3. National and Regional Discussions of Visibility

A. Introduction

This chapter presents visibility data from all of the sites in a series of national maps. The first section presents the subsets of data from the least-impaired, most-impaired, and mid-range days. The maps show the average visibility indices for these data subsets from 1994 through 1998 and also show the statistically significant trends at the sites over the entire operational periods of the particulate samplers.

The second section examines the concentrations of the five pollutant species found in fine particulate matter: sulfates, nitrates, organic carbon, elemental carbon, and soil and crustal material. National maps show the concentrations of these species, the percentages of the fine particulate matter that they constitute, the light extinction coefficients calculated from these species, and the percentages of the visibility impairment attributable to these species.

The final section of this chapter compares and contrasts visibility impairment in the East and West. Mean values for the regions are calculated by averaging the calculated light extinction coefficients from the sites. Likely causes are also presented to explain some of the annual and seasonal differences between Eastern and Western measurements of the five particulate matter components.

B. National Visibility

Trends for Least-Impaired Days

Figure 3–1 shows the annual average visibility indices for the least-impaired, or "best," days from 1994 through 1998 at the IMPROVE monitoring locations. The indices range from 3.9 deciviews (VR 165 miles) at the Jarbidge Wilderness Area (NV) to 19.2 deciviews (VR 36 miles) at the Sipsey Wilderness Area (AL). Other high deciview values were observed in the Southeast and mid-Atlantic states.

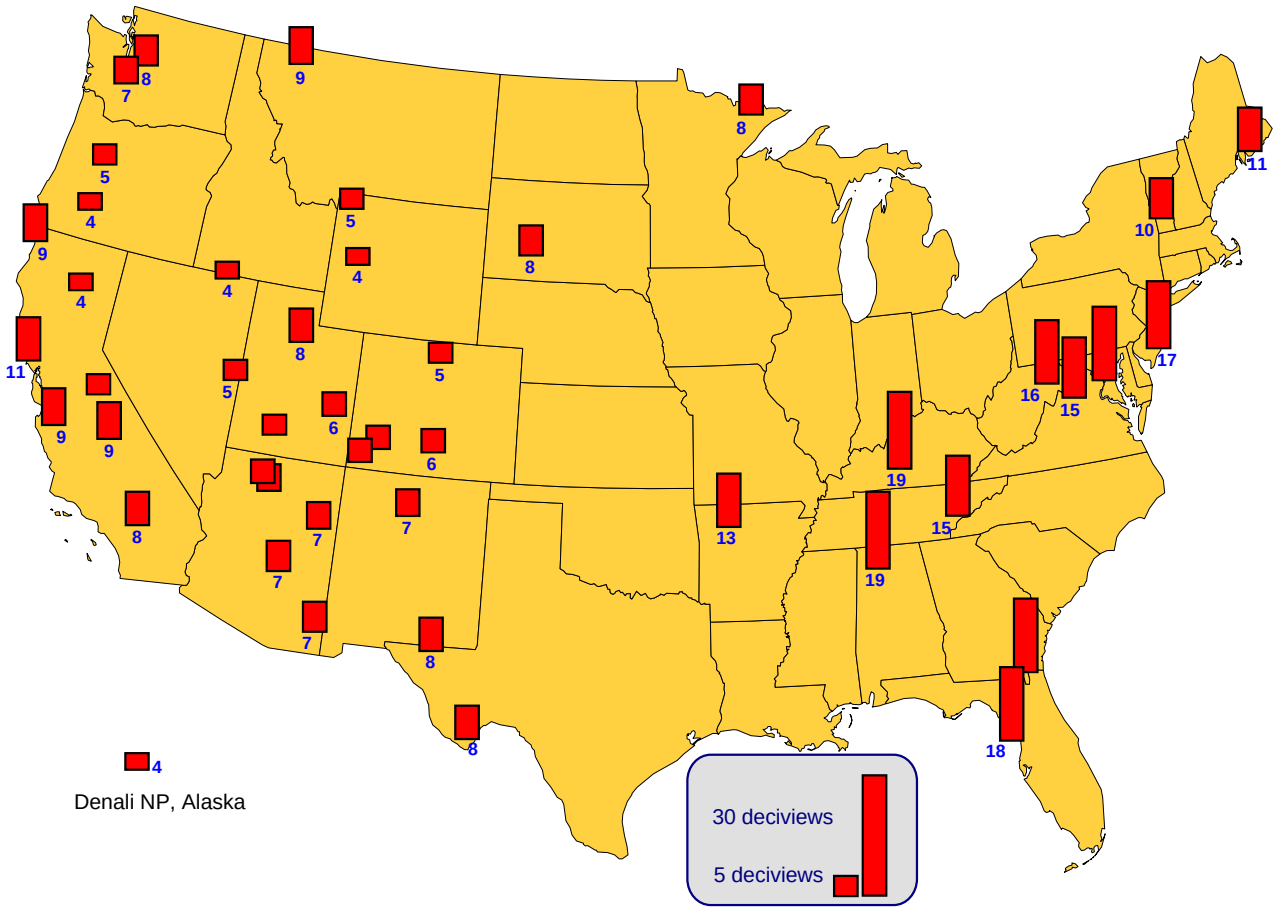

Figure 3–1. Annual Average Visibility Indices for Least-Impaired Days from 1994–1998

Figure 3–2 illustrates which IMPROVE sites showed statistically significant trends in visibility on their least-impaired days during their operational periods. Six monitors showed improvements in visibility on the least-impaired days, and three showed declines in the visibility on the least-impaired days. Only 2 of the 13 sites in eastern states showed improving trends on the least-impaired days, and only 4 of the 32 sites in western states showed improving trends on the least-impaired days. The western sites showing improvement could not be grouped spatially, and the western sites showing declines were found in both Washington State and along the southwestern U.S. border.

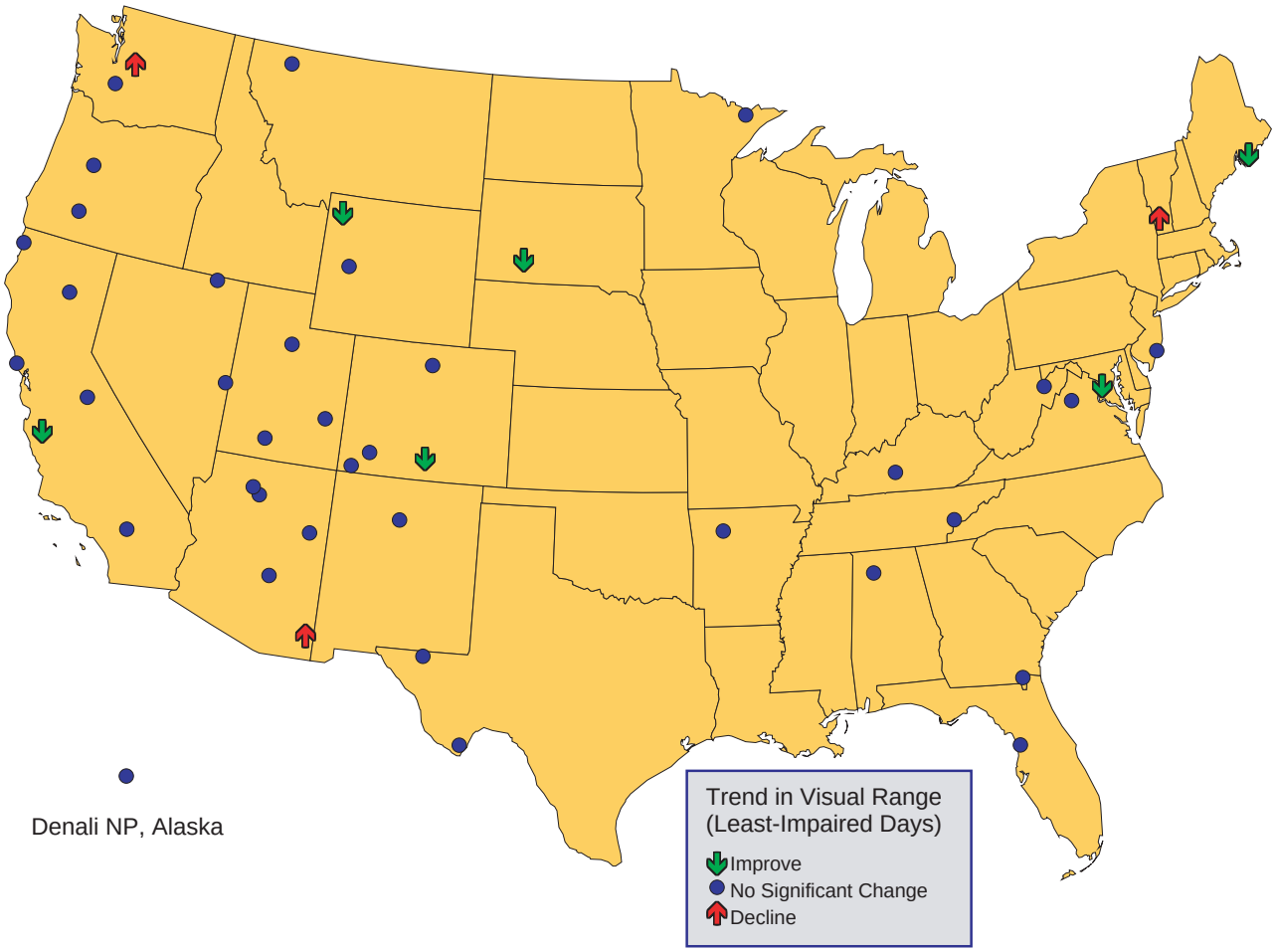

Figure 3–2. IMPROVE Sites Showing Statistically Significant Trends in Visibility on Least-Impaired Days

Trends for Mid-Range Days

Figure 3–3 presents the annual average visibility indices for the mid-range days from 1994 through 1998 at the IMPROVE monitoring sites. The indices range from 6.3 deciviews (VR 130 miles) at Denali National Park (AK) to 25.2 deciviews (VR 20 miles) at Mammoth Cave National Park (KY). Other high deciview values were observed in the Southeast, mid-Atlantic region, and four California sites.

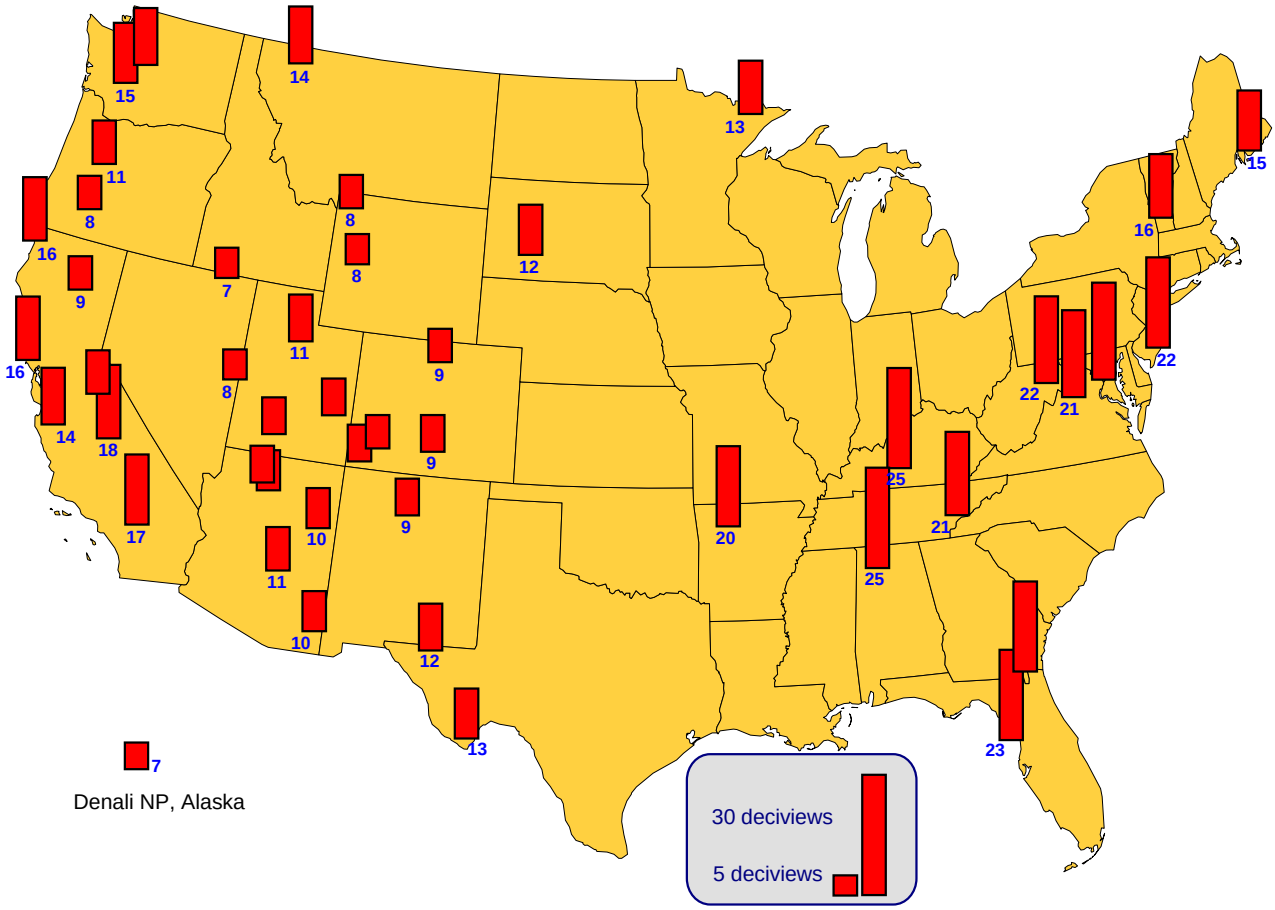

Figure 3–3. Annual Average Visibility Indices for Mid-Range Days from 1994–1998

Figure 3–4 shows which IMPROVE sites showed statistically significant trends in visibility on their mid-range days during their operational periods. None of the sites showed declining visibility on the mid-range days. Four of the 13 eastern sites showed improvements in visibility on the mid-range days, but only four of the 32 western sites showed statistically significant improvements in the calculated visibility. Four of the 8 sites showing improved visibility on mid-range days also showed improvement on the least-impaired days (Figures 3–2 and 3–4).

