The Distribution of Mercury in a Forest Floor Transect Across the Central United States

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Abstract.—Mercury (Hg) stored in soil organic matter may be released when the forest floor is consumed by fire. Our objective is to document the spatial distribution of forest floor Hg for a transect crossing the central United States. Samples collected by the Forest Service, U.S. Department of Agriculture's Forest Inventory and Analysis Soil Quality Indicator were tested for Hg using cold-vapor atomic absorption. We found patterns of Hg concentration that differ from earlier studies; the patterns of Hg concentration had a bimodal distribution with high values in both the northern Rocky Mountains and the Great Lake States. Future work will include an evaluation of the role of elevation and forest type on Hg storage.

Introduction

Soils can be sinks for atmospherically deposited mercury (Hg) (Grigal *et al.* 2000, Kolka *et al.* 2001). Soils act as sinks because the Hg that binds to organic matter in soils is not volatilized back to the atmosphere. Hg retention in soils increases with organic carbon content and climatic factors that influence microbial activity in soils (Fleck *et al.* 1999, Grigal *et al.* 2000, Kolka *et al.* 2001). Forest fires may release into the ecosystem Hg stored in organic matter (Kelly *et al.* 2006). As mercury emissions come under increasing scrutiny and regulation, the contribution of Hg from forest fires relative to other anthropogenic sources is unknown (Friedli *et al.* 2003, Turetsky *et al.* 2006).

The Forest Service, U.S. Department of Agriculture's Forest Inventory and Analysis (FIA) program produces data, information, and knowledge about the extent, condition, status, and trends of the Nation's forest resources across all land ownership categories (Smith 2002). Traditionally, FIA concentrated on the Nation's timber resources, but a change in focus was codified by the passage of the Agricultural Research, Extension and Education Reform Act of 1998, integrating FIA with the ground sampling components of the Forest Health Monitoring program. FIA collects samples from forested areas across the United States as part of its phase 3 sampling, and annual soils inventories are underway or completed in 44 of the 50 States (Alaska, Hawaii, Mississippi, Montana, New Mexico, and Oklahoma have yet to be sampled). The data is being used to facilitate State, national, and international assessments (Coulston *et al.* 2005, Smith 2002, Stolte *et al.* 2002).

Our objective is to document initial investigations into the spatial distribution of forest floor Hg for a transect crossing the central coterminous United States (fig. 1). We selected this region because atmospheric wet deposition rates and concentrations vary from west to east across the country (National Atmospheric Deposition Program 2007, Sweet and Prestbo 1999), providing gradients of Hg deposition and retention across the study area.

Methods

The collection of forest floor samples was accomplished as part of the standard FIA Phase 3 Soil Quality Indicator program. The forest floor is defined as "the entire thickness of organic material overlying the mineral soil, consisting of the litter and the duff (humus)," and field protocols include the measurement

