# Chapter 4. Air Pollution: Tropospheric Ozone, and Wet Deposition of Sulfate and Inorganic Nitrogen

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The influence of air pollutants on ecosystems in the United States is an important environmental issue. The term "air pollution" encompasses a wide range of topics, but acid deposition and ozone are primary concerns in the context of forest health. Acid deposition partially results from emissions of sulfur dioxide, nitrogen oxides, and ammonia that are deposited in wet form as sulfate ($SO_4^{2-}$), nitrate ($NO_3^-$), and ammonium ($NH_4^+$) by rain, snow, and sleet. Inputs of sulfur and nitrogen can also come from dry deposition or from clouds and fog (Driscoll and others 2001). Tropospheric ozone develops during photochemical reactions between nitrogen oxides and volatile organic compounds. Acid deposition can affect soil and water acidity (Driscoll and others 2001), and ozone can cause foliar injury (Chappelka and Samuelson 1998, Cleveland and Graedel 1979, Lefohn and Pinkerton 1988). However, dose-response relationships are complicated and depend heavily on species composition, edaphic factors, and climatic conditions.

Fenn and others (2003) provided a generalized comparison between air pollution in the Eastern and Western United States. In the East, sulfur deposition has been higher than nitrogen deposition and wet deposition is predominant. However, there is evidence that sulfur deposition has decreased. In the West, dry nitrogen deposition dominates. In the East, atmospheric pollution is considered a regional issue; in the West, where deposition rates decline quickly with increased distance from the pollutant source areas, this is not the case. In the West, ozone causes the most severe injury to forests. However, this mostly occurs in California in combination with nitrogen deposition. In the East, ozone causes injury to sensitive species in some areas, and nitrogen and sulfur deposition may be important factors in declining tree growth in some areas.

## Brief Methods

For the purposes of this report I examined wet inorganic nitrogen and sulfate deposition from 2000 through 2004, and ozone exposure for the same period. Inorganic nitrogen is total nitrogen in wet nitrate ($NO_3^-$) and wet ammonium ($NH_4^+$) deposition. Annual wet deposition summaries were acquired from the National Atmospheric Deposition Program (NADP) (http://nadp.sws.uiuc.edu/). Daily ambient ozone concentrations were acquired from the U.S. Environmental Protection Agency (EPA) Air Quality System (http://www.epa.gov/ttn/airs/airsaqs/index.htm). Annual 3-month growing season, 12-hour SUM06 ozone summaries were calculated based on suggestions provided by the EPA (2004). The SUM06 ozone index is the sum of all hourly concentrations > 0.06 parts per million (ppm), and I consider June, July, and August the 3-month growing season. The standard units for SUM06 are ppm-hours. The approach suggested by Coulston and others (2004) was used to estimate the status and trends in exposure of forests to ozone, wet sulfate deposition, and wet deposition of nitrogen. This technique uses the linear model $D = a+b(y)$, where $D$ is the weighted average deposition value, $b$ is the weighted average annual change, and y is year. The probability that $b = 0$ was tested with an F-test and significance was assigned at the 0.05 level. For display purposes, interpolated surfaces of each pollutant were created using gradient plus inverse distance squared interpolation (Nalder and Wein 1998). The accuracy of each surface was examined by calculating the root mean square error.

## Results

There was a strong eastwest gradient in average annual (2000–04) wet sulfate and wet inorganic nitrogen deposition amounts in the conterminous United States. Wet sulfate deposition was highest in the Northeast Forest Health Monitoring (FHM) region from 2000 through 2004 (fig. 4.1). On average, forests in the Northeast FHM region received approximately 17.6 kg ha$^{-1}$ per year of wet