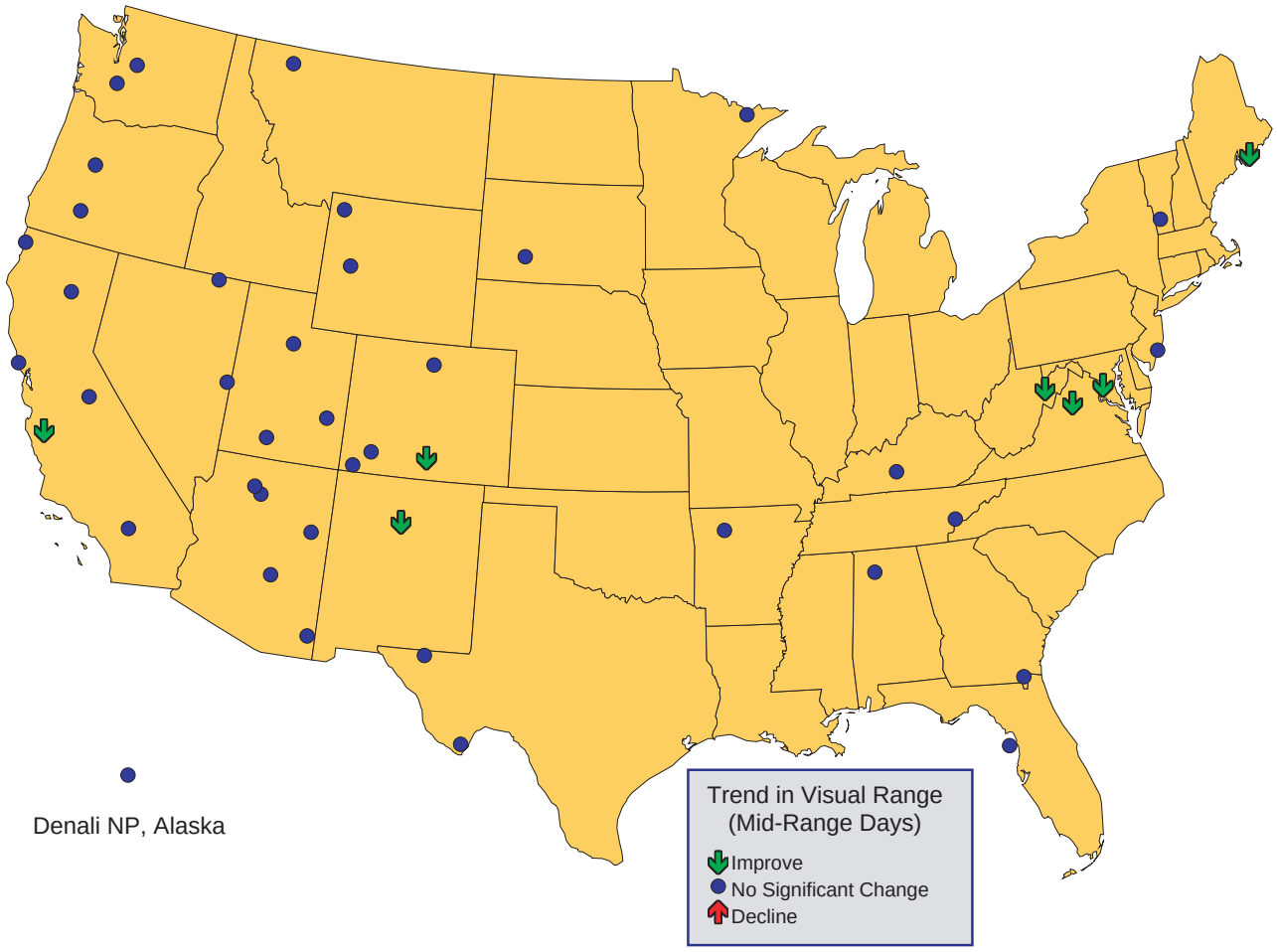

Figure 3–4. IMPROVE Sites Showing Statistically Significant Trends in Visibility on Mid-Range Days

Trends for Most-Impaired Days

The annual average visibility indices for the most-impaired days at the IMPROVE sites are presented in Figure 3–5. The indices represent data collected between 1994 and 1998. Denali National Park (AK) had the lowest index at 10.4 deciviews (VR 85 miles) for the most-impaired days, and Mammoth Cave National Park (KY) had the highest index at 32.1 deciviews (VR 10 miles). The ten sites with the highest indices for the most-impaired days were the ten located in the Southeast and mid-Atlantic states. They had visibility indices greater than 27 deciviews (VR less than 16 miles).

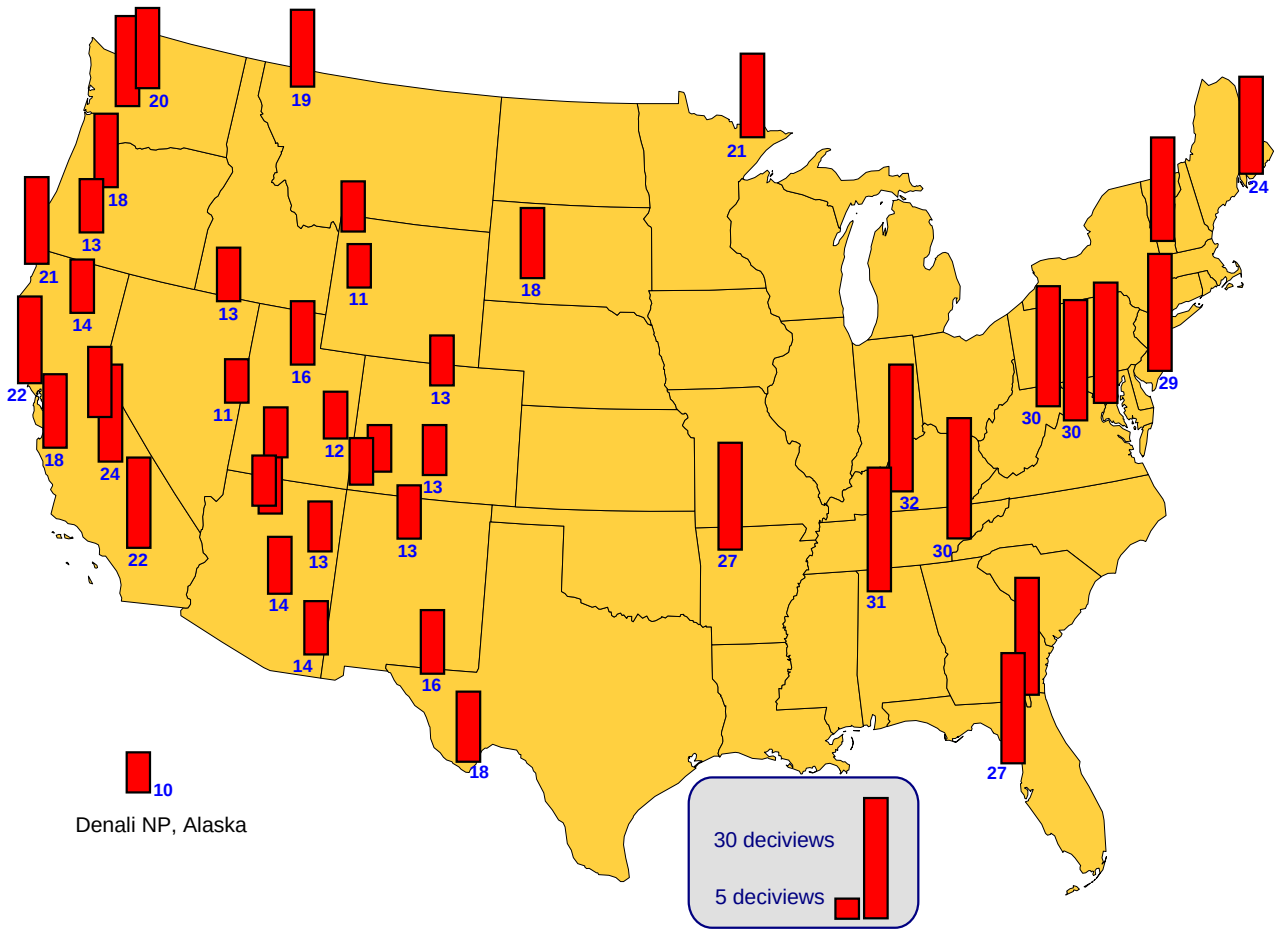

Figure 3–5. Annual Average Visibility Indices for Most-Impaired Days from 1994–1998

Figure 3–6 shows which IMPROVE sites showed statistically significant trends in visibility on their most-impaired days during their operational periods. The visibility on the most-impaired days did not decline at any of the sites. Only one of the 13 eastern sites (Mammoth Cave, KY) showed statistically significant improvements in the calculated visibility on the most-impaired days. Only 5 of the 32 western sites showed improvements on these days, four of the sites located in California. Only the Pinnacles site in California showed statistically significant improvements on the least-impaired, mid-range, and most-impaired days (Figures 3–2, 3–4, and 3–6).

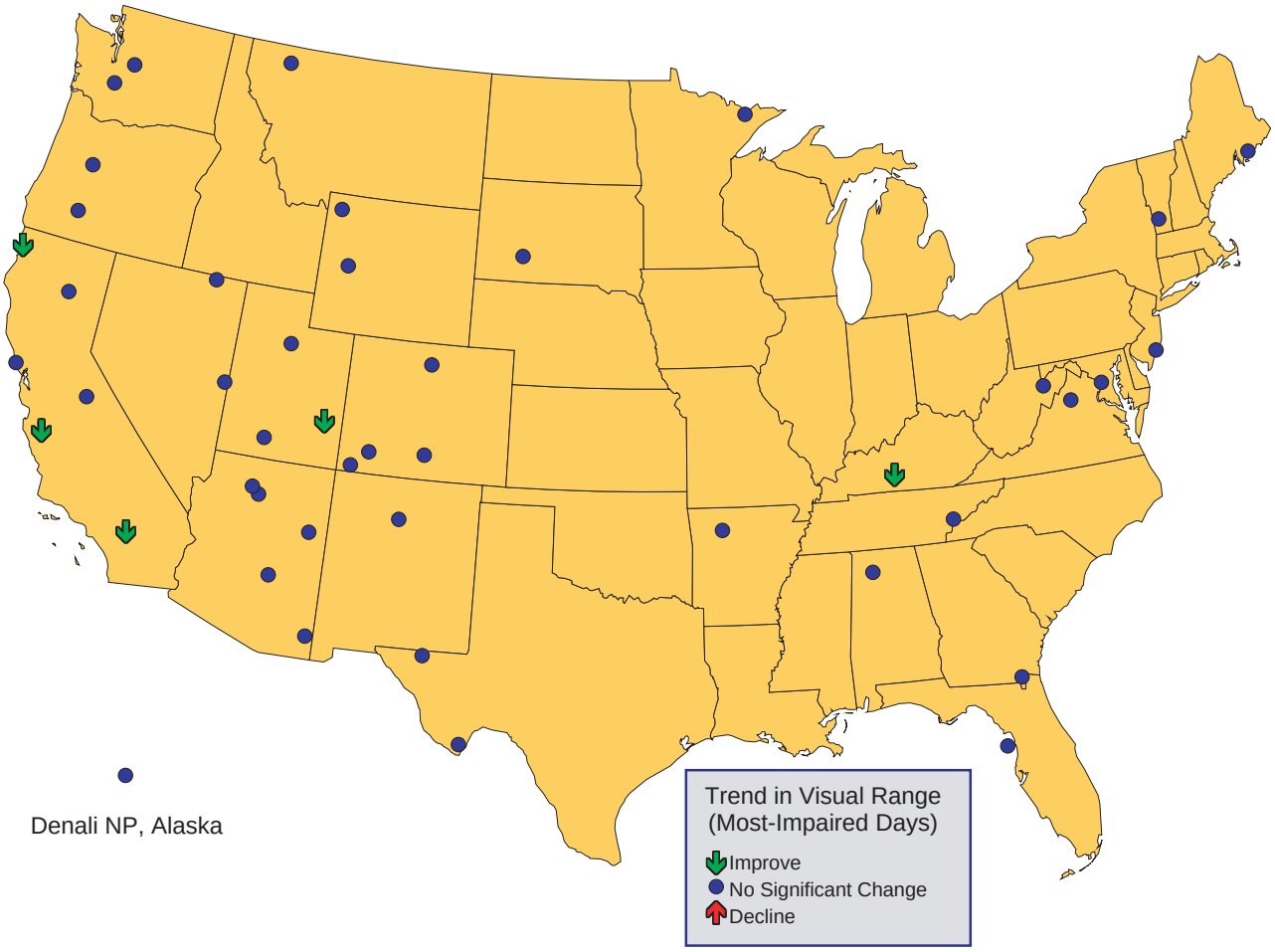

Figure 3–6. IMPROVE Sites Showing Statistically Significant Trends in Visibility on Most-Impaired Days

C. Contributors to Visibility Impairment

This section presents a series of four national maps associated with each pollutant: (1) annual average concentration (μg/m^3), (2) average annual contribution to the particulate fine mass (percent), (3) average annual calculated light extinction for the pollutant (Mm^{-1}), and (4) average annual contribution to the calculated aerosol light extinction coefficient (percent). The data presented show the averages for the years from 1994 through 1998.

Sulfate

Table 1–1 reported that the natural sources of sulfate particulate matter include sea spray and the oxidation of sulfur gases emitted by volcanoes, oceans, wetlands, and wildfires. The oxidized sulfur gases combine with ammonia (emitted from motor vehicles, animal husbandry, sewage treatment, land fertilizers, and wild animals) to form fine particulate matter. The major manmade source of sulfate particulate matter is fossil fuel combustion.

Figure 3–7 shows the average sulfate concentrations at the IMPROVE monitoring sites between 1994 and 1998. The figure shows that the sulfate concentrations were greater than 2.5 μg/m^3 at all locations in the eastern states except for the Boundary Waters site (MN). The average sulfate levels were below 2.5 μg/m^3 at all locations in the western states except for the Big Bend site (TX).

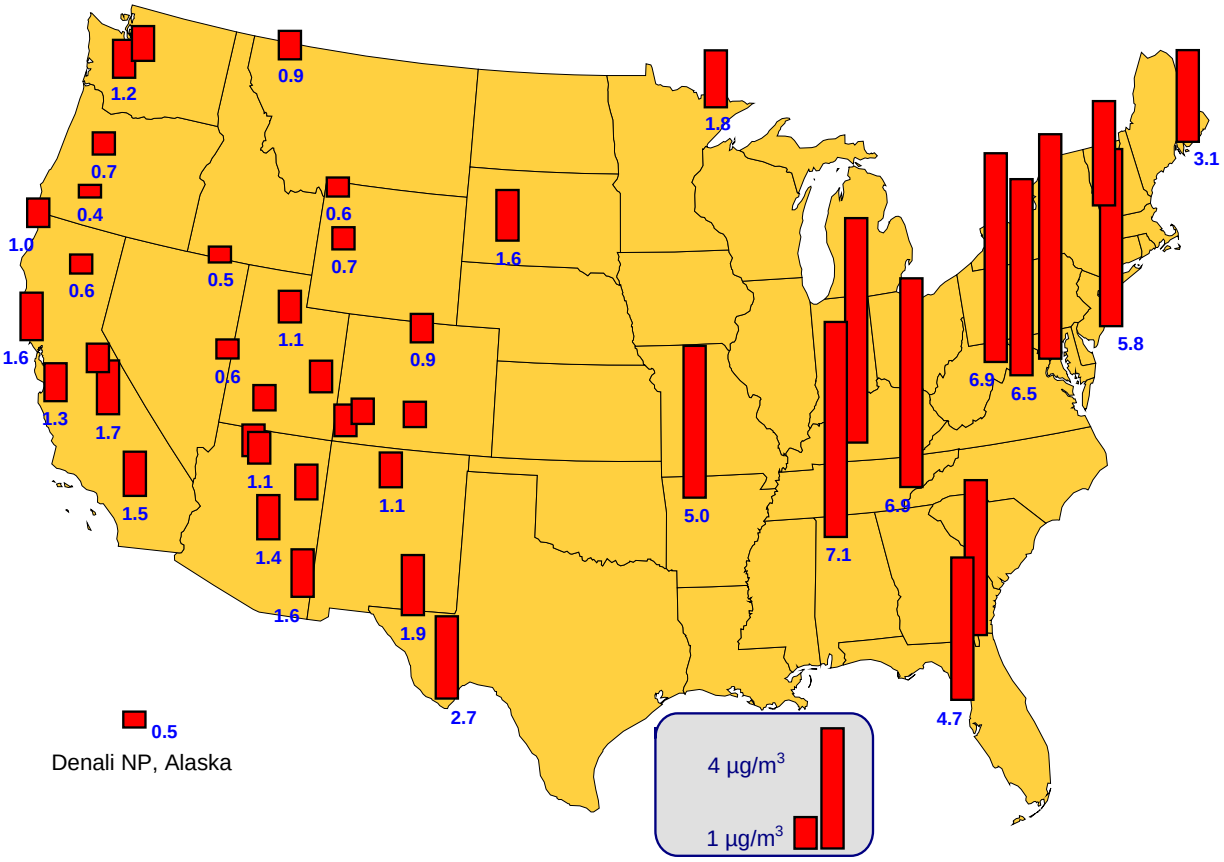

Figure 3–7. Average Annual Sulfate PM Concentrations at IMPROVE Monitoring Sites from 1994–1998

To better understand the causes of elevated sulfate levels (and reduced visibility) during recent years in Big Bend National Park (TX), the EPA and the National Park Service funded the Big Bend Regional Aerosol and Visibility Observational Study in 1999 (NPS, 1999). The study aims to identify and quantify the specific emission sources, emission types (e.g., petroleum refineries, fossil fuel power plants, urban areas), and source regions (by state and country) that contribute to the degraded visibility in the park.

