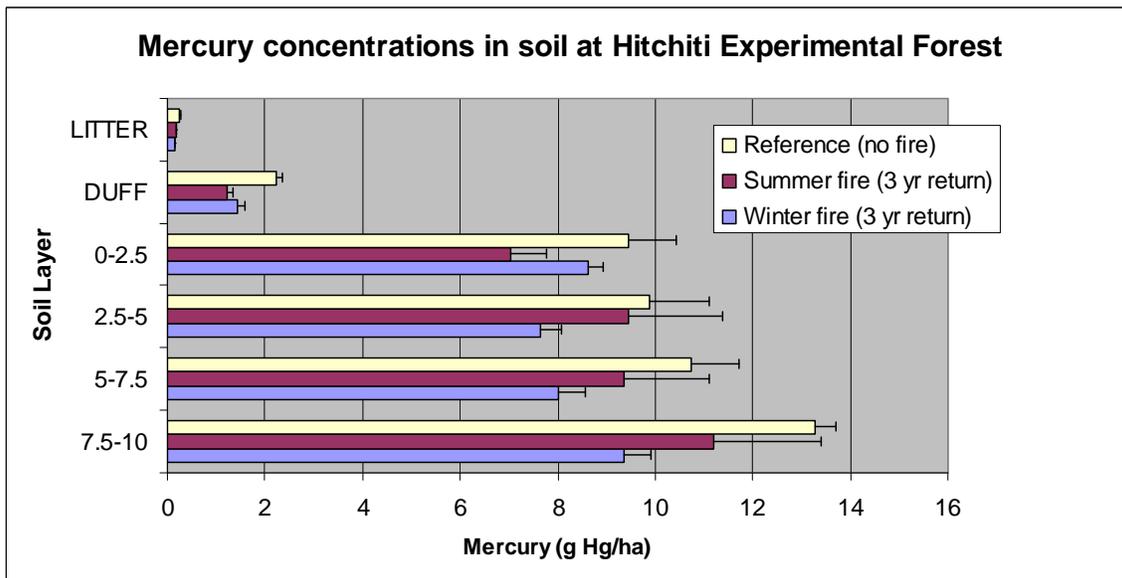


Figure 4.

For the Hitchiti data, there is nothing really surprising in light of the Osceola and Clemson data. The fairly standard pattern of significantly more Hg residing in the litter and duff of reference (unburned) plots is there, and statistically significant. The trend is there for the entire sampled profile, but not significant in the mineral horizons. No differences were observed between summer burns and winter burns. Interestingly, there was no evidence that fires resulted in movement of Hg into the mineral soil (as seen for the Osceola and Clemson sites). This is may be due to differences in clay content, differences in OM type and content, differences in fire frequency, or some combination of these factors. The greater amount of Hg in the duff of the unburned plots at the Clemson site compared to the Hitchiti site are in agreement with the lower annual deposition rates at the Hitchiti site (Figure 1).

Our results have suggested a noteworthy behavior of Hg during and after fire that may not have been previously observed. Although trends were statistically significant at only two of the three locations (Osceola and Clemson), total Hg and Hg in the B horizons were greatest when fire was present (Figures 2-4). If this trend is real, Hg storage in the subsoil of burned areas may result in less Hg volatilization during future fires and less transport of Hg to surface waters in the form of runoff. The logical explanation for increased Hg storage during fire is the leaching of ashen fire debris by rain. Assuming that the atmosphere is the primary source of Hg to the soils at these sites, the following general cycle of Hg is suggested by our results: Hg reaches the O horizon via litterfall and throughfall (Grigal 2002), is eventually incorporated into the A horizon, is transported out of the A and through the E horizon by mobile organic matter, and is subsequently deposited in the B horizon.

V. Management implications

The source of mercury in southern pine ecosystems is atmosphere. The amount of Hg in the surface duff and litter in pine forests is approximately in balance with the amount of Hg deposited since the last prescribed fire. All inputs of soil Hg were re-emitted each year from the O horizon of the annually burned plots. Assuming that the differences in the burned versus unburned forest floors are due only to Hg volatilization during fire, we extrapolated our results from one site (Osceola National Forest, Florida) receiving relatively heavy rates of annual Hg deposition to the maximum 1.7 million ha per year burned South-wide, the four- and one-year burn cycles emit approximately 0.1-0.3 metric tons of Hg per year. These emissions correspond to only 0.07–0.21 % of the 144 metric tons emitted annually in the US and are a fraction of the Hg estimated to be re-emitted by wildfires (Friedli et al., 2003a; Cannon, 2004; USEPA, 1997, p. 5-2). Thus we conclude that prescribed burning in the South contributes only a small amount to mercury emissions nationally.