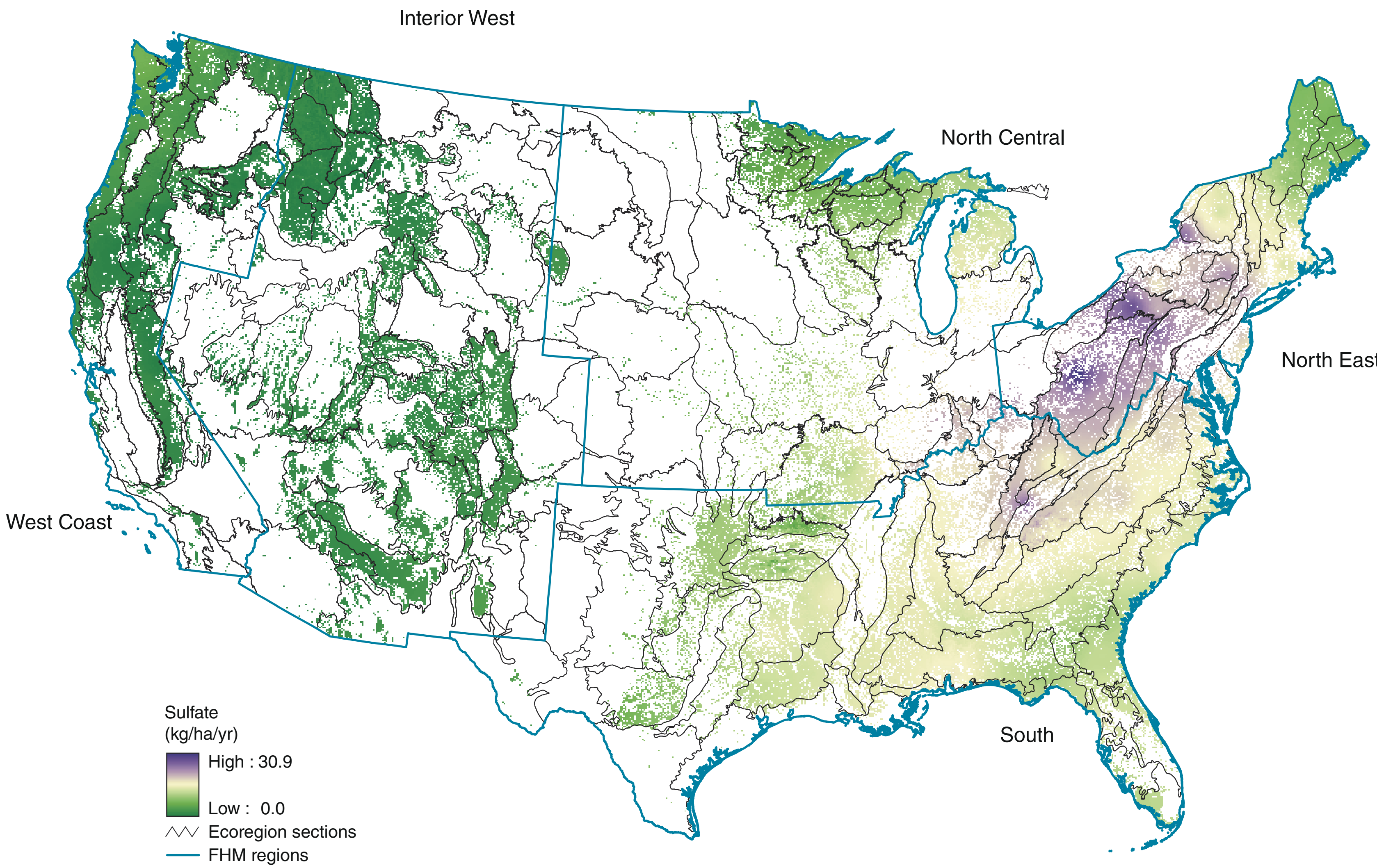


*Figure 4.1—Mean wet sulfate deposition for forested areas from 2000 through 2004. The average root mean square error of the interpolation was approximately 2.67 kg ha$^{-1}$ per year based on cross-validation. Ecoregion sections (Cleland and others 2005) are shown for reference. (Data source: National Atmospheric Deposition Program)*

sulfate deposition annually during the time period (table 4.1). Wet inorganic nitrogen deposition was highest in the North Central FHM region, where forests received on average 5.13 kg ha$^{-1}$ per year from 2000 through 2004 (fig. 4.2, table 4.1). Wet inorganic nitrogen deposition in the Northeast FHM region was similar, at 5.01 kg ha$^{-1}$ per year. For the period 2000–04, forested areas in the Interior West FHM region had the lowest average annual wet sulfate deposition rate (1.65 kg ha$^{-1}$ per year) and forested areas in the West Coast FHM region had the lowest wet inorganic nitrogen deposition rate (1.04 kg ha$^{-1}$ per year) (table 4.1).