Figure 3–8 presents the average contribution of sulfate particulate matter to the total $PM_{2.5}$ levels at the IMPROVE monitoring locations from 1994 to 1998. All of the sites located in the eastern states except Boundary Waters Canoe Area (MN) showed average sulfate contributions greater than 50 percent and averaged 57 percent. The sulfate contributions from the 33 western sites were all less than 48 percent and averaged just 31 percent. Since the manmade SO_2 emissions in states east of the Mississippi River were more than three times greater than those west of the Mississippi (E. H. Pechan and Associates, 1994), the higher sulfate observations in the East were not unexpected.

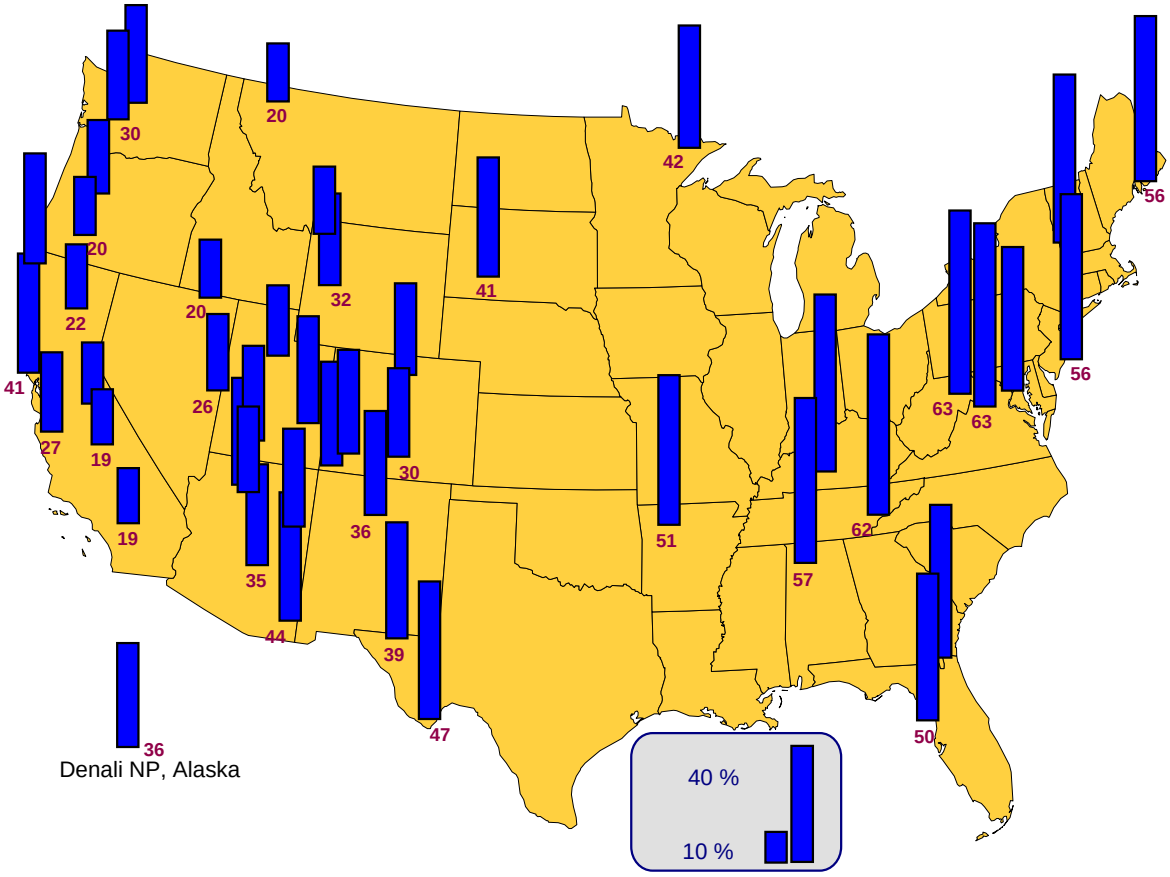

Figure 3–8. Average Annual Contributions of Sulfate PM to Total $PM_{2.5}$ Levels at IMPROVE Monitoring Sites from 1994–1998

The high average sulfate concentrations in the eastern states lead to high average sulfate extinction coefficients calculated for those sites (Figure 3–9). In eastern states, the calculated annual average sulfate extinction coefficients were as high as 101 Mm^{-1} (Mammoth Cave National Park, KY) and as low as 18 Mm^{-1} (Boundary Waters Canoe Area, MN). The average sulfate extinction coefficient was 61 Mm^{-1} in eastern states and 9 Mm^{-1} in western states. Some of the difference between the average sulfate extinction at eastern and western IMPROVE monitoring locations was because the extinction coefficients are calculated as a function of average relative humidity (Appendix C). Relative humidities near the western monitors were often considerably lower than those in eastern states. (See Section 3.D, Regional Pollutants for additional supporting data.) In western states, the calculated annual average sulfate extinction coefficients ranged from 3 Mm^{-1} (Jarbidge Wilderness Area, NV) to 25 Mm^{-1} (Redwood National Park, CA).

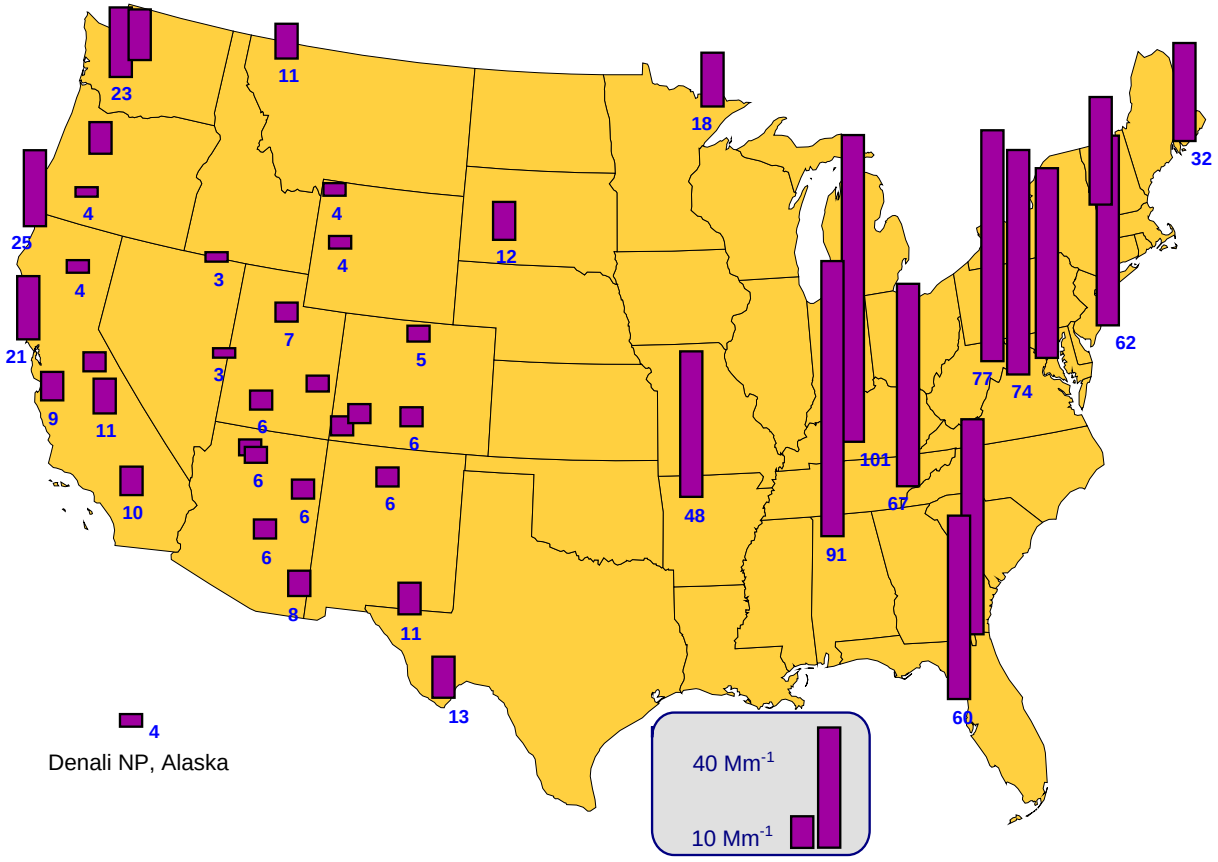

Figure 3–9. Average Annual Sulfate Extinction Coefficients at IMPROVE Monitoring Sites from 1994–1998

Figure 3–10 shows the average annual contributions of sulfate particulate matter to the calculated aerosol light extinction coefficients for the IMPROVE sites from 1994 to 1998. The contributions ranged from 23 percent at San Gorgonio Wilderness Area (CA) to 78 percent at Mammoth Cave National Park (KY) and Dolly Sods Wilderness Area (WV). The average was 47 percent for all sites. The eleven highest contributions occurred in eastern states and the lowest contribution from any eastern monitor was 52 percent. Since the annual average relative humidity is higher in the East and sulfate concentrations are higher in the East (Figure 3–7), the spatial distribution of Figure 3–10, showing higher percentages in the East, was not unexpected.

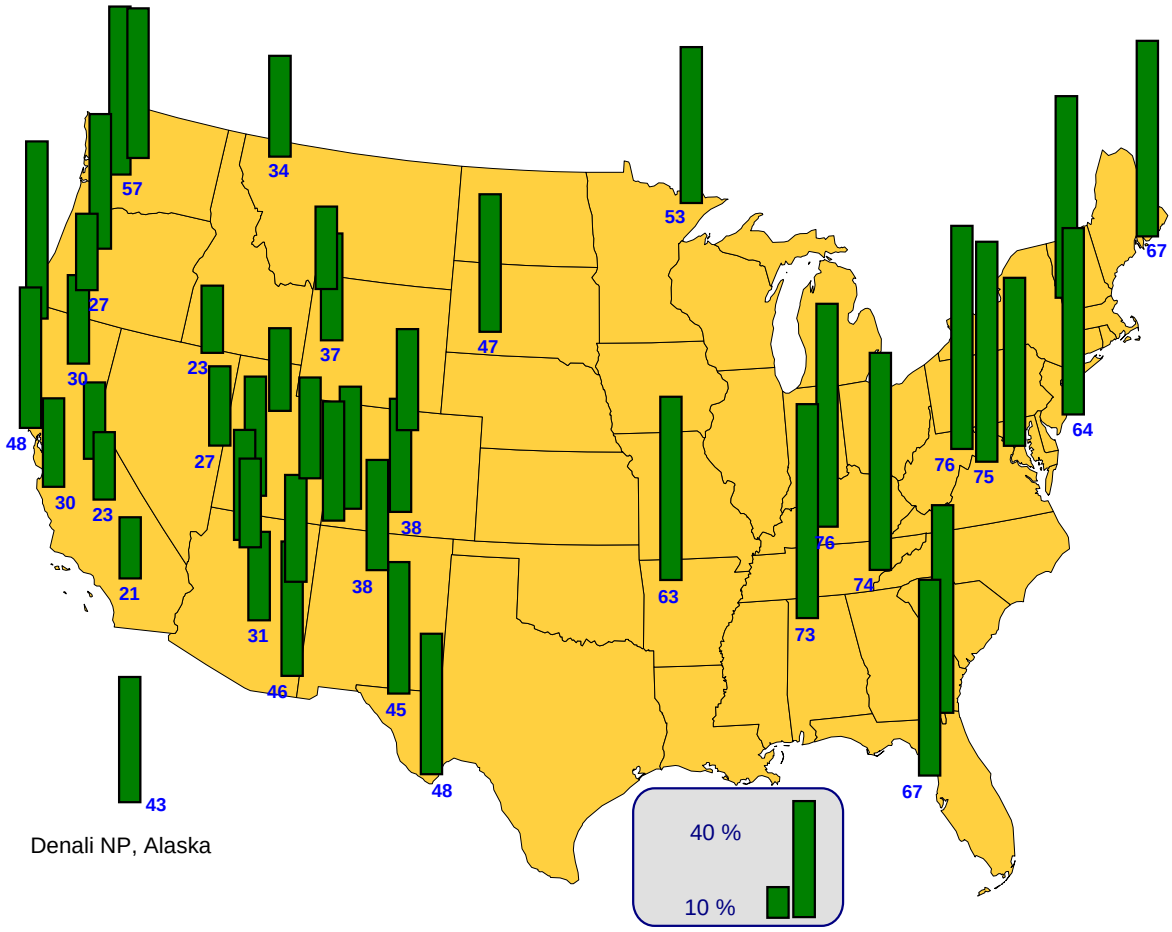

Figure 3–10. Average Annual Contributions of Sulfate PM to Calculated Aerosol Light Extinctions at IMPROVE Monitoring Sites from 1994–1998

Nitrate

Table 1–1 listed the oxidation of NO_x emissions as the major natural source of nitrate particulate matter. The natural sources of NO_x include soils, wildfires, and lightning. Oxidized nitrate gases combine with ammonia (emitted from motor vehicles, animal husbandry, sewage treatment, land fertilizers, and wild animals) to form particulate matter. Manmade sources of NO_x include motor vehicle exhaust, prescribed burning, and other fossil fuel combustion processes.

Figure 3–11 presents the annual nitrate concentrations averaged for the period from 1994 through 1998. In the eastern states, the annual average nitrate concentrations ranged from 0.3 μg/m^3 in Acadia (ME) to 1.6 μg/m^3 in Washington (DC). The average was 0.7 μg/m^3 among all the eastern sites. The average nitrate concentrations in western states ranged from 0.05 μg/m^3 in Denali National Park (AK) to 2.6 μg/m^3 in San Gorgonio Wilderness Area (CA). The average was 0.4 μg/m^3 among all the western sites. The highest nitrate levels (0.8 to 2.6 μg/m^3) in the western states were observed at southern California monitoring stations (Pinnacles, Point Reyes, San Gorgonio, and Sequoia).