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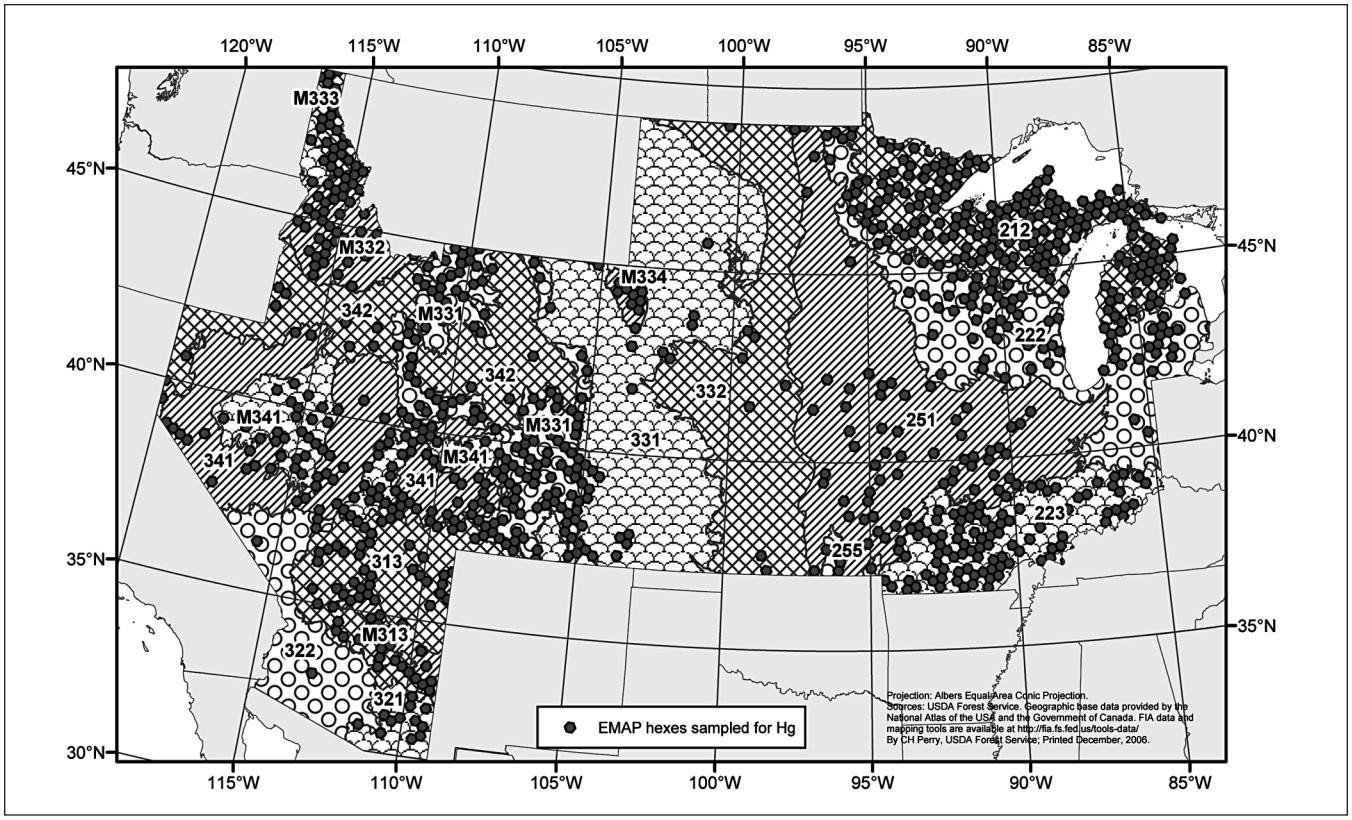
Figure 1.—*The distribution of soil samples tested for mercury. Patterned polygons and numbers refer to ecoprovinces of the region.*



of the thickness of the forest floor and the collection of the entire forest floor found within a sampling frame with a diameter of 30 cm (USDA Forest Service 2006). The samples were tested for a number of chemical and physical properties, not including Hg (Amacher *et al.* 2003).

We removed approximately 0.1 g of the sample for plots in our region of interest, and these were sent to two different laboratories for Hg analysis: the Forest Service Forestry Sciences Lab in Logan, UT, and XRAL Laboratories in Toronto, ON. Both laboratories used cold-vapor atomic absorption to measure the amount of Hg and calibrated their instruments against common Hg standards. We found good agreement between samples analyzed at both laboratories.

Observations of mercury concentrations were joined with the FIA Database (Alerich *et al.* 2006) to assign plot locations. These plots were assigned to ecoprovinces (table 1) and Environmental Monitoring and Assessment Program hexagons (Spence and White 1992, White *et al.* 1992) using a geographic

