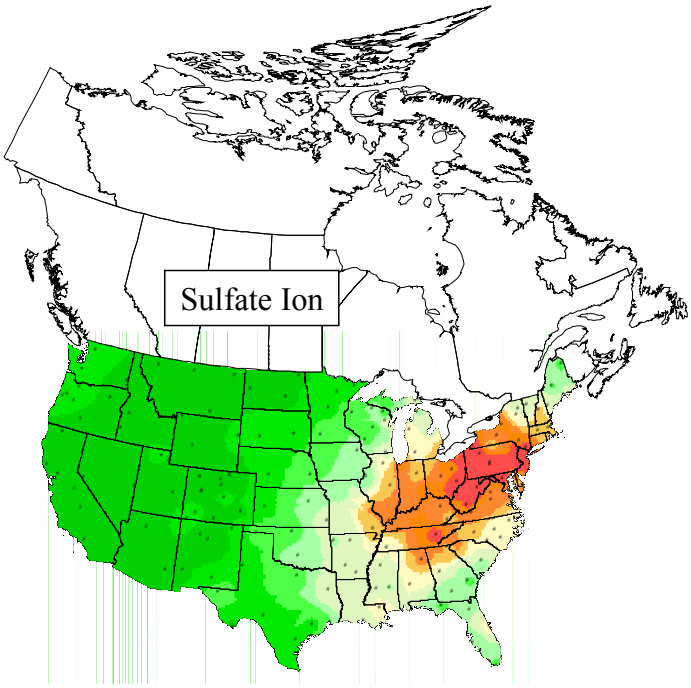
Technical Memorandum #4

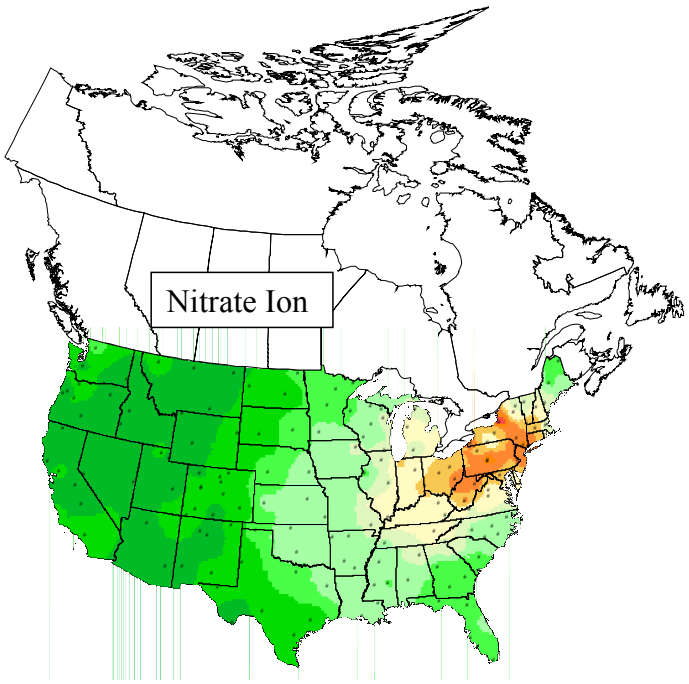
GIS Mapping of Regional Haze-Related Data in the MANE-VU Region

Prepared by Northeast States for
Coordinated Air Use Management
(NESCAUM)

For the MANE-VU Regional Planning
Organization

February 15, 2002





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February 15, 2002

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I. Introduction

In support of the Mid-Atlantic/Northeast Visibility Union (MANE-VU) Regional Planning Organization (RPO) goals, NESCAUM has expanded its capacity to present geographic information in a visually powerful manner. The figures contained in this memorandum have been developed using ArcView visualization software and provide graphical depictions of emissions, modeling and monitored data relevant to regional haze in the Northeast and Mid-Atlantic.

The data used to create these figures has been drawn from a variety of sources including: the United States Environmental Protection Agency (USEPA) National Emissions Trends (NET) Inventory, Environment Canada's Criteria Air Contaminant (CAC) Emission Inventory, the National Atmospheric Deposition Program (NADP), and the Interagency Monitoring of Protected Visual Environments (IMPROVE) program. Results from regional air quality modeling simulations conducted at NESCAUM have produced another set of regional haze data. These findings are presented in another NESCAUM technical memorandum (*Technical Memorandum #2, REMSAD Modeling Exercises, NESCAUM, 2001*) and benefit from the improved visualization techniques described here.