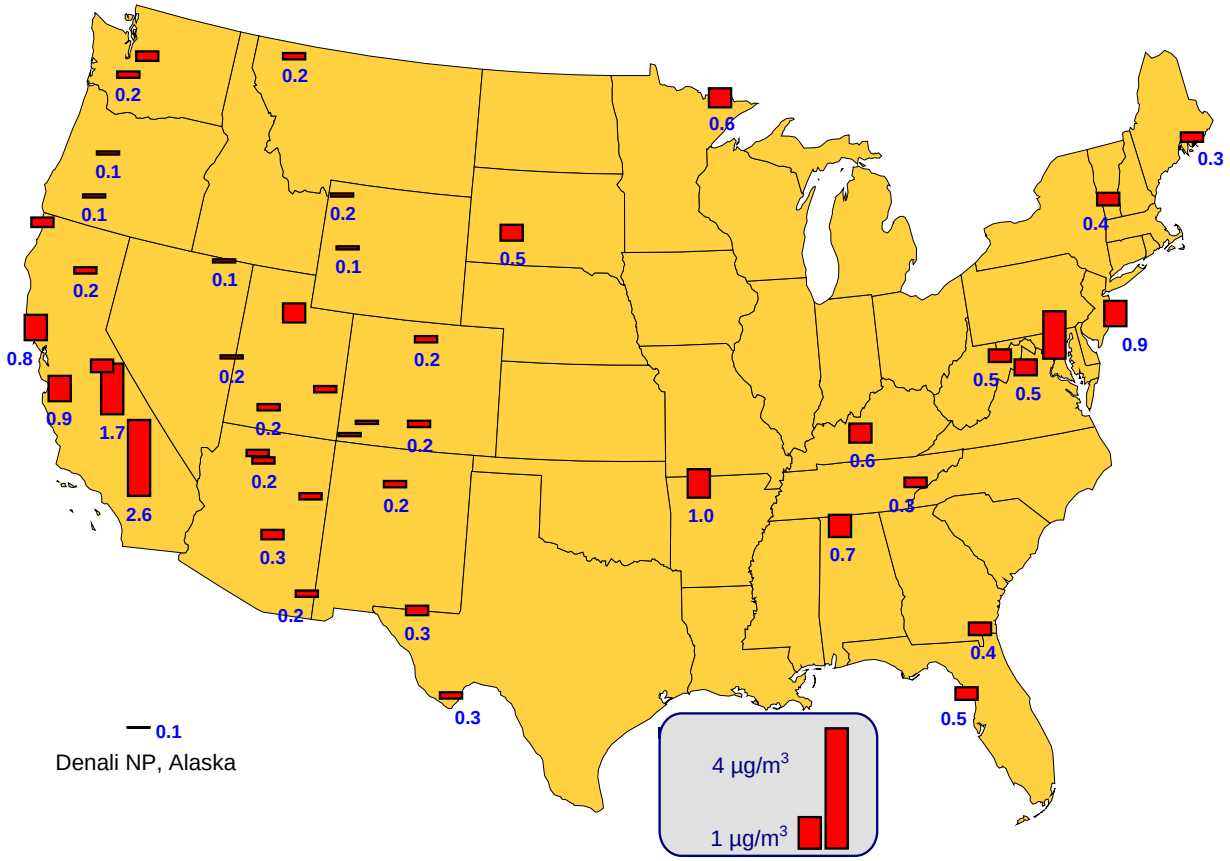

Figure 3–11. Average Annual Nitrate PM Concentrations at IMPROVE Monitoring Sites from 1994–1998

The annual nitrate concentrations at the rural southern California sites were still considerably lower than those measured at urban and suburban sites in southern California in 1993 and 1995 (Christoforou, et al. 2000; South Coast Air Quality Management District, 1997). For example, in 1993, the South Coast Air Quality Management District reported annual average nitrate concentrations between 2.3 and 9.7 $\mu g/m^3$ at four urban and suburban sites. The site measuring 9.7 $\mu g/m^3$ nitrate in 1993 (Rubidoux, CA) is located just 35 miles west of the San Gorgonio IMPROVE site, which measured 3.7 $\mu g/m^3$ as its 1993 annual average nitrate concentration.

Figure 3–12 presents the average contribution of nitrate particulate matter to the total $PM_{2.5}$ levels at the IMPROVE monitoring locations from 1994 through 1998. At sites in the eastern states, the nitrate contributions ranged from 3 percent at the Great Smoky Mountains National Park (TN) to 14 percent at Boundary Waters Canoe Area (MN). The average was 7 percent. The percent contribution of nitrate at Boundary Waters Canoe Area is perceived as high because the total fine mass and sulfate fine mass at this site averaged just 4.4 and 1.8 $\mu g/m^3$, while the other eastern sites averaged 10 $\mu g\ PM_{2.5}/m^3$ and 5.6 μg sulfate/m^3. The highest nitrate contributions in western states occurred at Point Reyes (21 percent) and San Gorgonio (36 percent), both near major metropolitan areas in California. The average nitrate contribution to $PM_{2.5}$ among the monitoring stations in the western states was 9 percent.

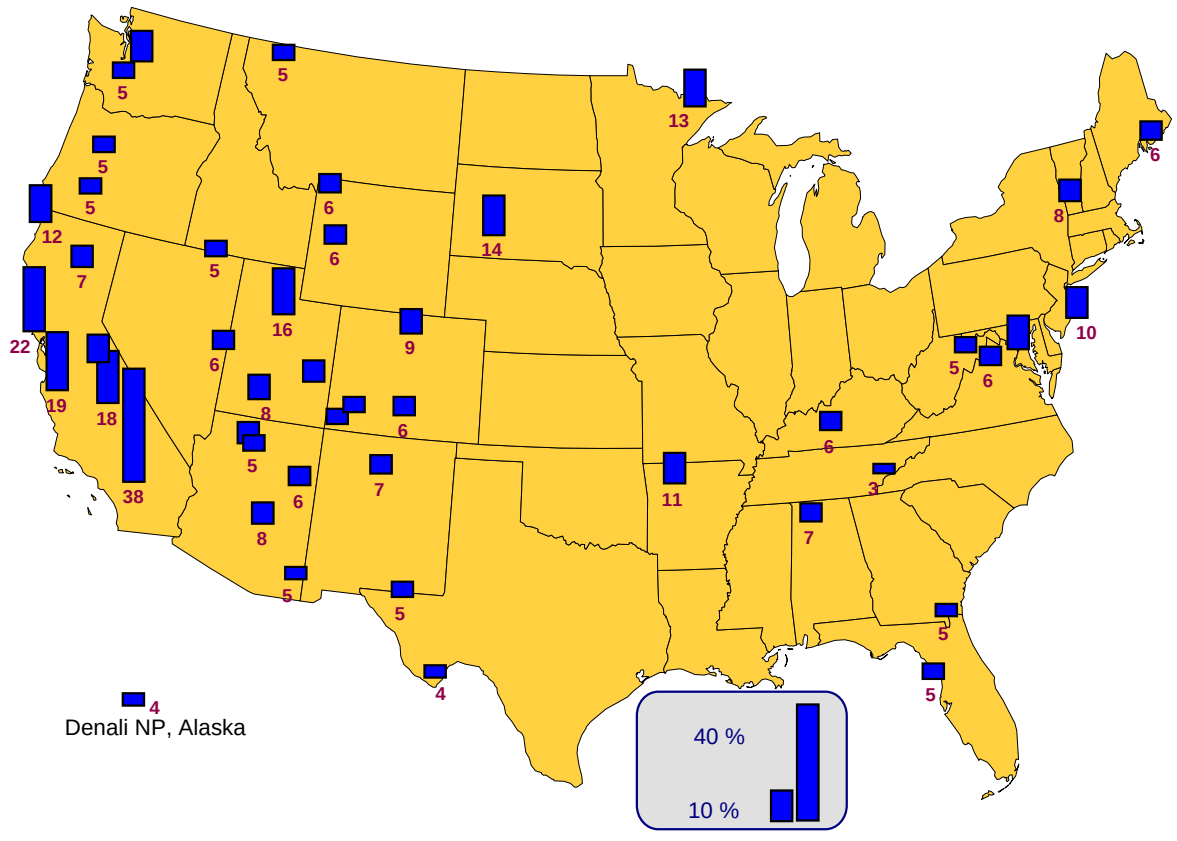

Figure 3–12. Average Annual Contributions of Nitrate PM to Total $PM_{2.5}$ Levels at IMPROVE Monitoring Sites from 1994–1998

Figure 3–13 shows the calculated annual average nitrate extinction coefficients for the period from 1994 through 1998. In the eastern states, the extinction coefficients from nitrate ranged from 3 Mm^{-1} in Acadia National Park (ME) and Great Smoky Mountains National Park to 16 Mm^{-1} at the Washington (DC) site. In the western states, the calculated extinction coefficients for nitrate ranged from 0.5 Mm^{-1} for Denali National Park (AK) to 17 Mm^{-1} for San Gorgonio Wilderness Area (CA). The average was 3 Mm^{-1} for all western sites. When comparing Figures 3-11 and 3-13, readers may note that the relative differences between the desert sites and the less arid sites are higher for the light extinction figure. This behavior can be attributed to the low relative humidity in the desert areas, which prevents water droplets from joining the particulate aerosols and efficiently obscuring visibility.

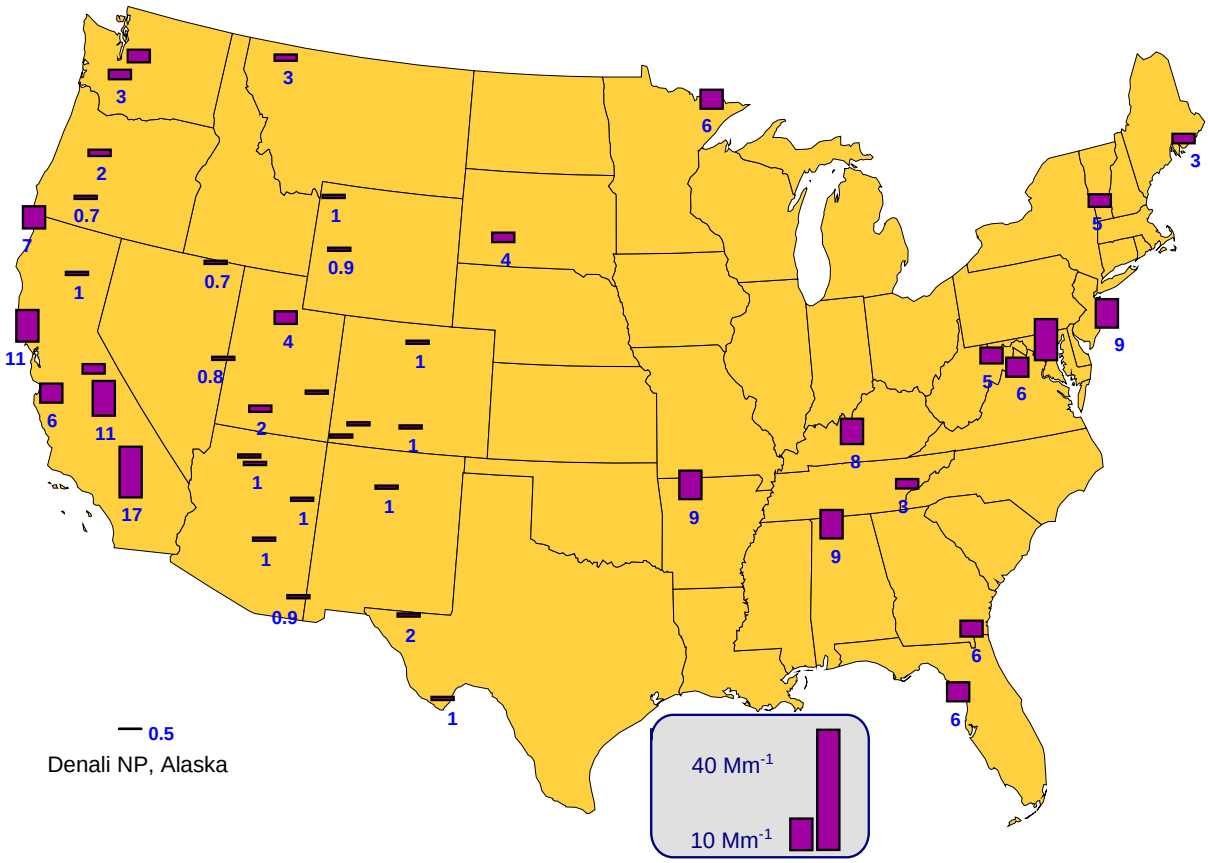

Figure 3–13. Average Annual Nitrate Extinction Coefficients at IMPROVE Monitoring Sites from 1994–1998

Figure 3–14 shows the average contributions of nitrate particulate matter to the calculated aerosol light extinction coefficients for the IMPROVE sites from 1994 to 1998. In eastern states, the nitrate contributions to light extinction ranged from 3 percent at Great Smoky Mountains National Park (TN) to 18 percent at Boundary Waters Canoe Area (MN). The average was 9 percent for all 13 sites. The nitrate contribution to light extinction in western states averaged 11 percent. In western states, the nitrate contributions to light extinction were lowest at Big Bend National Park (TX), 5 percent, and remained below 20 percent for all but four sites. The four western sites with nitrate contributions over 20 percent were all located in California: Sequoia (22 percent), Pinnacles (21 percent), Point Reyes (25 percent), and San Gorgonio (39 percent).

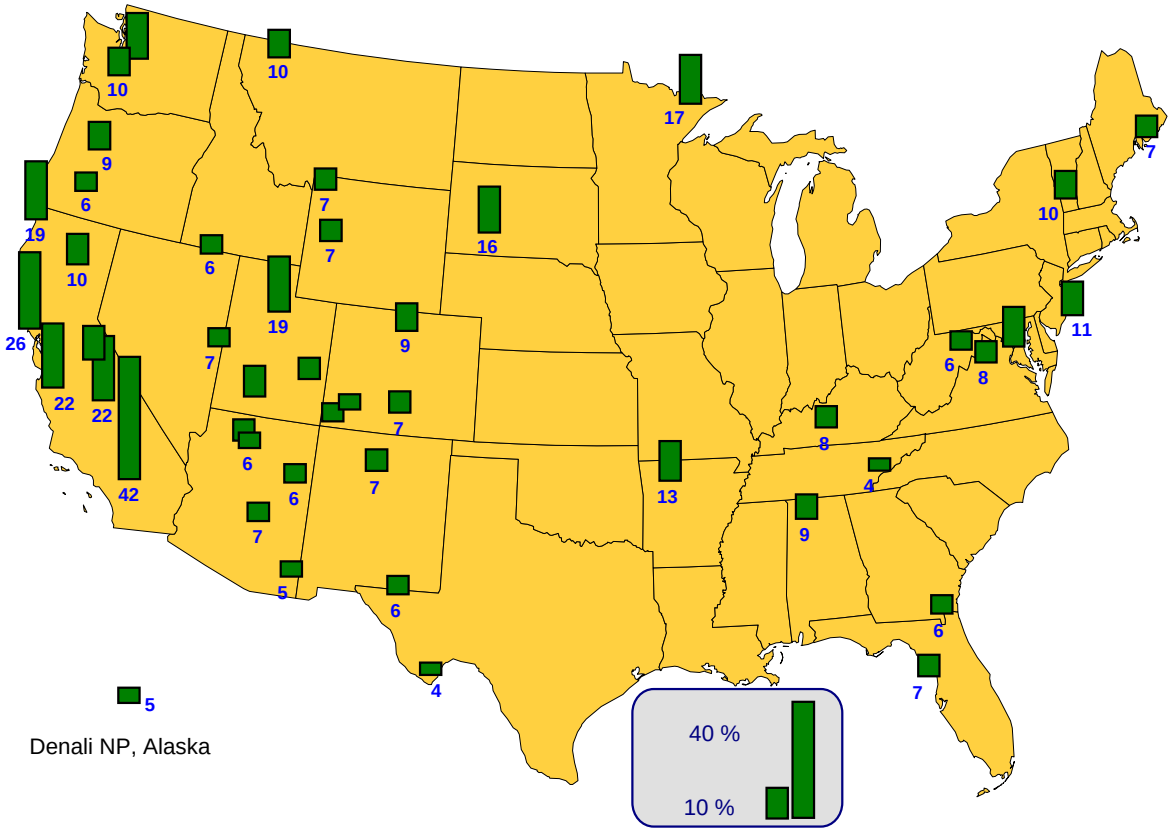

Figure 3–14. Average Annual Contributions of Nitrate PM to Calculated Aerosol Light Extinctions at IMPROVE Monitoring Sites from 1994–1998

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Organic Carbon

Table 1–1 reported major natural sources of organic carbon particulate matter to be wildfires and the oxidation of hydrocarbons emitted by vegetation. Daily measurements from the Yosemite and Glacier National Park IMPROVE monitoring locations between 1994 and 1998 confirmed that organic carbon concentrations rose significantly during major wildfire events (National Interagency Fire Center, 1998). Manmade sources of organic carbon particulate matter include open burning, wood burning, prescribed burning, cooking, motor vehicle exhaust, incineration, tire wear, and the oxidation of hydrocarbons emitted from motor vehicles, open burning, wood burning, prescribed burning, fuel storage and transport, and solvent usage.