Table 1.—*Ecoprovinces sampled for forest floor mercury.*

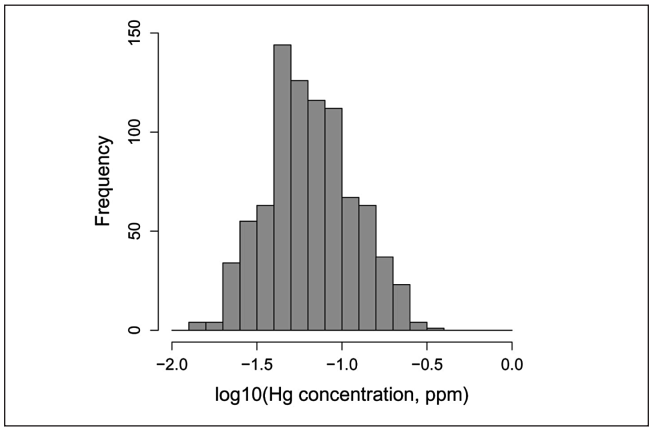
Label	Ecoprovince name	Number of samples
212	West Laurentian mixed forest	210
222	Midwest broadleaf forest	69
223	Central interior broadleaf forest	101
251	Prairie parkland (temperate)	54
313	Colorado Plateau semidesert	56
321	Chihuahuan semidesert	11
331	Great Plains—Palouse dry steppe	20
332	Great Plains steppe	11
341	Intermountain semidesert and desert	36
342	Intermountain semidesert	14
M313	Arizona-New Mexico mountains semidesert—open woodland— coniferous forest—alpine meadow	17
M334	Black Hills coniferous forest	11
M332	Middle Rocky Mountains steppe—coniferous forest—alpine meadow	43
M341	Nevada-Utah Mountains semidesert—coniferous forest—alpine meadow	55
M333	Northern Rocky Mountains steppe—coniferous forest—alpine meadow	25
M331	Southern Rocky Mountain steppe—open woodland—coniferous forest—alpine meadow	120

information system (fig. 1). Mean plot-level values of Hg concentration were tested against ecoprovince, latitude, and longitude using analysis of variance in R, a free software environment for statistical computing and graphics that is similar to the S language (Maindonald and Braun 2003).

Results and Discussion

We expected a strong regional component, with Hg concentrations increasing to the north and east, mimicking observations of mercury deposition (Nater and Grigal 1992, National Atmospheric Deposition Program 2007, Sweet and Prestbo 1999). The concentration of Hg in our samples was log-normally distributed (fig. 2) and ranged between 0.013 and 0.36 parts per million (ppm); the mean and median were 0.077 and 0.063 ppm, respectively. All statistical analyses were completed using the log-transformed concentration data.

Figure 2.—*Histogram of mercury concentrations (parts per million) for the study region.*



Mercury concentrations were highest in the northeastern part of our study region (ecoprovince 212), but high values were observed in the Rocky Mountains (ecoprovinces M332 and M333) as well (fig. 3). Ecoprovince was a significant predictor of Hg concentration in our analysis of variance model ($p < 0.001$) (fig. 4). As might be surmised from figure 3, latitude was a significant predictor ($p = 0.006$) but longitude was not ($p = 0.60$).

Figure 3.—*Spatial distribution of mean mercury concentrations (parts per million) for the study region. Numbers refer to ecoprovinces in the study region*