Frequent low intensity fires have been shown to re-distribute carbon in soils under pine forests. More frequent fires cause C to decrease in the O horizon and increase in the A and B horizons (DiCosty et al. 2006). There may be a similar relationship of fire

frequency and Hg distribution under pine forests, such that Hg is sequestered in mineral soil under frequent burning. However, these trends may be absent on sites where runoff and erosion are important, for example on sloping terrain or where sites denuded by wildfire. Mercury emissions undoubtedly vary according to local conditions and may be relatively high where fire is reintroduced after a lengthy period of suppression.

VI. Relationship to other recent findings and ongoing work on this topic

Recent work by Demers and others (2007) suggests that mercury fluxes differ in deciduous versus coniferous forests. In deciduous forests, litterfall dominates whereas throughfall dominates fluxes in coniferous forest. They observed greater mercury mass in decomposing deciduous litter during the growing season than could be accounted for by throughfall inputs. They suggested that Hg was translocated from the mineral soil to the decomposing deciduous litter. A mass balance assessment suggests that the ultimate fate of mercury in the landscape depends upon forest type and associated differences in the delivery and incorporation of mercury into the soil. These results, however, are from unburned forests in the Adirondack region of New York.

In collaboration with the smoke modelers in our group, we are using these results to estimate the effect of both prescribed burning and wildfires on regional air quality, using the CMAQ modeling tool. The Georgia-Florida Wildfires in 2007 presented an unique opportunity to utilize the Hg estimates from the Osceola NF site to estimate the impact of Hg re-emission.

VII. Future work needed

There needs to be a mass-balance analysis to determine whether the loss of Hg in periodic fires is mitigated by the long-term storage mechanism. In order to accomplish such a balance, we need to explore the distribution of deposited Hg on the vegetation in the unburned versus burned plots, including the relative amount in litterfall versus throughfall and stemflow. In general, we find a shift from woody to herbaceous understory vegetation with increasing fire frequency accompanied by a decrease in understory live plant biomass. For example at the Osceola NF site, overstory basal area and canopy cover were similar among all treatments but understory biomass of the annual burned plots was less than 25% of the live biomass of the unburned plots.

The recent work by Demers and others (2007) suggests that prescribed burning in predominantly deciduous overstory may result in different effects on Hg cycling than we have found in pine forests. While our complete results comparing Hg in litter and duff before and after a burn in our mountain sites will provide some indication of possible differences, a complete answer requires the establishment and maintenance of a long-term fire exclusion study in hardwoods. Our Green River Fire Surrogate site provides the beginnings of such a study.

The differences in understory vegetation in hardwood forests with ericaceous shrubs as compared to the understory in the Northern Hardwood forests (Demers et al. 2007) warrants further examination in terms of Hg cycling.

VIII. The deliverables crosswalk table

Proposed	Delivered	Status
Presentations		
USEPA National Air Quality Conference	DiCosty, R.J., M.A. Callaham, Jr. and J.A. Stanturf. 2006. Impact of Prescribed Fire on Mercury Cycling in Southeastern U.S. Forests, Poster at 8 th International Conference on Mercury as a Global Pollutant, Madison, WI	August 2006
Chattahoochee-Oconee National Forest Staff	Fire in southern Appalachians workshop Stand-replacement fire for restoring Table Mountain pine	May-05
Georgia or South Carolina Prescribed Fire Council	3rd annual Southern Appalachian FLN meeting Fire history; demonstration installation updates; Tallulah Gorge and Chattahoochee National Forest demonstration sites field tour	May-09
Society of American Foresters – Georgia or South Carolina Division	North Carolina Chapter of the Wildlife Society Impacts of fuel reduction treatments on vegetation, fuels, fire behavior, wildlife, soils, and tree diseases; Restoration of Table Mountain pine	Mar-07
Clemson University – Department of Forestry and Natural Resources	Stand replacement prescribed fires for regenerating Table Mountain pine Field tour FFS -- Green River Using stand-replacement fire to perpetuate Table Mountain pine communities	Apr-06 Apr-06 May-08
Georgia or South Carolina Forest Watch or Sierra Club	Southern Blue Ridge Project Field tour FFS -- Green River	Apr-07
Publications		
Article in: Environmental Science and Technology	DiCosty, R.J., Callaham, M.A., Jr., Stanturf, J.A. 2006. Atmospheric deposition and re-emission of mercury estimated in a prescribed forest-fire experiment in Florida, USA. <i>Water, Air, Soil Pollution</i> 176: 77-91.	2006
Article in: Southern Journal of Applied Forestry	Waldrop, T.A., Callaham, M.A., Jr., Stanturf, J.A., Sheko, B., DiCosty, R.J. Mercury re-emission from prescribed fire in the South. <i>Southern Journal Applied Forestry</i> .	In preparation
Web posting of data	Unit website, http://forestdisturbance.net	In preparation