From 2000 through 2004 in the conterminous United States, wet deposition exposure rates to forests were relatively constant. Over that period, forests in most FHM regions had average annual changes in wet deposition of sulfate and of inorganic nitrogen that did not significantly differ from 0 kg ha$^{-1}$ per year per year at the $p<0.05$ level (table 4.1). Forests in the South FHM region were the exception. They experienced a statistically significant ($p<0.05$) increase in wet inorganic nitrogen deposition (0.17 kg ha$^{-1}$ per year per year) over the period (table 4.1).

**Table 4.1—Average and average annual change of forest exposure to wet inorganic nitrogen deposition, wet sulfate deposition, and SUM06 ozone from 2000 through 2004 by FHM region**

| | Inorganic N | | $SO_4^{2-}$ | | SUM06 | |
|---|---|---|---|---|---|---|
| FHM region | Average | Average annual change | Average | Average annual change | Average | Average annual change |
| | *kg ha$^{-1}$ yr$^{-1}$* | *kg ha$^{-1}$ yr$^{-2}$* | *kg ha$^{-1}$ yr$^{-1}$* | *kg ha$^{-1}$ yr$^{-2}$* | *ppm-hrs yr$^{-1}$* | *ppm-hrs yr$^{-2}$* |
| Interior West | 1.23 | 0.05 | 1.65 | 0 | 18.37 | -1.04[a] |
| North Central | 5.13 | -0.11 | 10.13 | -0.15 | 9.46 | -0.85[a] |
| North East | 5.01 | -0.02 | 17.6 | 0.19 | 13.64 | -0.86[a] |
| South | 4.1 | 0.17[a] | 13.75 | 0.28 | 15.84 | -3.97[a] |
| West Coast | 1.04 | 0 | 2.23 | -0.08 | 13.09 | 0.53 |

[a]Indicates statistical significance at $P<0.05$.