As states and tribes proceed with their regional planning efforts to combat regional haze, the enhanced graphical capacity demonstrated here will provide a visually powerful means of conveying technical data. These resources will be critical in improving our understanding of the physical mechanisms that cause and contribute to regional haze. These graphical depictions of large data sets are also expected to play a useful role in communicating the causes and extent of regional haze to the public.

II. Graphical depiction of haze data sets

A. Emissions data

Figure 1 through 6 present maps of U.S. and Canadian emissions of several haze-related species. The data used to create these maps came from the 1996 USEPA NET inventory (USEPA, 2001) and the 1995 Environment Canada CAC inventory (Environment Canada, 2001).[1] The NET inventory provides emissions information at the county level that has been aggregated by state for the current work. The Canadian emissions data was provided for each province.

Figure 1 illustrates three different ways to visualize sulfur dioxide emissions in the U.S. and Canada: absolute emissions, deviation of emissions from the mean, and emissions per capita. Total emissions, including mobile, area and point sources are included in this figure. Texas, Florida, Illinois, Indiana, Ohio and Pennsylvania release the greatest annual emissions of sulfur dioxide among all the states and provinces (greater than 800,000 tons/yr). However only Ohio's emission levels are more than three standard deviations greater than the mean of U.S. state emissions (387,000 tons/year).[2] All of Canada is shown to emit less than or near the national U.S. average, highlighting the more significant role that U.S. states play in contributing to overall sulfur dioxide emissions. The third panel of Figure 1 shows per capita sulfur dioxide emissions. This representation is useful for distinguishing those states and provinces that produce significantly more sulfur dioxide than their population would suggest is needed to satisfy power generation needs.[3] Wyoming, North Dakota, West Virginia, Alberta, Manitoba and the Northwest Territory are areas with greater than 0.2 tons/year/population. When displayed on a per capita basis, states with the lowest population and in some cases, the lowest total emissions tend to be highlighted.

Sulfur dioxide emissions in the U.S. and Canada have been plotted in terms of emissions density in Figure 2. The units here are tons per square-mile per year, a unit that accounts for increased generation needs among states with greater land area. This technique puts all states on a consistent spatial scale so that total emissions of larger states may be equitably compared to neighboring smaller states. As Figure 2 illustrates, the majority of states along the East Coast emit at levels greater than 5.0 tons per square-mile per year. A more refined analysis of the Eastern U.S. shows that Indiana, Ohio,

[1] US EPA and Canadian data is located at http://www.epa.gov/ttn/chief/net/index.html and http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm, respectively.
[2] Mean sulfur dioxide emission level of 387,000 tons/year and standard deviation of 406,754 tons/year are based on averaging annual emissions of U.S. states only.
[3] Under electricity deregulation, it has become increasingly common for some states to provide significant generation capacity to adjacent states or states some distance away. Power is a key export for some of these states. This is not accounted for in a per capita representation.

West Virginia, New Jersey and Delaware emit the greatest levels of sulfur dioxide per unit area.

Figure 3 plots sulfur dioxide emissions exclusively from large elevated point sources within the 26 source categories eligible for Best Available Retrofit Technology (BART) under the regional haze rule. A threshold emission criterion of 10,000 tons per year was selected to emphasize how many very large elevated sources exist. Stack heights of 50 meters or more were examined because sulfur dioxide emitted at elevation is more easily transported and thus likely to play a more significant role in *regional* haze, as opposed to *reasonably attributable* visibility impairment. By focusing exclusively on the first BART-eligible category (fossil-fuel fired steam electric generating facilities with greater than 250 million BTU/hr heat input), those power plants which may be BART-eligible can be identified by year of construction as shown in the second panel.[4]

In Figure 4, the emissions density maps have been further resolved both spatially and by source category. The first panel shows total sulfur dioxide emissions density (in tons per square mile for 1996) for each U.S. county. While the increased resolution in this figure makes it harder to distinguish broad regions of significantly increased emissions, it is clear that a large number of high emitting counties are dispersed throughout the East consistent with the maps in Figure 2. This figure also breaks total sulfur dioxide emissions down into separate panels for point, area and mobile sources.[5] Point sources are shown to represent the majority of sulfur dioxide emissions in the U.S. Area sources add significantly to the total emissions in the greater Philadelphia, New York, Boston, and Portsmouth metropolitan areas. It should be noted, however, that uncertainties for the area source emission inventory (upon which these figures are based) are greater than for other inventory categories. Mobile sources are not shown to contribute significantly to total sulfur dioxide emissions. These graphics demonstrate the primary role point source emissions of sulfur dioxide play in the overall emission inventory.