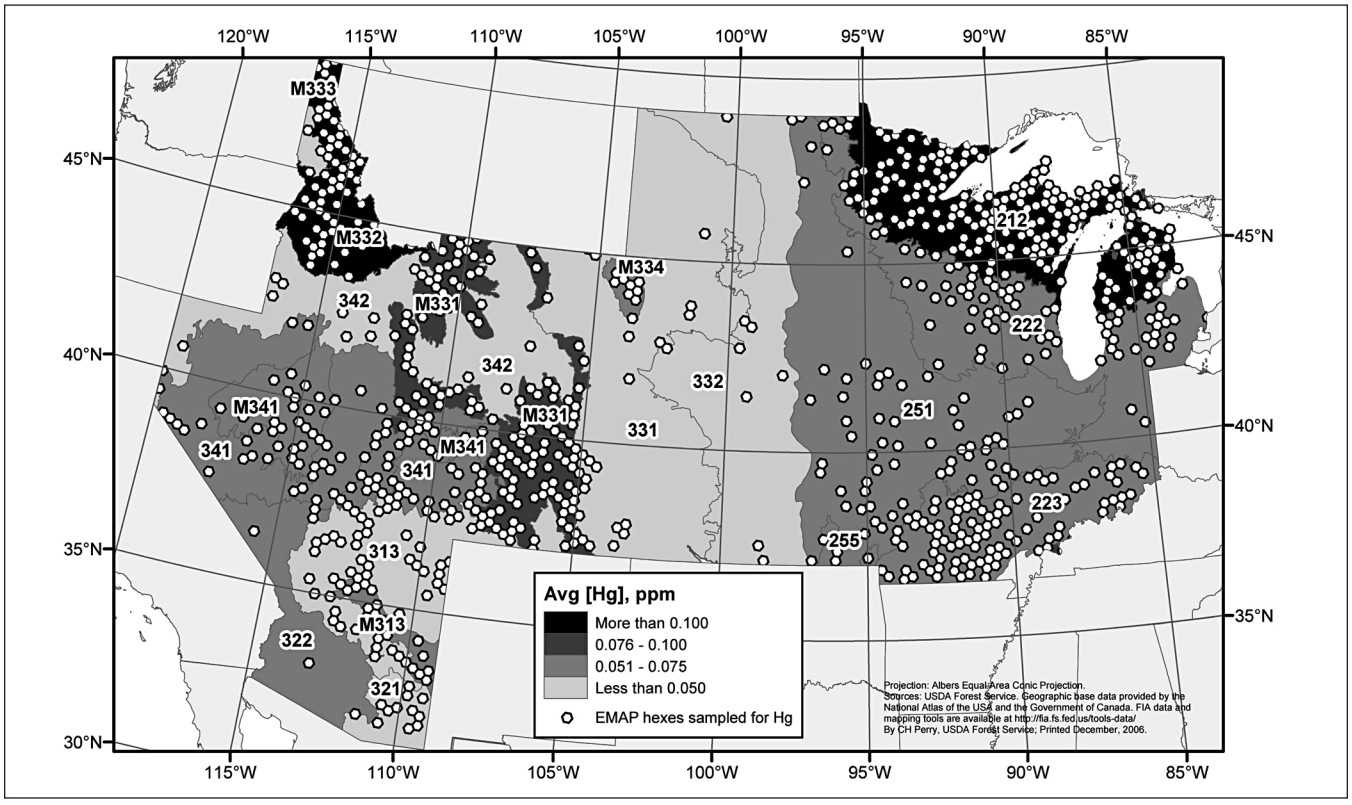
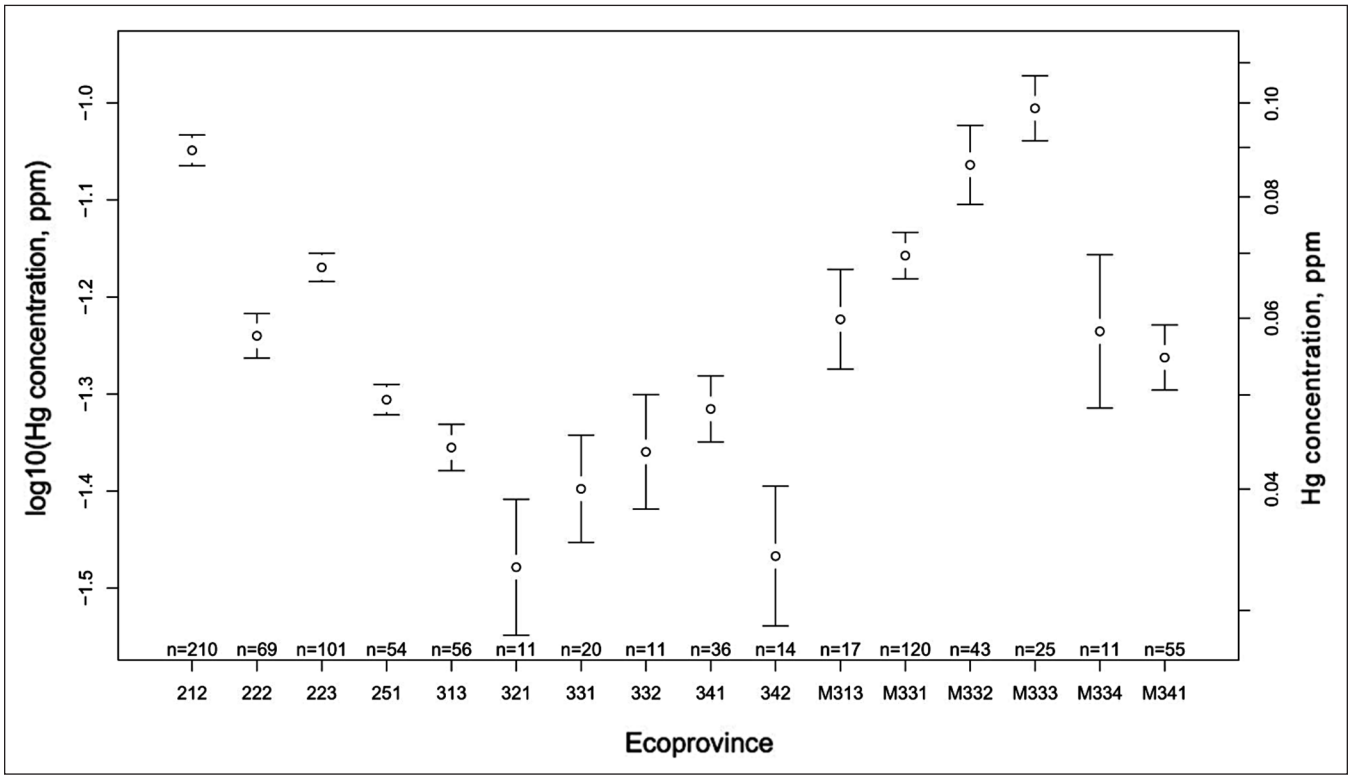