VII. Outreach activities in addition to proposed deliverables

Item	Delivered	Status
Journal article	Callaham, M.A., Jr., O'Brien, J.J., DiCosty, R.J., Williams M.A. Long term soil organic carbons responses to fire frequency in longleaf pine forests. <i>Soil Science Society of America Journal</i>	In preparation
Journal article	Liu, Y-Q, Goodrick, S.L., Stanturf, J.A., Callaham, M.A., Jr., Waldrop, T.A., Sheko, B., DiCosty, R.J. Mercury emissions and dispersion from wildfire and prescribed burning in the southern US. <i>International Journal Wildland Fire.</i>	In preparation
Field Tour	Waldrop, National University Forest Managers Group	March 2005
Conference presentation	Waldrop et al. Current research on fuels, fuel models, and fire behavior in eastern hardwood forests Workshop of Fire in Eastern Oak Forests	November 2005
Conference presentation	DiCosty, R.J., M.A. Callaham, Jr., and J.A. Stanturf. 2005. Atmospheric deposition and re-emission of mercury quantified in a prescribed forest fire experiment in Florida, USA. Presentation at Soil Science Society of America annual meetings, Salt Lake City, UT	November 2005
Briefing	Waldrop, to the Forest Service Chief, Restoring ecosystems with fire and mechanical treatments	May 2006
	Waldrop, JFSP Governing Board Field tour FFS -- Green River; Table Mountain pine restoration	May 2006
Conference presentation	Waldrop, Early stand development of Table Mountain pine after stand replacement prescribed fires, 3rd International Fire Ecology and Management Congress	Nov 2006
Conference presentation	Liu, Y.-Q., G. Achtemeier, and S. Goodrick, 2006, Modeling air quality effects of prescribed forest burns in the South with CMAQ-Daysmoke, Workshop on Agricultural Air Quality, Potomac, MD, June 5-8, 2006.	June 2006

Conference presentation	Goodrick, Scott; Liu, Yongqiang; DiCosty, Ralph; Callaham, Mac; and Stanturf, John. 2007. Mercury emissions and dispersion from the 2007 south Georgia wildfires. 7th Symposium on Fire and Forest Meteorology held at Bar Harbor, ME. Amer. Meteor. Soc. [Achteimeier presented] (http://ams.confex.com/ams/7firenortheast/techprogram/paper_127359.htm)	November 2006
Conference presentation	Waldrop, Delayed mortality of eastern hardwoods after prescribed fire, 14th Biennial Southern Silviculture Research Conference, Athens, GA	Feb 2007
Field Tour	Waldrop, Forestry students Clemson University Using stand-replacement fire to perpetuate Table Mountain pine communities	May 2007
Field Tour	Waldrop, North Carolina Wildlife Resources Commission Field tour FFS -- Green River	Nov 2007
Field Tour	Waldrop, JFSP review board Field tour FFS -- Clemson and Green River	May 2008
Field Tour	Waldrop, Southern Appalachian FLN Field tour FFS -- Green River	June 2008
Field Tour	Waldrop, Management options to promote smooth coneflower and Table Mountain pine	Oct-08
Conference presentation	Callaham, M.A., Jr., DiCosty, R.J., Lamoncha, K.L., O'Brien, J.J., Outcalt, K.W., Williams, M.A., Stanturf, J.A. 2009. Effects of long-term fire frequency manipulations on soil chemical and biological properties in a north Florida longleaf pine forest. Workshop on Global Soil Change, Duke University, Durham, NC [poster]	June 2009
Training Session	Callaham, M.A., Jr. Fire and Aviation Academy, RX 310 Fire Effects course; presentation on fire effects on soils. Held Chattanooga, TN	June 2009
Field Tour	Waldrop, Southwide forest disease workshop Delayed mortality of hardwoods after prescribed fire	Jul-09