An important lesson to take away from Figures 1 through 4 is that there are many ways to present similar data and that care must be taken in how these different representations are interpreted. For the purposes of this memorandum, a wide variety of display techniques have been explored. In future haze planning efforts, the RPO's must use care in selecting the appropriate representation to suit specific circumstances.

Figure 5 illustrates U.S. and Canadian emissions of nitrogen oxides. Most of the U.S. states and Canadian provinces emit at levels greater than 100,000 tons/year. Manitoba, the Atlantic Provinces and the Northern New England States are the exception. California, Texas, Florida, Illinois, Ohio and Pennsylvania emit the greatest amount of nitrogen oxides at more than one million tons per year. When plotted as a difference from the mean U.S. value, California and Texas represent the extreme emitters on a total

[4] See *A Basis for Control of BART-Eligible Sources* (NESCAUM, 2001) for more complete information on plant construction date information.

[5] The shading within each county represents the sum of all sources within that county as entered in the NET inventory.

tonnage basis.[6] Again, all of Canada emits below or near the national U.S. average. The last panel in this figure depicts per capita emissions. Wyoming is shown to emit the greatest tonnage per person per year followed by Montana, North Dakota and West Virginia.

Figure 6 maps the density (in tons per square mile) of U.S. and Canadian nitrogen dioxide emissions. Here New Jersey is highlighted as the state contributing the greatest amount of nitrogen oxide emissions per square-mile per year followed by Connecticut, Delaware, Indiana, Maryland, Massachusetts, Ohio, Pennsylvania, Rhode Island, and West Virginia.

Similar to Figure 3 for sulfur dioxide, Figure 7 maps nitrogen oxide emissions density on a county level and illustrates the relative contribution of three source categories: area, mobile and point sources. Unlike sulfur dioxide where stationary sources dominate, similar quantities of nitrogen oxides are emitted by mobile, stationary and area sources. Figure 7 shows a fairly uniform level of nitrogen oxide emissions across the Eastern and Midwest states.

In Figure 8, nitrogen oxide emissions from large elevated point sources are shown similar to the sulfur dioxide emissions shown in Figure 4. Also similar to sulfur dioxide, nitrogen oxide emitted at altitude is more likely to form nitrates which are subject to transport as opposed to ground level emissions which are more easily deposited near the emission sources. The second panel of this figure focuses on power plants which may be subject to BART based on their dates of construction.

Figures 9a and 10 through 12 show similar plots of emissions density for other haze-forming pollutants based on the NET inventory including ammonia, primary $PM_{2.5}$, primary PM_{10}, and VOC, respectively. Ammonia emissions, as shown in Figure 9a, are dominated by area sources in the Midwest and North Carolina. Figure 9b shows a similar plot for ammonia emissions based on a recently released national ammonia inventory developed by MARAMA and NESCAUM (NESCAUM/MARAMA, 2001), and Figure 9c shows the differences between the two inventories. It should be noted that researchers at Carnegie Mellon University who developed the new ammonia inventory place large uncertainties on the estimated soil emissions and therefore one may expect to see large differences between two highly uncertain inventories. In fact, large differences do exist with the largest differences on the order of 100% across many areas of the Midwest.

Primary $PM_{2.5}$ emissions, shown in Figure 10, largely originate from eastern area sources. Primary PM_{10} emissions (Figure 11) are more uniformly distributed, but are dominated by area sources. Volatile Organic Compounds (Figure 12) originate from area and mobile sources in nearly equal amounts. Emissions are generally highest in the Eastern U.S. and along the West Coast.

[6] Mean nitrogen oxide emission level of 500,000 tons/year and standard deviation of 404,000 tons/year are based on averaging annual emissions of U.S. states only.

B. Deposition

Wet deposition data for sulfate, nitrate and ammonium ion for 1996 were obtained from the NADP (NADP,2001).[7] Figure 13 maps this data with each point on the map representing the location of a wet deposition monitor. This data is displayed on a contour map using an inverse-distance weighting scheme.[8] Significant levels of sulfate ion are deposited in the Midwest and Eastern United States. The reader is cautioned, however, that this map only represents wet deposition and no data is provided to represent dry deposition which is estimated to contribute to over half of total sulfate deposition (Seinfeld and Pandis, 1998).

Nitrate ion is also wet deposited in greater amounts across the Northeast and Midwest U.S. Ammonium ion exhibits a somewhat different deposition pattern stretching across a greater expanse of the Midwest and Southern U.S. in addition to parts of the Northeast. Given that husbandry is a significant source of ammonia emissions (see Figure 9b), it is not surprising that agricultural areas of the Midwest and Southeast receive relatively high concentrations of ammonia deposition. As these maps demonstrate, states within the MANE-VU region receive some of the greatest levels of wet deposition of acidic ions associated with fine particulate components.