Figure 3–15 was constructed from satellite imagery and represents the level of photosynthetic activity in the vegetation during July 1988 (Los et al., 1994). The Normalized Difference Vegetation Index represents the green leaf density of vegetation, with higher numbers indicating greater photosynthetic activity. Figure 3–15 is presented here to illustrate vegetation growth in the 48 contiguous states. The figure clearly shows more vegetation growth in July 1988 in the East, along the Pacific Coast, and in Idaho and western Montana than in other parts of the United States.

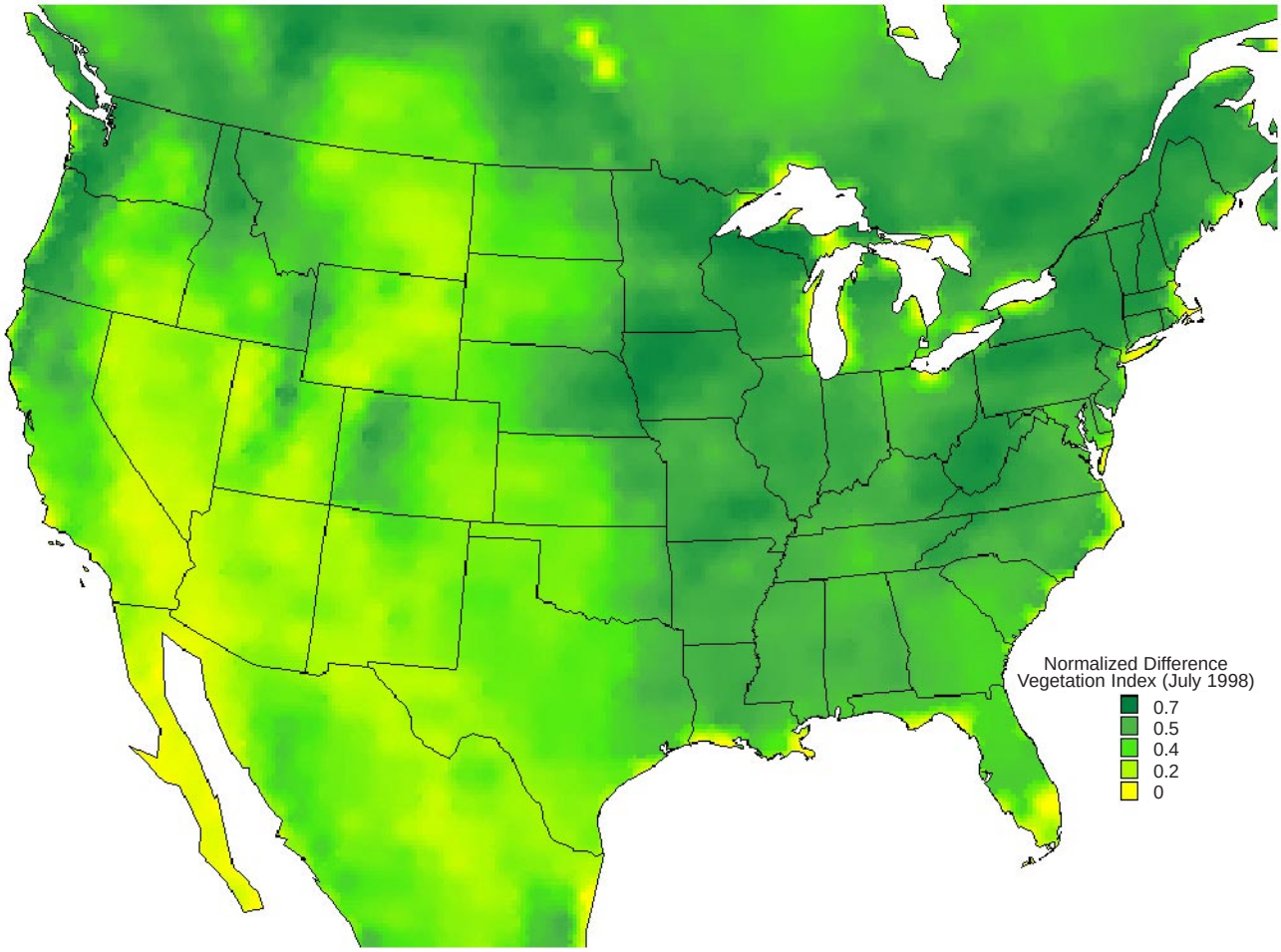

Figure 3–15. Level of Photosynthetic Activity in Vegetation during July 1988

Figure 3–16 presents the annual average concentrations of organic carbon particulate matter at the IMPROVE monitoring sites for the period from 1994 through 1998. The organic carbon concentrations range from 0.6 μg/m^3 at Denali National Park (AK) to 3.9 μg/m^3 at the National Mall in Washington (DC). Higher concentrations of organic carbon were observed in the Southeast and near Sequoia and Yosemite National Parks than at other rural sites. The major natural sources of organic carbon emissions are wildfires and the atmospheric oxidation of hydrocarbons emitted from vegetation (Table 1–1). Therefore, organic carbon concentrations would be expected to be higher closer to these activities (i.e., where growing seasons are longer) and lower in areas with slower vegetation growth (yellow areas in Figure 3–15). When vegetation grows more slowly, less is available to burn in wildfires and prescribed burns over several decades. Besides Denali National Park, the sites with annual average organic carbon concentrations less than 0.9 μg/m^3 were all located in the arid Four Corners area of the Southwest (Bryce Canyon and Canyonlands, UT; Grand Canyon, AZ; and Mesa Verde, Weminuche, and Great Sand Dunes, CO).

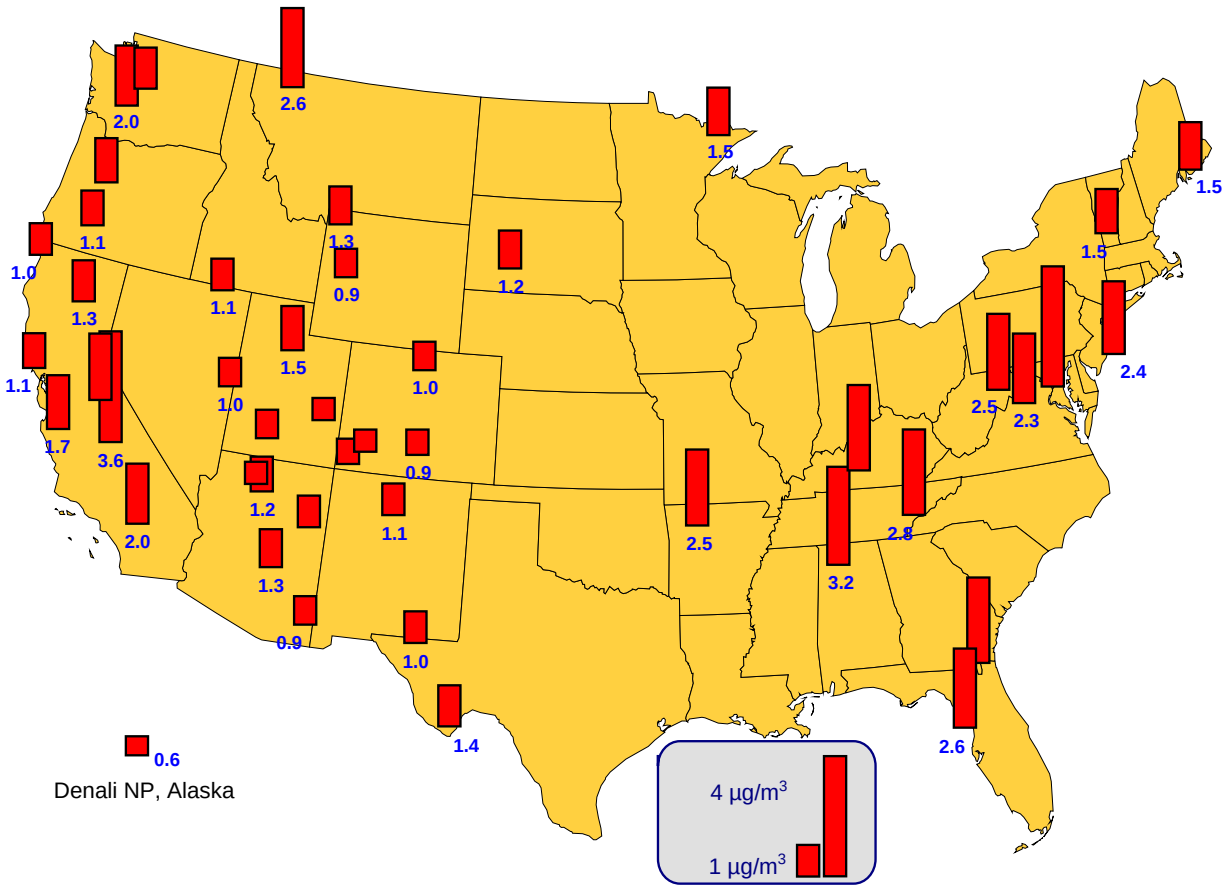

Figure 3–16. Average Annual Organic Carbon PM Concentrations at IMPROVE Monitoring Sites from 1994–1998

Figure 3–17 presents the average contribution of organic carbon particulate matter to the total $PM_{2.5}$ levels at the IMPROVE sites from 1994 through 1998. The lowest percent contributions from organic carbon (between 20 and 25 percent) were observed at mid-latitude eastern sites (Mammoth Cave, KY; Dolly Sods, WV; Shenandoah, VA; and Brigantine, NJ) and the three monitors closest to the Mexican border (Chiricahua, AZ; Guadalupe Mountains, TX; and Big Bend, TX). The highest percent contributions from organic carbon (40 to 55 percent) were found at the monitors in the northwestern sites in Alaska, Washington, Montana, Oregon, Wyoming, and northern California.

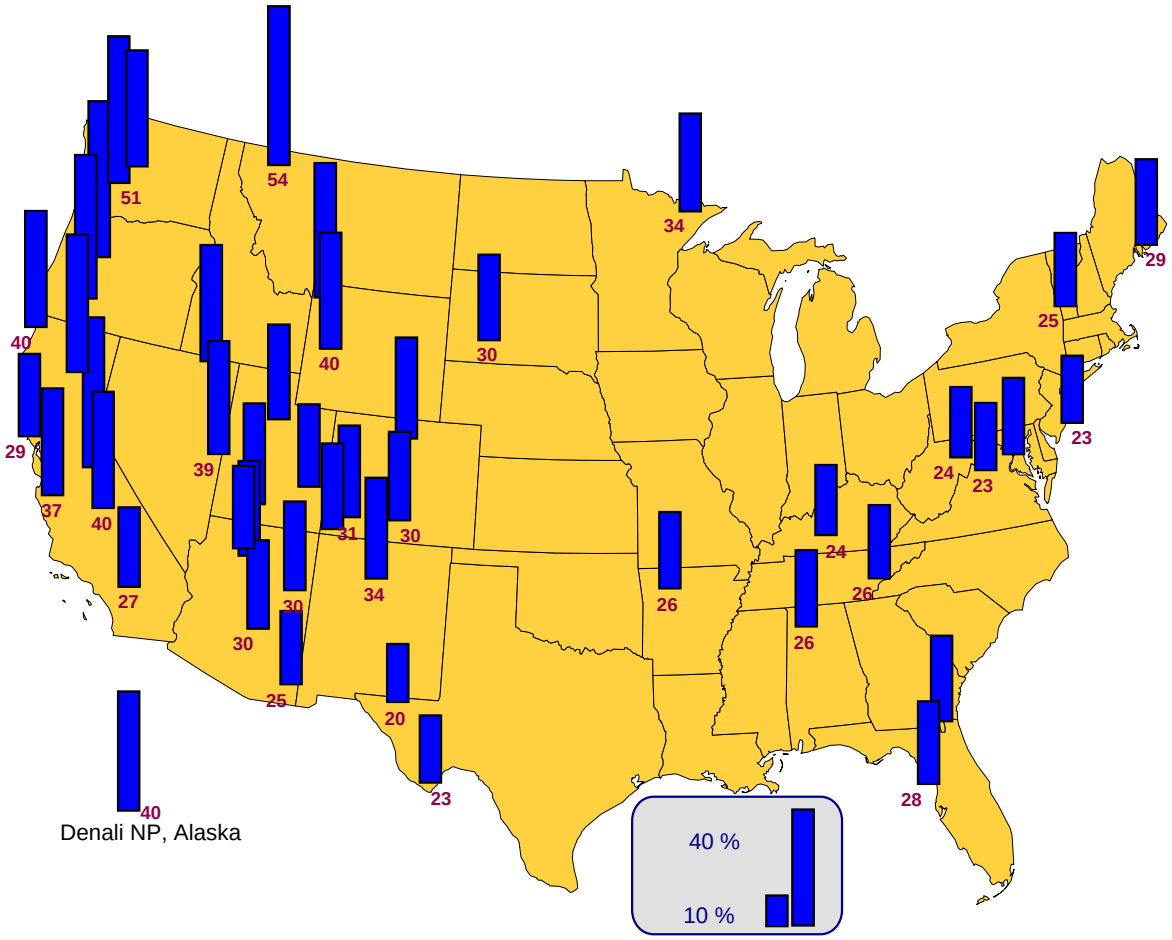

Figure 3–17. Average Annual Contributions of Organic Carbon PM to Total $PM_{2.5}$ Levels at IMPROVE Monitoring Sites from 1994–1998

Figure 3–18 shows the annual average organic carbon extinction coefficients for the period from 1994 through 1998. The lowest light extinction coefficients (from 2.3 to 3.6 Mm^{-1}) for organic carbon were observed at Denali National Park, AK and the sites in the Four Corners area of the Southwest (Bryce Canyon and Canyonlands, UT; Grand Canyon, AZ; and Mesa Verde, Weminuche, and Great Sand Dunes, CO). The annual average organic carbon concentrations at all seven of these sites were below 0.9 $\mu g/m^3$. The highest light extinction coefficients for organic carbon (from 10.5 to 16 Mm^{-1}) were at Sequoia National Park (CA), Washington (DC), and the mandatory Federal Class I areas in the southeastern states of Kentucky, Tennessee, Alabama, Georgia, and Florida.