Figure 4.—*The mean concentration of mercury (parts per million) by ecoprovince. Ecoprovinces are mapped in figures 1 and 3. Error bars represent one standard error.*



The spatial trends in Hg concentration were not consistent across all ecoprovinces; significant interactions were found between ecoprovince and latitude ($p = 0.02$) as well as ecoprovince and longitude ($p = 0.003$). For example, the general trend was increasing Hg concentration with latitude, but concentrations increased more slowly in ecoprovince 251 and more quickly in ecoprovince M334. Also, the concentration of Hg generally increased from west to east, but concentrations actually declined moving east in ecoprovince M341 and M334. Because these interactions are largely observed in mountainous ecoprovinces, this evidence would suggest that elevation should be investigated further.

It is important to remind the reader that we are reporting concentration data; the total mass of the forest floor on each plot is required to determine the total mass of Hg stored in the forest floor. Carbon storage in the forest floor is comparable between the northern Rocky Mountains and the Lake States (Perry and Amacher, in press) indicating similar amounts of total forest floor mass (kg ha^{-1}). This suggests that the stored mass of Hg will follow the patterns of Hg concentrations in forest floor material across the study region.

Summary

This article provides initial results of a spatial model of forest floor Hg for a transect crossing the central United States, and we are very curious about the patterns emerging from our data. Mercury concentration in the forest floor ranged from 0.013 to 0.36 ppm across our study area. The elevated concentrations (and anticipated large mass) of Hg in the northern Rocky Mountains require further analysis as the spatial patterns do not completely mimic current patterns of Hg deposition (National Atmospheric Deposition Program 2007). Additionally, preliminary tests on subsets of the data suggest the important predictive role of forest-type groups. Each of these issues will be addressed in greater detail as the study progresses.