Figure 14 combines the results of Figure 1 and Figure 13 to show total sulfur dioxide emissions (in tons/year/state) overlain with contours of sulfate wet deposition (in kilograms/hectare/year). The translation of contours denoting maximum deposition in the direction of prevailing wind patterns from the states with the highest total emissions provides evidence of meteorological transport of these pollutants. Since clouds provide an environment that can quickly convert sulfur dioxide to sulfate, the wet deposition of sulfate shown here may represent only that portion of sulfur dioxide which is converted and deposited quickly. Dry deposition processes, which are significantly slower, are likely to result in deposition further upwind of high emitting areas.

C. Haze-Related Parameters

A number of visibility related parameters are measured and reported by the IMPROVE program (IMPROVE, 2001).[9] The IMPROVE network operates several sites

[7] NADP data can be obtained from their website at: http://nadp.sws.uiuc.edu/nadpdata/ More information regarding the quality control and quality assurance procedures used in producing this data can be obtained on the NADP website.

[8] Inverse distance weighting is the interpolation scheme used in this memo for contouring. This method assumes that the value observed at a particular monitoring site represents the surrounding area with diminishing reliability as the distance from that site increases. These contour maps provide a sense of national trends in wet deposition, however, many of the monitors shown here are sparsely located throughout the U.S. and do not provide adequate coverage to create maps with complete accuracy.

[9] A companion document to this technical memorandum was produced entitled Updated Statistics for the MANE-VU Region (NESCAUM, 2002) which makes extensive use of the IMPROVE data and provides additional detail regarding the measurement techniques and quality assurance procedures for these data. IMPROVE data can be found at: http://vista.cira.colostate.edu/improve/

in the Eastern U.S. These sites are located throughout the MANE-VU region and in several Southeast States adjacent to the MANE-VU region. Figure 15 shows the locations of the IMPROVE monitors in this area. These sites are clustered near national parks and wilderness areas designated as Federal Mandatory Class I Areas including: Moosehorn Wilderness Area, Maine, Roosevelt-Campobello International Park, New Brunswick, Acadia National Park, Maine, Great Gulf Wilderness Area and the Presidential Range/Dry River Wilderness Area, New Hampshire,[10] Lye Brook Wilderness Area, Vermont, Brigantine Wilderness Area, New Jersey, Shenandoah National Park, Virginia, DollySods/Otter Creek Wilderness Area, West Virginia, James River Face Wilderness Area, Virginia, and the Great Smoky Mountains National Park in Tennessee. The IMPROVE monitors located near these mostly remote parks and wilderness areas provide a regional signature of air quality since there tend to be few significant local influences. Contour maps based on data from these sites provide reasonable approximations of the visibility parameters mapped, but the reader is cautioned that the sparseness of the network limits the accuracy of these maps in some locations. IMPROVE maintains an urban monitor in Washington, DC that was included in this analysis, but may not be as representative of regional influences as the other nine sites.

Figure 16 shows the annual variability in reconstructed light extinction[11] across the MANE-VU region. The general pattern is consistent across the time period illustrated; however, there are noticeable year-to-year differences, particularly in the Mid-Atlantic region. Changes in extinction are strongly influenced by relative humidity. However, in this figure, extinction was calculated using climatological average values of relative humidity to remove interannual variability due to this effect (see footnote 11). Observed variability is therefore due to changes in observed mass concentrations, which are a function of emissions as well as meteorological parameters such as wind speed and temperature.

To investigate the potential seasonality of regional haze, seasonal visibility conditions are presented for the period between 1995 and 2000 plotted in terms of atmospheric extinction. This parameter increases linearly with respect to ambient fine particle mass concentrations and thus variability is more evident relative to the deciview. The Northeast, on the whole, displays substantially less visibility degradation than the Mid-Atlantic region. Figure 17 shows winter extinction and Figure 18 shows summer extinction (in Mm^{-1}) for the MANE-VU region.[12] Relatively little interannual variability is observed, though visibility conditions in the Mid-Atlantic region were relatively poor in the winter and spring of 1995 and 1996 compared to the other five years shown. Figures 19 and 20 map visibility conditions for the Summer and Fall of the same years. Here we see that visibility conditions have tended to deteriorate at New Hampshire and Vermont Class I sites during the Fall in recent years.