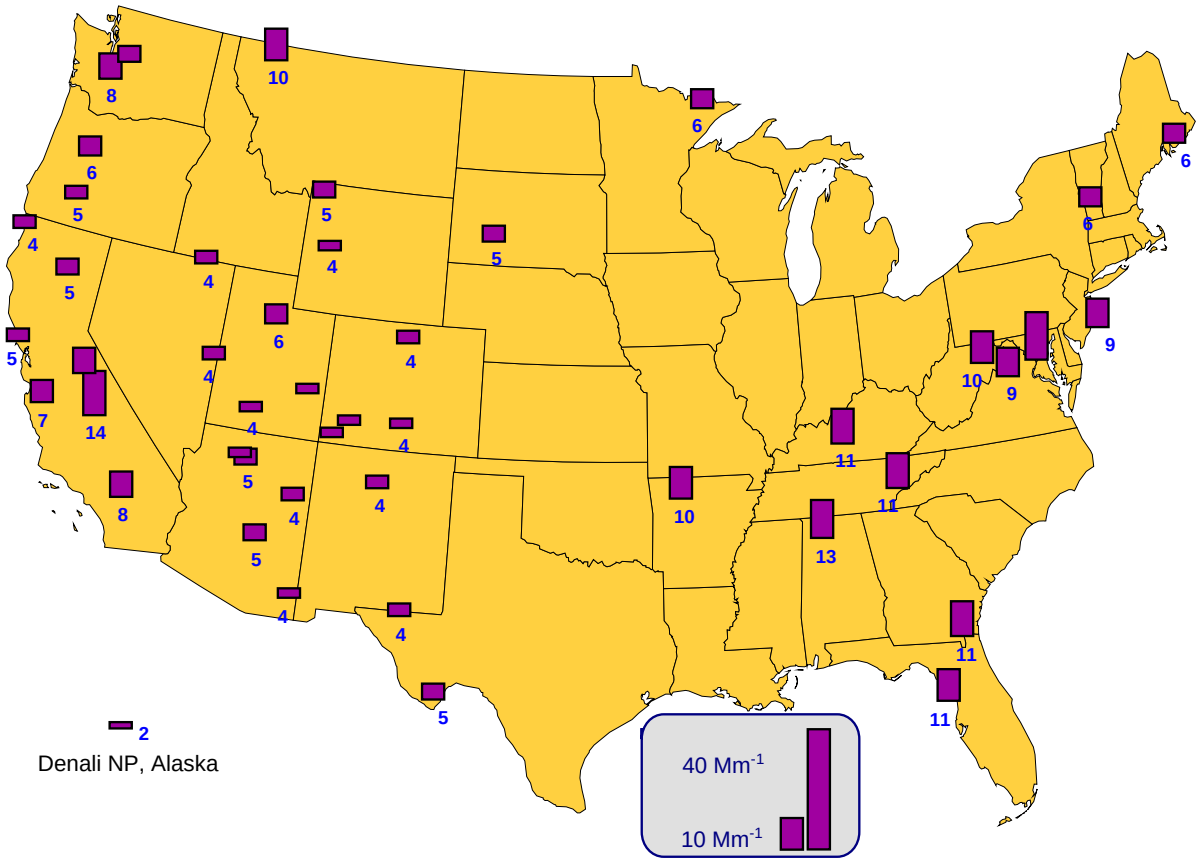

Figure 3–18. Average Annual Organic Carbon Extinction Coefficients at IMPROVE Monitoring Sites from 1994–1998

Figure 3–19 shows the average contributions of organic carbon particulate matter to the calculated aerosol light extinction coefficients for the IMPROVE sites from 1994 to 1998. The lowest percent contribution from organic carbon (9 percent) occurred at the Mammoth Cave National Park (KY) monitor site, the site that showed the highest total visibility impairment on the least-impaired, most-impaired, and mid-range days (Figures 3–1, 3–3, and 3–5). The highest percent contributions from organic carbon (30 to 38 percent) were observed at seven sites in the Northwest: Glacier National Park (MT), Crater Lake National Park (OR), Yellowstone National Park (WY), Lassen Volcanic and Yosemite National Parks (CA), and Great Basin National Park and Jarbidge Wilderness Area (NV).

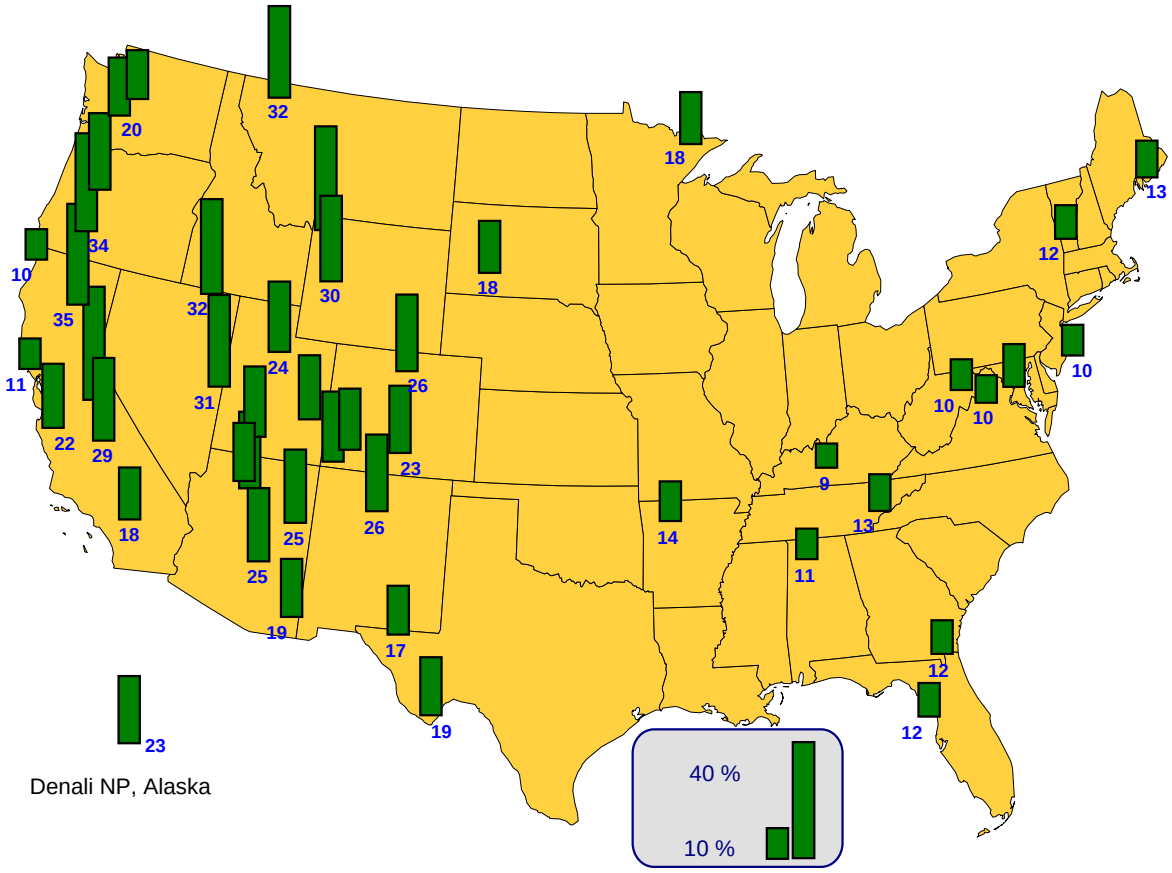

Figure 3–19. Average Annual Contributions of Organic Carbon PM to Calculated Aerosol Light Extinctions at IMPROVE Monitoring Sites from 1994–1998

Elemental Carbon

Table 1–1 reported wildfires as the natural source of elemental carbon particulate matter and motor vehicle exhaust, wood burning, prescribed fires, and cooking as the manmade sources of elemental carbon particulate matter.

Figure 3–20 presents the annual average concentrations of elemental carbon particulate matter at the IMPROVE sites for the period from 1994 through 1998. The lowest average concentration of elemental carbon (0.09 μg/m^3) was observed at Denali National Park, AK. The highest concentrations (0.35 to 0.60 μg/m^3) at rural sites were observed at Glacier National Park (MT), three sites in southern California (Pinnacles, Sequoia, and San Gorgonio), the mid-Atlantic sites (Brigantine, Dolly Sods, and Shenandoah), and the sites in the Southeast (Mammoth Cave, Upper Buffalo, Great Smoky Mountains, Sipsey, Okefenokee, and Chassahowitzka). In addition, the concentration observed at the urban Washington (DC) site was 1.24 μg/m^3, more than double any of the other readings.

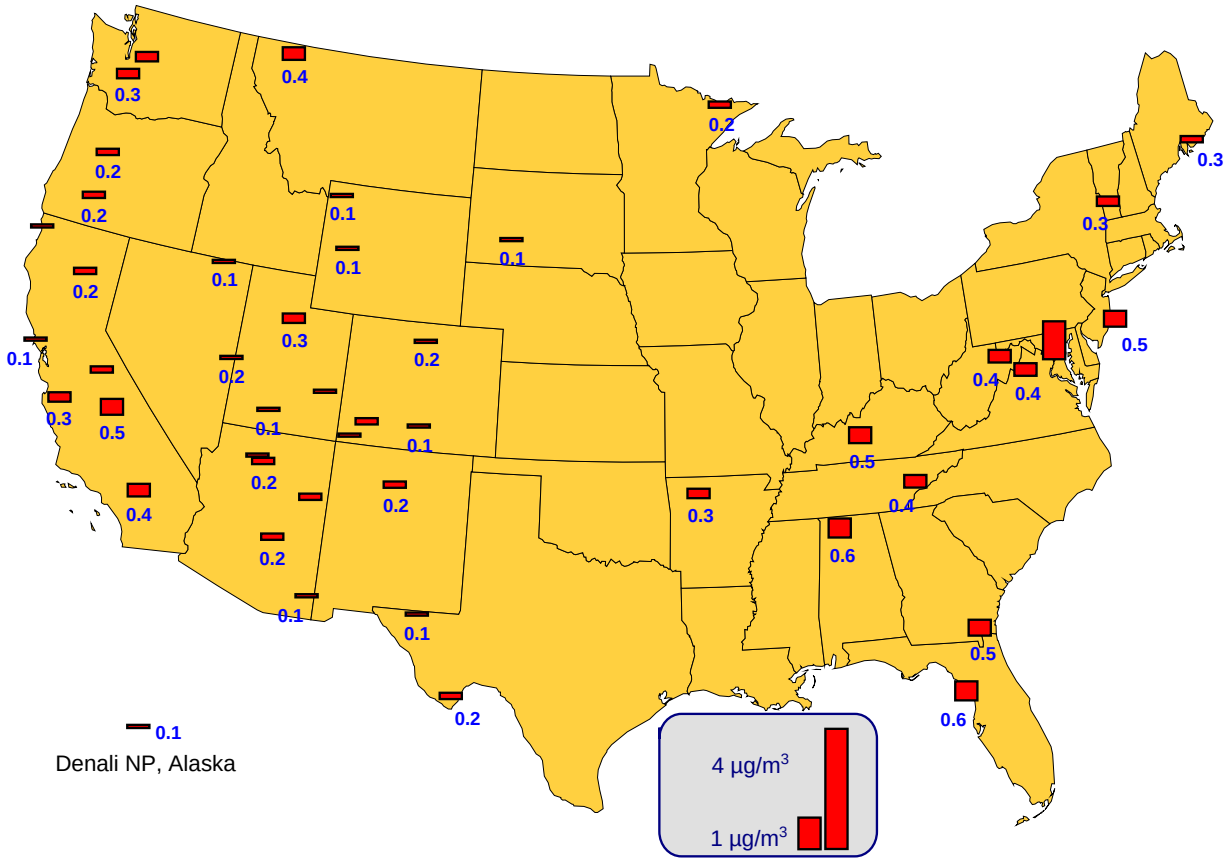

Figure 3–20. Average Annual Elemental Carbon PM Concentrations at IMPROVE Monitoring Sites from 1994–1998

Figure 3–21 presents the average contribution of elemental carbon particulate matter to the total $PM_{2.5}$ levels at the IMPROVE monitoring locations from 1994 through 1998. The two sites in Texas (Big Bend and Guadalupe Mountains National Parks) had the lowest percent contribution (3 percent) from elemental carbon to the total $PM_{2.5}$ concentrations. The highest percent contributions (8 to 9 percent) from elemental carbon occurred at Washington (DC) and four sites in the Northwest: Mount Rainier National Park and Snoqualmie Pass (WA), Glacier National Park (MT), and Crater Lake National Park (OR).

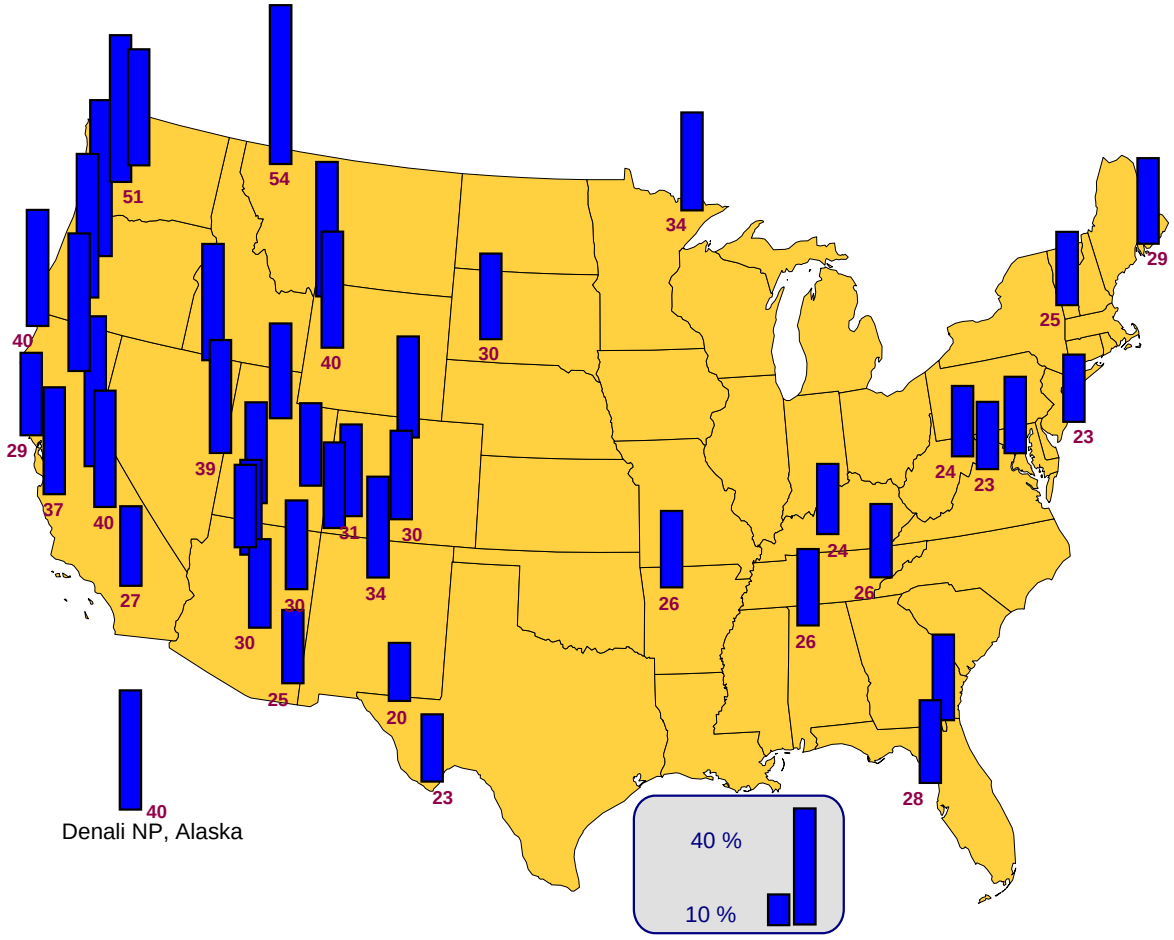

Figure 3–21. Average Annual Contributions of Elemental Carbon PM to Total $PM_{2.5}$ Levels at IMPROVE Monitoring Sites from 1994–1998

Figure 3–22 shows the calculated annual average elemental carbon extinction coefficients for the period from 1994 through 1998. The lowest average extinction coefficient for elemental carbon (0.92 Mm^{-1}) was observed at Denali National Park (AK). The highest coefficients (3.5 to 6.0 Mm^{-1}) at rural sites were observed at Glacier National Park (MT), three sites in southern California (Pinnacles, Sequoia, and San Gorgonio), the mid-Atlantic sites (Brigantine, Dolly Sods, and Shenandoah), and the sites in the Southeast (Mammoth Cave, Upper Buffalo, Great Smoky Mountains, Sipsey, Okefenokee, and Chassahowitzka). In addition, the coefficient calculated at the urban Washington (DC) site was 12.4 Mm^{-1}, more than double any of the other light extinction coefficients calculated for elemental carbon.