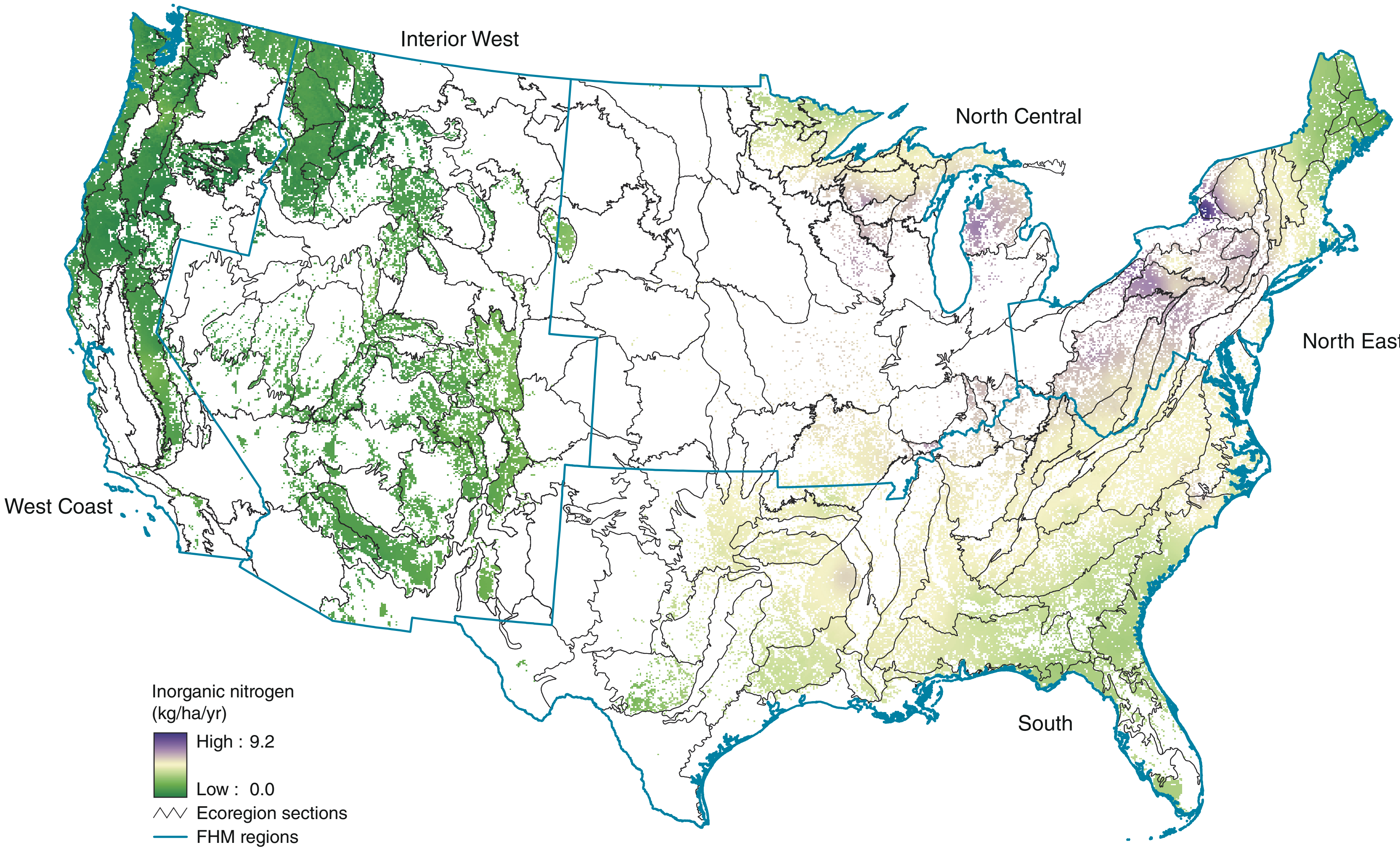


*Figure 4.2—Mean wet inorganic nitrogen deposition for forested areas from 2000 through 2004. The average root mean square error of the interpolation was approximately 0.87 kg ha$^{-1}$ per year based on cross-validation. Ecoregion sections (Cleland and others 2005) are shown for reference. (Data source: National Atmospheric Deposition Program)*

Average annual (2000–04) ambient 3-month growing-season SUM06 ozone exposures in some portion of the forested areas exceeded 20 ppm-hours per year in all FHM regions (fig. 4.3). Average exposure was highest in forests in the Interior West FHM region (18.4 ppm-hours per year) (table 4.1). In the West Coast FHM region the average exposure was 13.1 ppm-hours per year for the period 2000–04. However, this region had both forests with the highest exposures, e.g., section M261E—Sierra Nevada in California, and forests with very low exposures, e.g., section M242D—Northern Cascades in Washington. In the Eastern United States, forests in the South FHM region had ozone exposure that averaged 15.8 ppm-hours per year, but there was a statistically significant decreasing trend ($p<0.05$) of 3.97 ppm-hours per year per year from 2000 through 2004 (table 4.1). Forests in the Interior West, North Central, and Northeast FHM regions also had statistically decreasing trends in ozone exposure of 1.04 ppm-hours per year, 0.85 ppm-hours per year per year, and 0.86 ppm-hours per year per year, respectively (table 4.1).

## Discussion

There is a complex air pollution dose-response relationship in forests. In the case of wet sulfate and inorganic nitrogen deposition, factors such as watershed bedrock composition, land use history, vegetation type, soil depth, and the ability of the soil to neutralize acidic inputs partly determine whether the input will result in a response such as soil acidification (Ecological Society of America 2000). The influence of ambient ozone concentrations on vegetation depends on climatic conditions and species composition.

The EPA (2002) described the following forest-type groups as sensitive to and subject to high deposition rates: high-elevation spruce/fir, southern pine and pine/hardwood, eastern hardwoods in the Great Lakes area, the Colorado alpine meadow, western conifers, and southern California urban forests. The analysis presented here did not identify “high” wet deposition rates in the Western United States. However, estimates of dry deposition were not included, and according to Fenn and others (2003) dry deposition is an important source of nitrogen input. Also, this analysis did not take any information about soil or vegetation type into account. The results only relate to inputs to forest ecosystems.