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[10] Note that the IMPROVE monitoring site is located at Camp Dodge which is near, but not within the boundaries of the two New Hampshire Class I areas.

[11] Reconstructed extinction was calculated for all days with all data available using climatological mean monthly values of the relative humidity adjustment factor. See NESCAUM (2002) for more details.

[12] Note: Winter is defined according to the former IMPROVE convention which includes the three month period beginning with December of the prior year and ending with February of the listed year.

Figure 21 charts the contribution to total extinction due each visibility impairing species measured at each site during January.[13] Sulfate is the greatest contributor for almost all years and all sites. It is interesting to note that in January of 1995, Rayleigh scattering (natural scattering due to air molecules) contributed nearly as much to visibility impairment at Lye Brook as all components of particle scattering combined. Since Rayleigh scattering is constant across all years, this result suggests lower concentrations of other sources of light extinction were present in Southern Vermont in January of 1995. Total carbon – the sum of organic and elemental carbon – also appears to be a large contributor to visibility degradation. While elemental carbon tends to be present in significantly lower concentrations in the Northern MANE-VU region, the levels are comparable to organic carbon at the urban Washington D.C. site.

Overall, Summer shows substantially greater levels of visibility impairment compared with Winter. Figure 22 provides some information that may explain some of the observed seasonal differences. Sulfate is a substantial contributor to atmospheric extinction in both months, but it often contributes more than twice as much to extinction observed during July relative to January. Some of this additional contribution is can be explained due to differences in relative humidity, however, the monthly average relative humidity adjustment factors in July range between 3 and 3.8 versus a range of 2.7 to 3.3 in January; much less than a factor of two difference.

The percentages of July extinction due to sulfate are substantially higher – from 50 to over 80 percent of total atmospheric extinction – compared to that of January. Sulfate, again, appears to disproportionately affect the extinction in the Mid-Atlantic States relative to the Northeast.

[13] Rayleigh extinction is due to air molecules in the gas form and is a uniform function of altitude. This contribution is not measured directly at IMPROVE sites.

III. Conclusion

Overall, graphical displays of visibility metrics and other haze related data sets are useful for understanding the major contributing influences to visibility impairment in the MANE-VU region. However, as with any analysis technique, care must be used in the graphical presentation and interpretation of these data. The choice of units (e.g. per capita vs per unit area emissions density) can affect conclusions drawn from data.

As visibility related data continues to be collected and analyzed, it is anticipated that the enhanced capability to utilize advanced visualization software will become even more important in the regional haze planning process.