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Literature Cited

Alerich, C.L.; Klevgard, L.; Liff, C.; Miles, P.D.; Knight, B.; Conkling, B.L. 2006. The forest inventory and analysis database: database description and users guide. Version 2.1. http://www.ncrs2.fs.fed.us/4801/FIADB/fiadb_documentation/FIADB_v2-1_07_05_06.pdf. (1 December).

Amacher, M.C.; O'Neill, K.P.; Dresbach, R.; Palmer, C. 2003. Forest inventory and analysis manual of soil analysis methods. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, 860 North 12th East, Logan, UT 84321. 62 p.

Coulston, J.W.; Ambrose, M.J.; Riitters, K.H.; Conkling, B.L. 2005. Forest health monitoring: 2004 national technical report. Gen. Tech. Rep. SRS-90. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 81 p.

Fleck, J.A.; Grigal, D.F.; Nater, E.A. 1999. Mercury uptake by trees: an observational experiment. Water, Air, and Soil Pollution. 115(1-4): 513-523.

Friedli, H.R.; Radke, L.F.; Prescott, R.; Hobbs, P.V.; Sinha, P. 2003. Mercury emissions from the August 2001 wildfires in Washington State and an agricultural waste fire in Oregon and atmospheric mercury budget estimates. Global Biogeochemical Cycles. 17(2): 1039.

Grigal, D.F.; Kolka, R.K.; Fleck, J.A.; Nater, E.A. 2000. Mercury budget of an upland-peatland watershed. Biogeochemistry. 50(1): 95-109.

Kelly, E.N.; Schindler, D.W.; St. Louis, V.L.; Donald, D.B.; Vladicka, K.E. 2006. Forest fire increases mercury accumulation by fishes via food web restructuring and increased mercury inputs. Proceedings of the National Academy of Sciences. 103(51): 19380-19385.

Kolka, R.K.; Grigal, D.F.; Nater, E.A.; Verry, E.S. 2001. Hydrologic cycling of mercury and organic carbon in a forested upland-bog watershed. Soil Science Society of America Journal. 65(3): 897-905.

Maindonald, J.; Braun, J. 2003. Data analysis and graphics using R: an example-based approach. New York: Cambridge University Press. 362 p.

Nater, E.A.; Grigal, D.F. 1992. Regional trends in mercury distribution across the Great Lakes states, north central USA. Nature. 358: 139-141.

National Atmospheric Deposition Program. 2007. Mercury deposition network: a NADP network. http://nadp.sws.uiuc.edu/mdn/. (5 January).

Perry, C.H.; Amacher, M.C. [In press]. Soil carbon. In: Ambrose, M.J.; Conkling, B.L., eds. Forest Health Monitoring 2005 national technical report. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Smith, W.B. 2002. Forest inventory and analysis: a national inventory and monitoring program. Environmental Pollution. 116: S233-S242.

Spence, M.; White, D. 1992. EMAP sampling grid technical report. Corvallis, OR: ManTech Environmental Technology, Inc.; U.S. Environmental Protection Agency, Environmental Research Laboratory. 64 p.

Stolte, K.; Conkling, B.L.; Campbell, S.; Gillespie, A. 2002. Forest health indicators: Forest Inventory and Analysis program. Washington, DC: U.S. Department of Agriculture, Forest Service. 24 p.

Sweet, C.W.; Prestbo, E. 1999. Wet deposition of mercury in the U.S. and Canada. In: Proceeedings, international specialty conference on mercury in the environment. Pittsburgh, PA: Air and Waste Management Association: 306-315.

Turetsky, M.R.; Harden, J.W.; Friedli, H.R. *et al.* 2006. Wildfires threaten mercury stocks in northern soils. Geophysical Research Letters. 33: L16403.

U.S. Department of Agriculture (USDA) Forest Service. 2006. Phase 3 field guide: soil measurements and sampling. http://www.fia.fs.fed.us/library/field-guides-methods-proc/. (1 December).

White, D.; Kimerling, A.J.; Overton, W.S. 1992. Cartographic and geometric components of a global sampling design for environmental monitoring. Cartography and Geographic Information Systems. 19(1): 5-21.