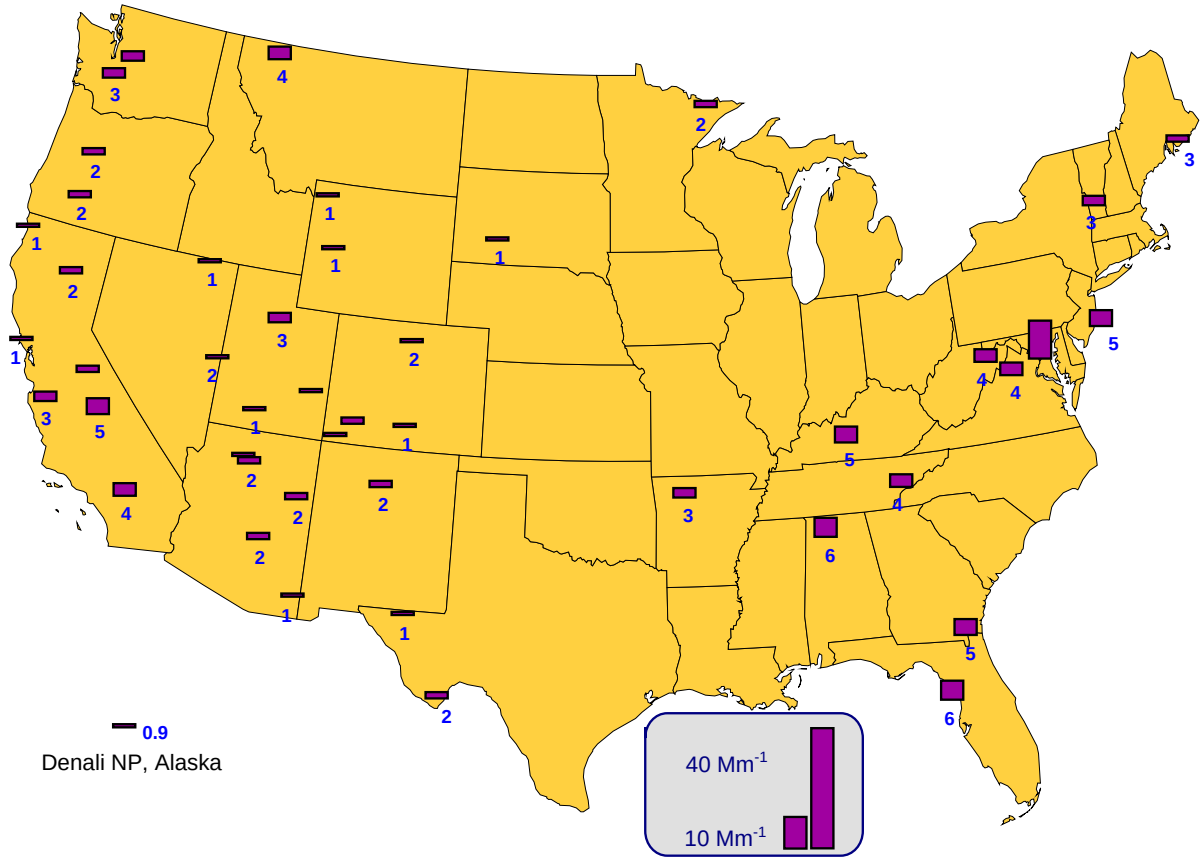

Figure 3–22. Average Annual Elemental Carbon Extinction Coefficients at IMPROVE Monitoring Sites from 1994–1998

Figure 3–23 shows the average contributions of elemental carbon particulate matter to the calculated aerosol light extinction coefficients for the IMPROVE sites from 1994 to 1998. The lowest percentage contributions from elemental carbon occured at California's two coastal sites, Redwood National Park (2 percent) and Point Reyes National Seashore (3 percent). Values at other sites ranged from 4 percent at several eastern sites up to 16 percent at Crater Lake National Park (OR).

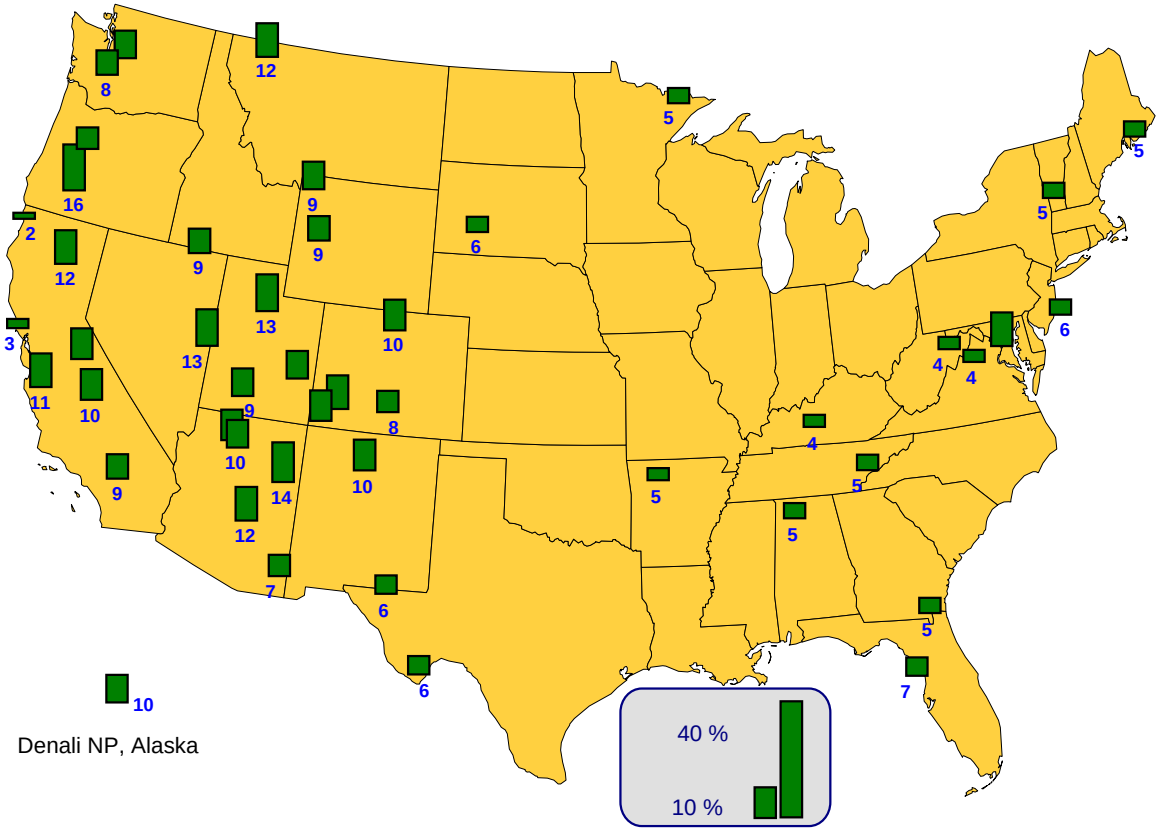

Figure 3–23. Average Annual Contributions of Elemental Carbon PM to Calculated Aerosol Light Extinctions at IMPROVE Monitoring Sites from 1994–1998

Soil and Crustal Material

Soil data in the IMPROVE network reflect measurements of various components emitted from soil emission activities: aluminum, silicon, calcium, titanium, and iron, and their calculated oxides. The soil data are independent of the soil types, such as sediment, sandstone, or limestone and are measured and calculated for the fraction of particulate matter less than 2.5 microns in aerodynamic diameter.

In the IMPROVE calculations, processes emitting earthen particles (e.g., mining and quarrying activities, construction, agriculture, and fugitive road dust) also contribute to the coarse mass fraction (particles larger than 2.5 microns but smaller than 10 microns) of particulate matter. Therefore, the soil data are combined with the coarse mass fraction to describe crustal material. Since smaller particles impair visibility to a greater extent than larger particles (on a mass basis), the fine soil and coarse mass concentrations are not weighted equally when calculating light extinction from crustal material (see Appendix C for the calculation method).

Table 1–1 reports two natural emissions sources of crustal material in the $PM_{2.5}$ range: wind erosion and the re-entrainment of deposited particles. Manmade sources of crustal material include fugitive dust from paved and unpaved roads, agricultural operations, construction and demolition, forestry, mining and quarrying activities, and some industrial processes (e.g., stone cutting and finishing).

Figure 3–24 presents the annual average concentrations of fine soil particulate matter at the IMPROVE sites for the period from 1994 through 1998. The highest fine soil concentrations (1.3 to 1.65 $\mu g/m^3$) were observed at the Sequoia National Park site (CA) and the two monitors in Texas: Big Bend and Guadalupe Mountains National Parks. The lowest fine soil concentrations (0.15 to 0.30 $\mu g/m^3$) were observed at Denali National Park (AK) and six additional monitor sites: Mount Rainier and Snoqualmie Pass (WA), Three Sisters (OR), Point Reyes and Redwood (CA), and Acadia (ME). The data trends suggest a general observation that sites near major bodies of water may tend to have lower annual average fine soil concentrations than sites further inland. Since fewer emission sources of fine soil are spatially available near coastal sites (i.e., less land mass near the coast), this observation is not unexpected.

Figure 3–25 presents the average contribution of fine soil particulate matter to the total $PM_{2.5}$ levels at the IMPROVE monitoring locations from 1994 through 1998. The highest percent contributions of fine soil (18 to 32 percent) occurred at the 19 sites in Wyoming, Nevada, Utah, Colorado, Arizona, New Mexico, and Texas. The lowest annual fine soil contributions (4 to 5 percent) were at Point Reyes National Seashore (CA) and the eastern sites from Tennessee northward: Great Smoky Mountains (TN), Mammoth Cave (KY), Dolly Sods (WV), Shenandoah (VA), Washington (DC), Brigantine (NJ), Lye Brook (VT), and Acadia (ME). The fine soil represents only a small fraction of the total $PM_{2.5}$ at the eastern sites because the annual average sulfate concentrations were high at these sites.

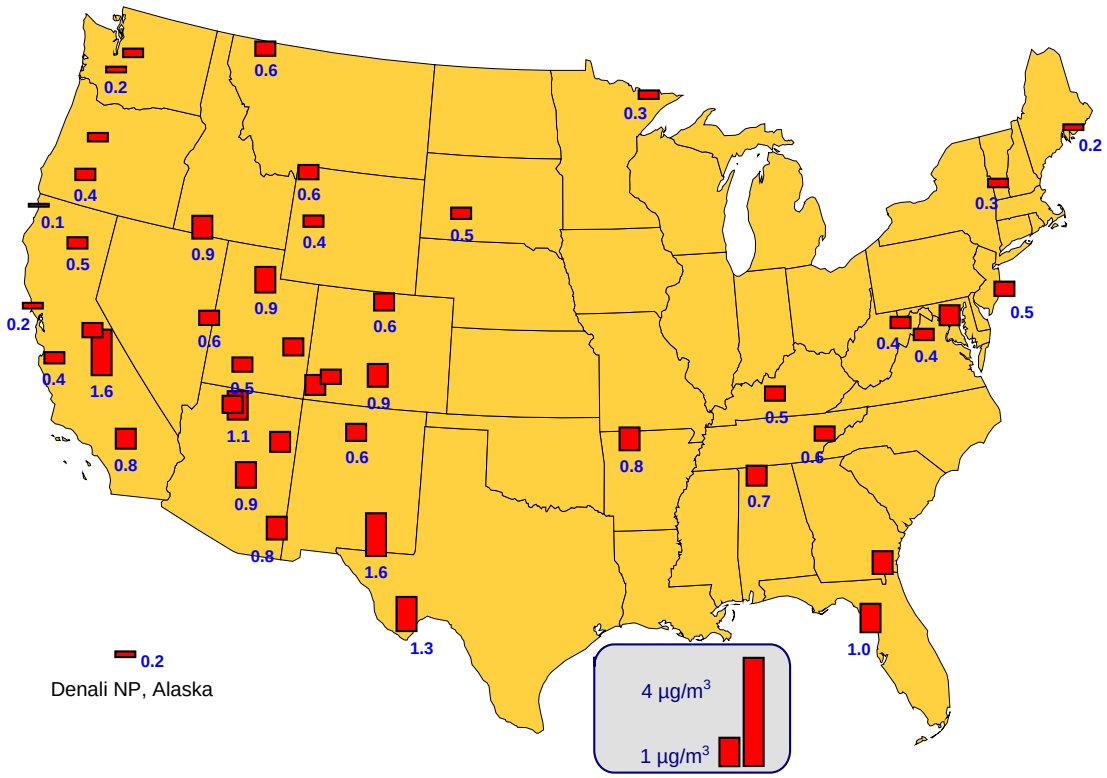

Figure 3–24. Average Annual Fine Soil PM Concentrations at IMPROVE Monitoring Sites from 1994–1998

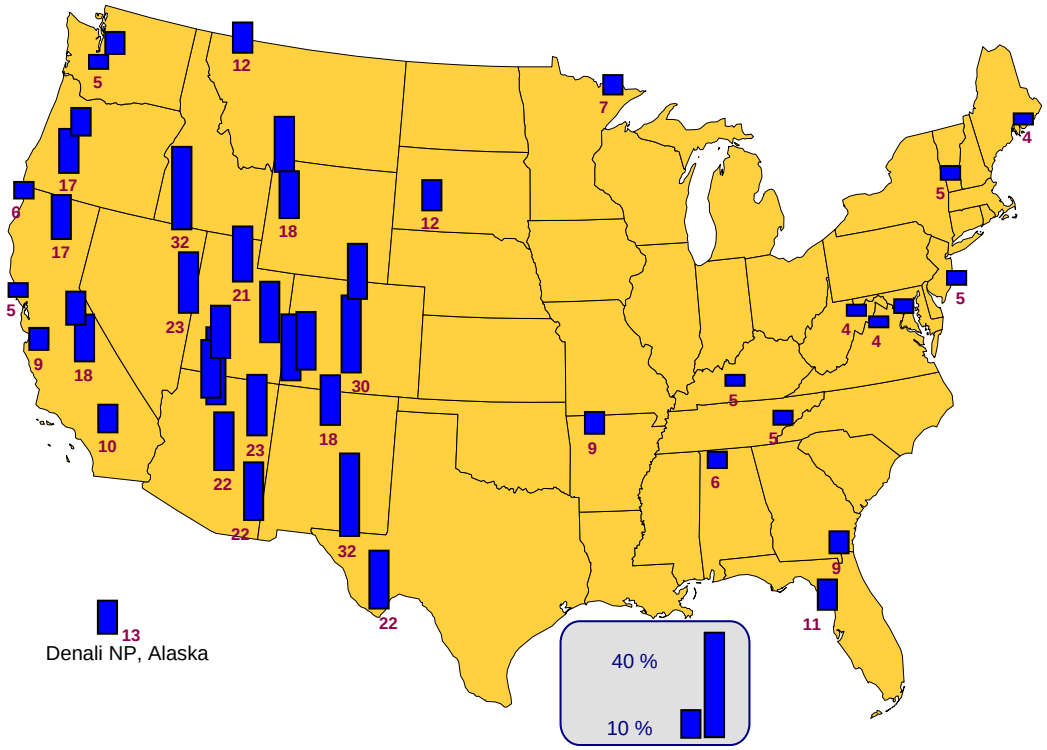

Figure 3–25. Average Annual Contributions of Fine Soil PM to Total $PM_{2.5}$ Levels at IMPROVE Monitoring Sites from 1994–1998

The crustal material extinction coefficients are calculated from both the fine soil and the coarse mass measurements. Since the ratio of coarse mass to fine soil for the annually averaged data ranged from 4.3 at Mesa Verde National Park (CO) up to 42 at Point Reyes National Seashore (CA), the fine soil component represented less than 20 percent of the crustal material concentration on an annual basis. The highest ratios (17 to 42) of coarse mass to fine soil were observed at the sites closest to the coast: Pinnacles, Point Reyes, and Redwood (CA), Acadia (ME), and Brigantine (NJ). The high concentrations of coarse mass at these sites may be due to sea spray, which is composed primarily of particles greater than 2.5 but less than 10 microns in aerodynamic diameter (USEPA, 1997a).