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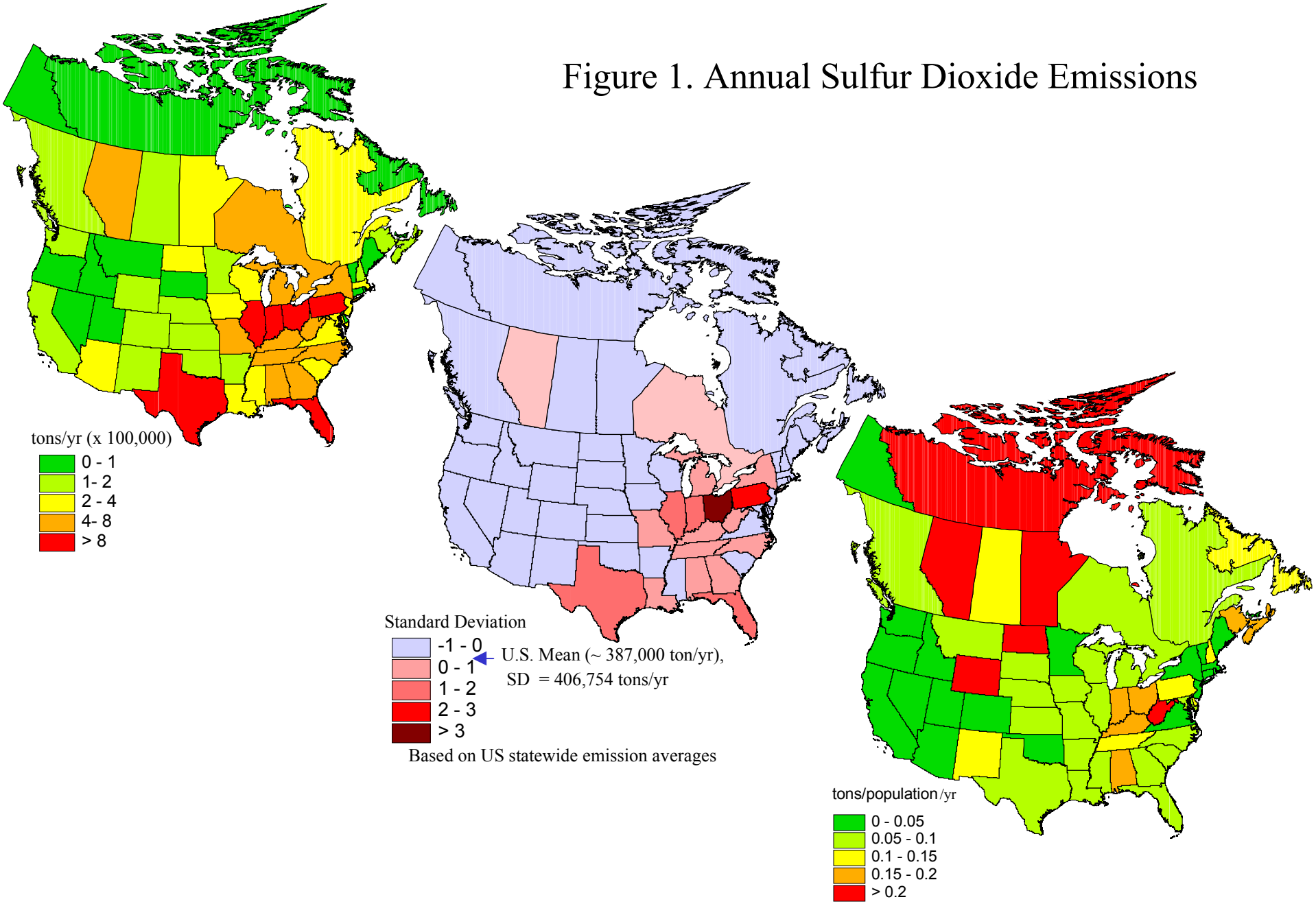
NESCAUM/MARAMA, *Development of an Improved Ammonia Emissions Inventory for the United States*, Prepared by C. Davidson, R. Strader, N. Anderson, M. Goebes, and J. Ayers, Carnegie Mellon University, for Northeast States for Coordinated Air Use Management and Mid-Atlantic Regional Air Management Association, Baltimore, MD, November, 2001.

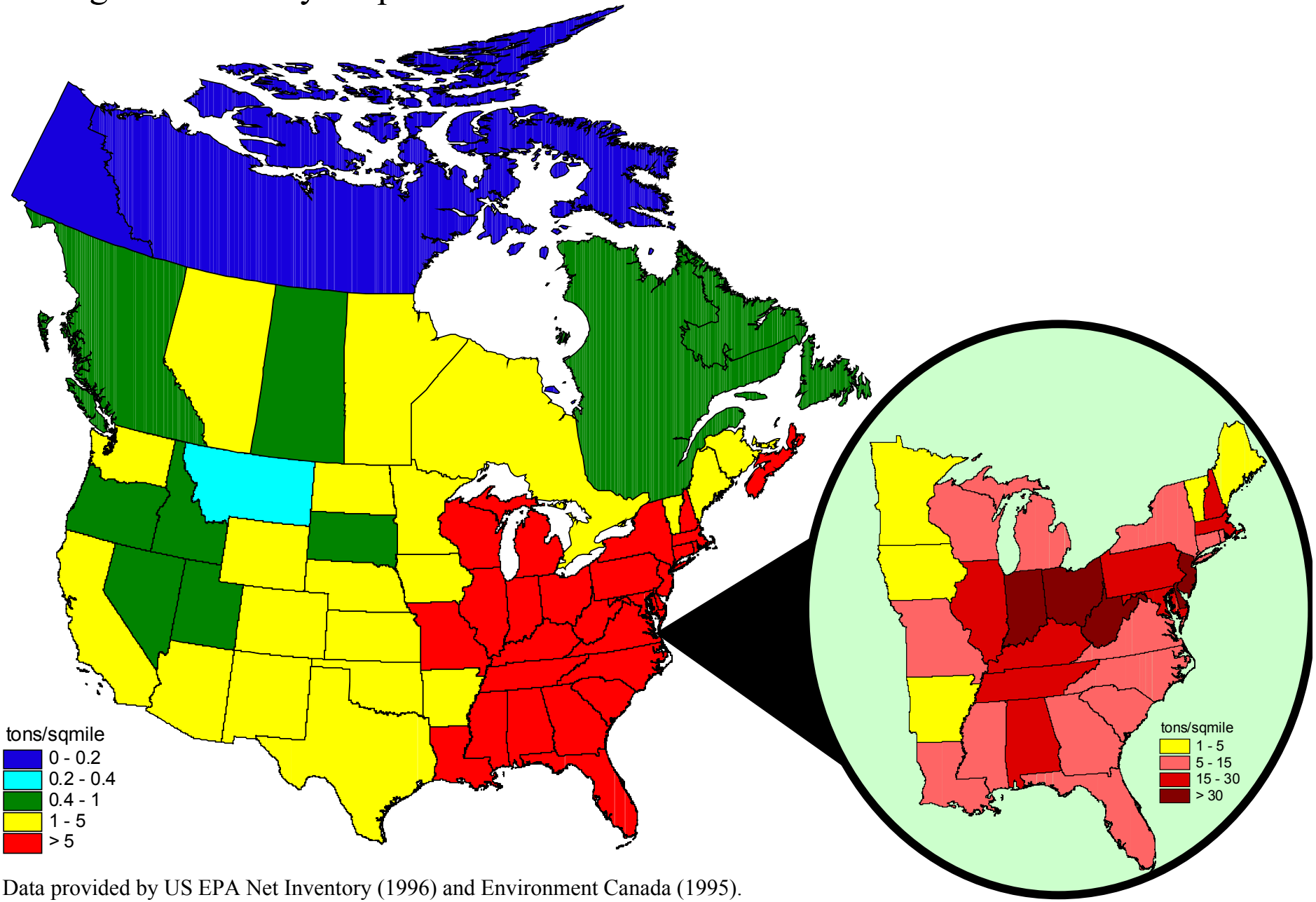
IMPROVE, Interagency Monitoring of Protected Visual Environments monitoring data, available online: http://vista.cira.colostate.edu/improve/, 2001.