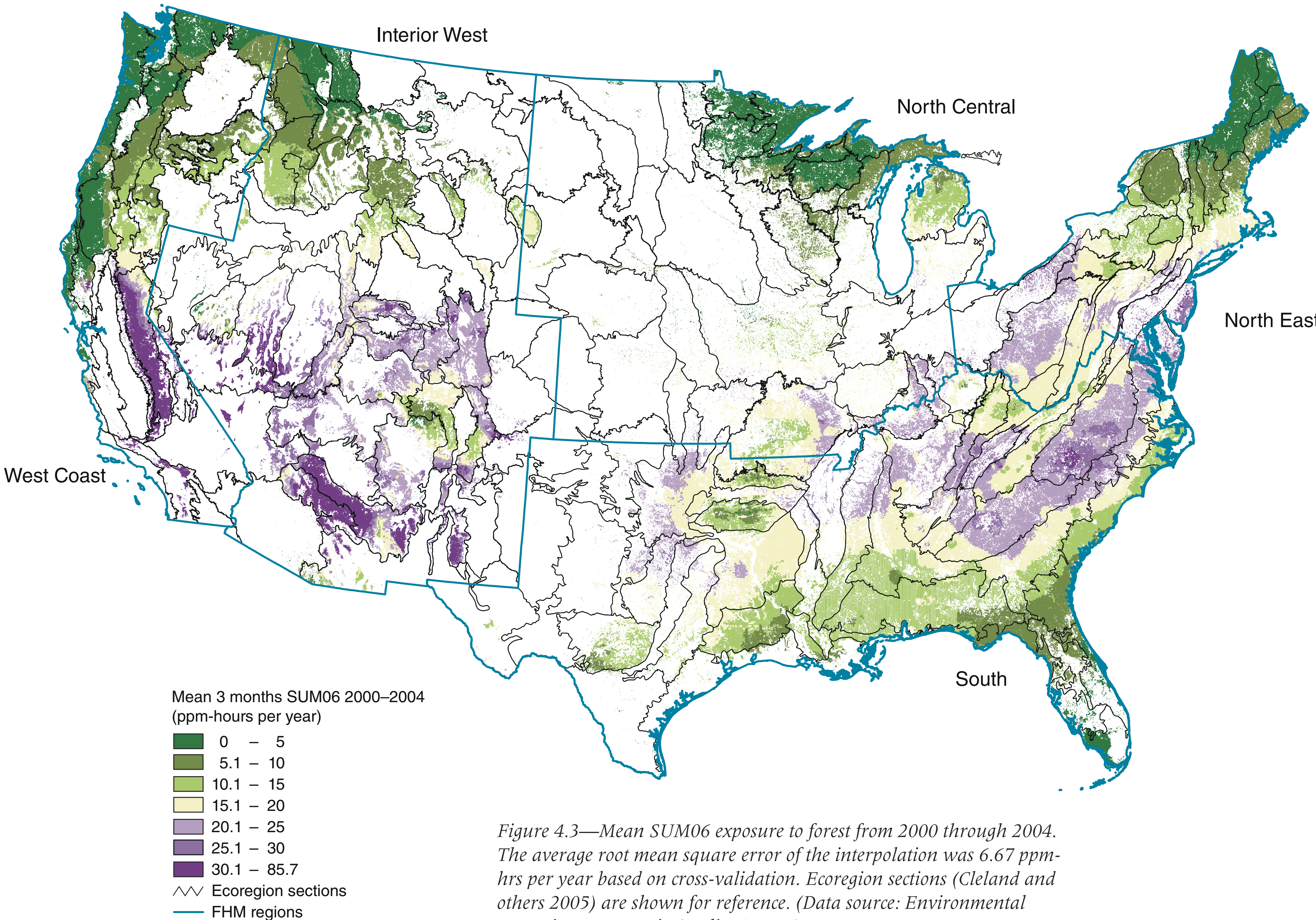


*Figure 4.3—Mean SUM06 exposure to forest from 2000 through 2004. The average root mean square error of the interpolation was 6.67 ppm-hrs per year based on cross-validation. Ecoregion sections (Cleland and others 2005) are shown for reference. (Data source: Environmental Protection Agency Air Quality System)*

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