Figure 3–26 shows the annual average crustal material extinction coefficients for the period from 1994 through 1998. Lassen Volcanic (CA) and Denali (AK) monitoring sites showed the lowest extinction coefficients with values near 1.9 Mm^{-1}. The highest crustal material extinction coefficients were observed at the Sequoia site (CA, 8.1 Mm^{-1}) and the Brigantine site (NJ, 8.2 Mm^{-1}).

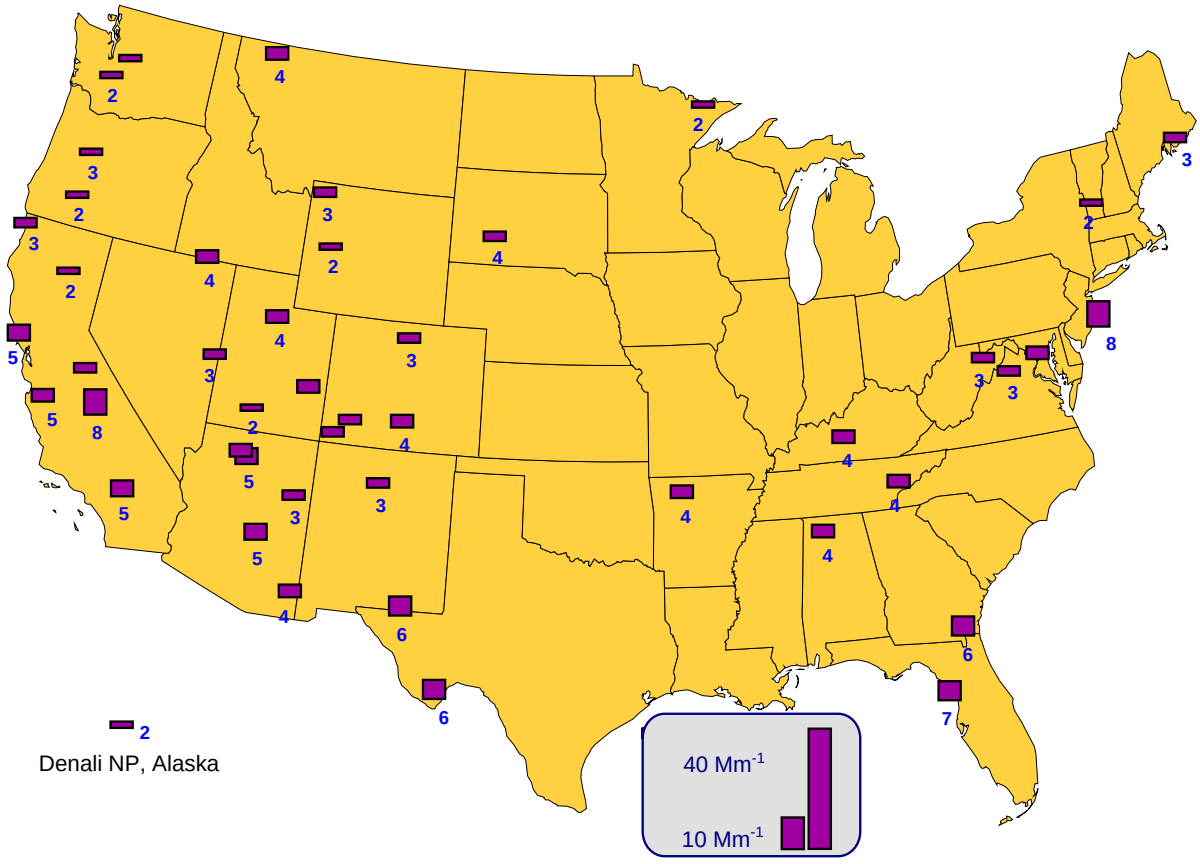

Figure 3–26. Average Annual Crustal Material Extinction Coefficients at IMPROVE Monitoring Sites from 1994–1998

Figure 3–27 shows the average contributions of crustal material particulate matter to the calculated aerosol light extinction coefficients for the IMPROVE sites from 1994 to 1998. Crustal material was responsible for only 3 percent of the aerosol light extinction coefficient at the Sipsey (AL), Mammoth Cave (KY), Dolly Sods (WV), and Shenandoah (VA) sites. Crustal material was responsible for 16 to 31 percent of the aerosol light extinction coefficients at Denali National Park (AK), Crater Lake National Park (OR), Sequoia National Park (CA), and all nineteen monitoring locations in Wyoming, Nevada, Utah, Colorado, Arizona, New Mexico, and Texas.

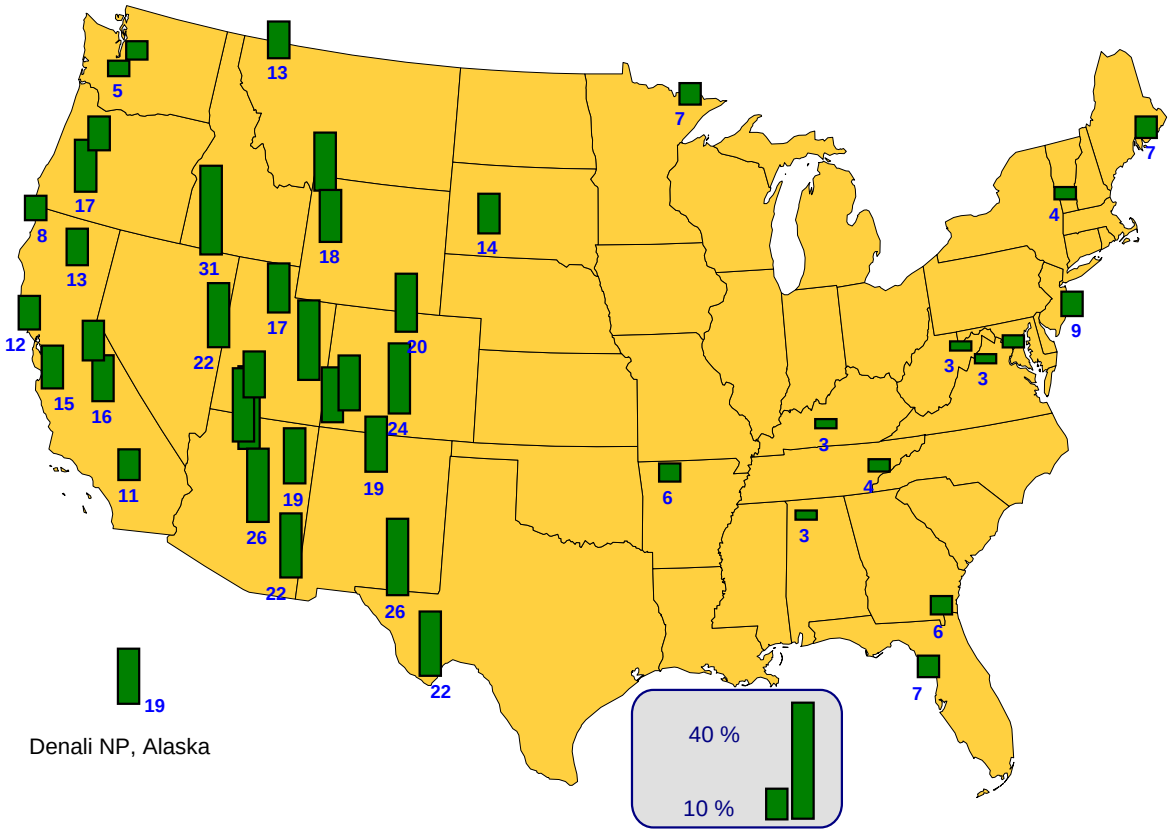

Figure 3–27. Average Annual Contributions of Crustal Material PM to Calculated Aerosol Light Extinctions at IMPROVE Monitoring Sites from 1994–1998

D. Regional Pollutants

From the discussions in the previous section, it is readily apparent that pollutants affect the monitor readings differently in the various regions of the continental United States. Figure 3–28 presents the mandatory Federal Class I areas and the IMPROVE monitoring sites divided into a western region (greater than 100°W) and an eastern region (less than 100°W), with Alaska lying in the western region. Thirteen sites are located in the East and 33 in the West. Since the calculated annual aerosol light extinction coefficient at the urban Washington (DC) (not a mandatory Federal Class I area) site was within one standard deviation (28 Mm^{-1}) of the average for all eastern sites, it was included in the analysis as an eastern site.

Figure 3–28. Mandatory Federal Class I Areas and IMPROVE Particulate Matter Samplers Divided into Western and Eastern Regions

Table 3–1 presents the light extinction coefficients for the East and West as averages from all of the sites within the region. The calculated total aerosol extinction coefficients represent the sum of the extinction coefficients for the five pollutant species: sulfate, nitrate, organic carbon, elemental carbon, and crustal material. The aerosol extinction coefficients, as well as the extinction coefficients for the individual species, are presented on annual and seasonal bases.

Table 3–1. Average Calculated Total Light Extinction Coefficients from 1994–1998

Season	Region	Calculated Total Aerosol Extinction Coefficient (Mm^{-1})	Pollutant Extinction Coefficient (Mm^{-1})				
			Sulfate	Nitrate	Organic Carbon	Elemental Carbon	Crustal Material
Annual	East	87	61.4	6.8	10.0	4.8	4.2
	West	22	8.6	2.9	5.2	2.0	3.6
Spring	East	72	48.3	5.9	8.8	4.4	4.5
	West	22	8.9	3.1	4.4	1.7	4.0
Summer	East	138	108.1	7.6	12.8	4.5	5.2
	West	27	10.6	2.4	6.9	2.2	4.6
Autumn	East	83	57.4	7.1	9.7	5.2	3.8
	West	22	7.8	2.6	5.9	2.3	3.5
Winter	East	59	36.2	6.3	8.6	5.0	3.2
	West	16	5.4	3.4	3.3	1.7	2.4

On an annual basis, the eastern sites showed calculated total aerosol extinction coefficients 4 times higher than those at the western sites. This ratio between East and West varied from 3.3 times higher in the spring to 5.1 times higher in the summer season. The lowest average light extinction coefficients were calculated for the winter in both eastern and western regions. The highest average aerosol light extinction coefficients occurred during the summer in both regions.

Table 3–1 shows that the sulfate light extinction coefficients were also highest in the summer and lowest in the winter in both East and West. These seasonal trends are consistent with known sulfate aerosol chemistry principles. On an annual basis, the eastern region showed sulfate light extinction coefficients 7.1 times higher than the western region. The sulfate ratio between East and West varied from near 5.4 in the spring to 10.2 in the summer season. One reason for the large difference in sulfate extinction between East and West is that sulfur dioxide emissions in the East were 3 times higher than those in the West (E. H. Pechan and Associates, 1994).

The difference in sulfate extinctions between East and West can also be partially attributed to the higher relative humidities in the East compared to the West. On an annual basis, the sulfate and nitrate adjustment factor for relative humidity averaged 3.7 in the East (equivalent to 86 percent relative humidity) and 2.6 in the West (equivalent to 79 percent relative humidity). To illustrate how this affects the calculated visibility, an ambient concentration of 1.0 $\mu g/m^3$ of sulfate would contribute 11.1 Mm^{-1} to the light extinction coefficient in the East but only 7.8 Mm^{-1} to the average western site.

The annual nitrate extinction coefficients in Table 3–1 were 2.3 times higher for the East than for the West. In both East and West, the nitrate extinction coefficients were highest in the winter and lowest in the summer, consistent with the chemical equilibrium calculations for nitrate aerosol formation (Matsumoto and Tanaka, 1996). The nitrate ratio between East and West was lowest during the winter at 1.9 and rose to 3.2 in the summer.

The annual organic carbon extinction coefficients in Table 3–1 were 1.9 times higher for the East than for the West. One source of organic carbon is the oxidation of hydrocarbons released by vegetation. The highest organic carbon extinction coefficients were observed in both East and West in the summer, the season when vegetation growth is rapid. In both regions, the lowest organic carbon extinction coefficients were found during the winter, when vegetation growth is slowest. These observations are consistent with the findings of Goldstein, et al. (1996) that biogenic emissions of certain hydrocarbons from vegetation exceeded manmade emissions during the summer, while manmade emissions dominated during the winter seasons.

The organic carbon ratio between East and West was lowest in the autumn and highest in the winter (Table 3–1). Western states conducted more than 40 percent of their prescribed burning activities in the autumn, whereas eastern states conducted more than 40 percent in the winter (Ward et al. 1993). Since fires are a source of organic carbon and prescribed burning often takes place near mandatory Federal Class I areas, this activity may be partly responsible for the low organic carbon ratio between East and West in the autumn (1.6) and the high ratio in the winter (2.6).

Elemental carbon ratios between the East and West were also highest in the winter. Since vegetation burning (both prescribed burning and wildfires) produces elemental carbon and often occurs near mandatory Federal Class I areas, this activity may be partly responsible for the high winter ratio between East and West. (Eastern prescribed burning is predominantly a winter activity.)

On an annual basis, the elemental carbon extinction coefficients in Table 3–1 were 2.4 times higher for the East than the West. The higher elemental carbon extinction coefficients in the East were calculated in autumn and winter–as high as 20 Mm^{-1} in Washington (DC)–and the lower coefficients in the spring and summer. In the West, the higher coefficients were calculated in the summer and autumn (as high as 10 Mm^{-1} at Sequoia National Park, CA), and the lower coefficients during winter and spring.

The extinction coefficients for crustal material showed less variation between East and West than the other four components. Table 3–1 shows that the crustal material in the East was only 17 percent higher than crustal material in the West on an annual basis, and the percentage did not change considerably from one season to the next. In the East, crustal material was responsible for 5 percent of the annual aerosol light extinction coefficient, less impairment than the other four components. However, in the West, 16 percent of the annual aerosol extinction coefficient was attributed to crustal material. Only 9 and 13 percent were attributed to elemental carbon and nitrates in the west.