Figure 1. Annual Sulfur Dioxide Emissions



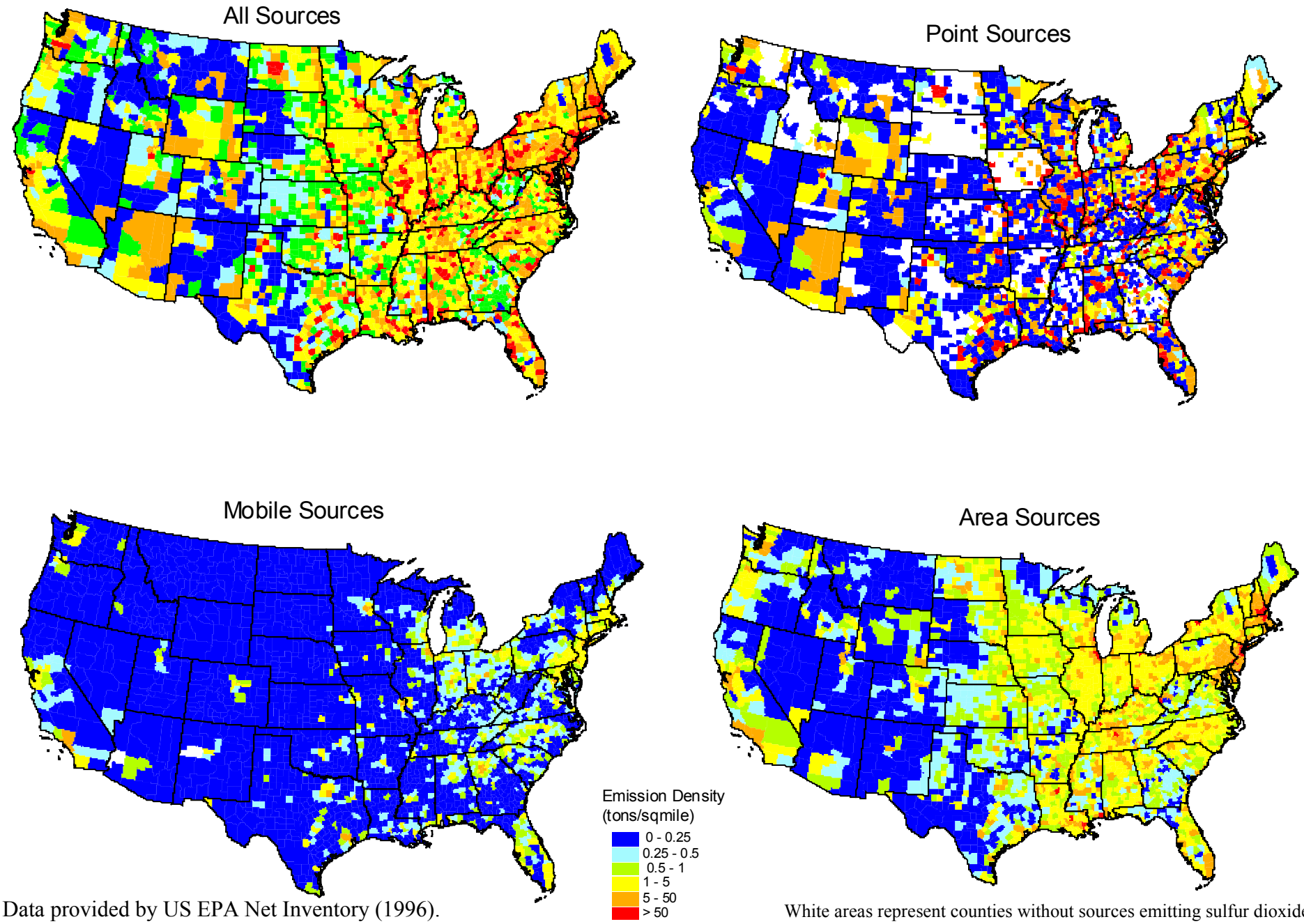
Data provided by US EPA Net Inventory (1996) and Environment Canada (1995).

Figure 2. Density Map of Sulfur Dioxide Emissions



Data provided by US EPA Net Inventory (1996) and Environment Canada (1995).

Figure 3. 1996 Sulfur Dioxide Emissions (by county)

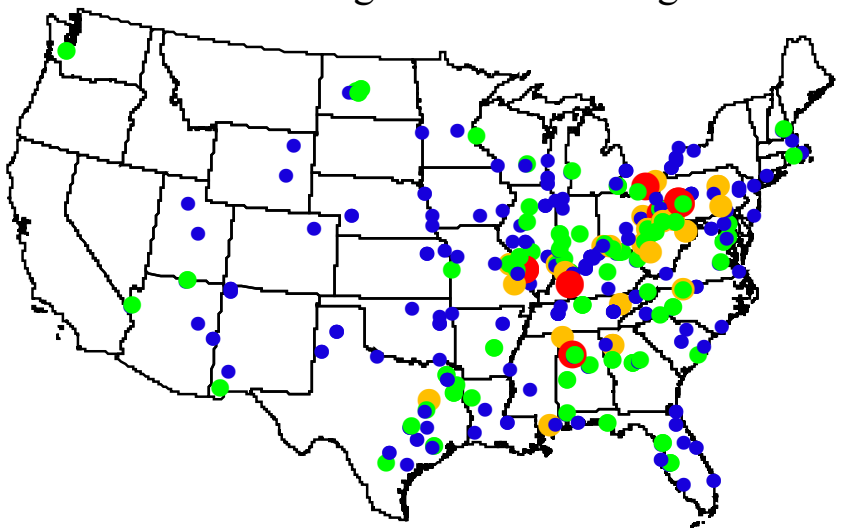


Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting sulfur dioxide.

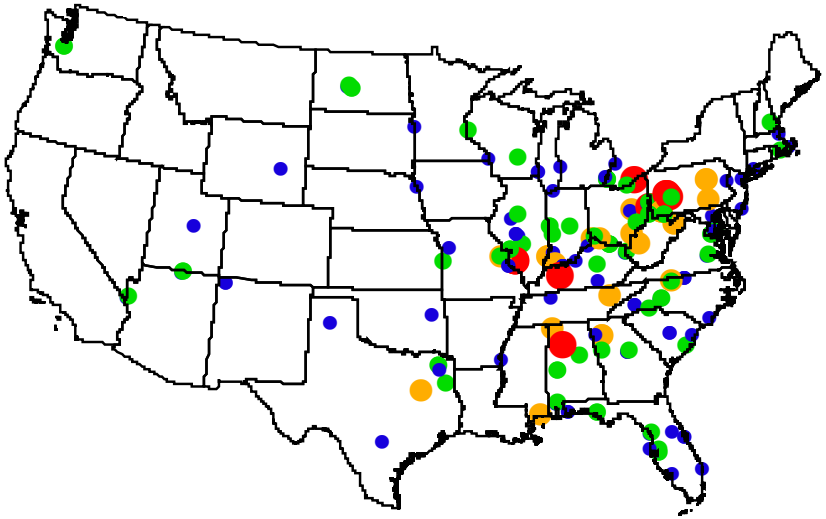
Figure 4. 1996 Sulfur Dioxide Emissions From Potential BART Eligible Point Sources With Stack Heights Over 50 Meters

Large (>10,000 tons/yr) sources from
26 BART Eligible Source Categories



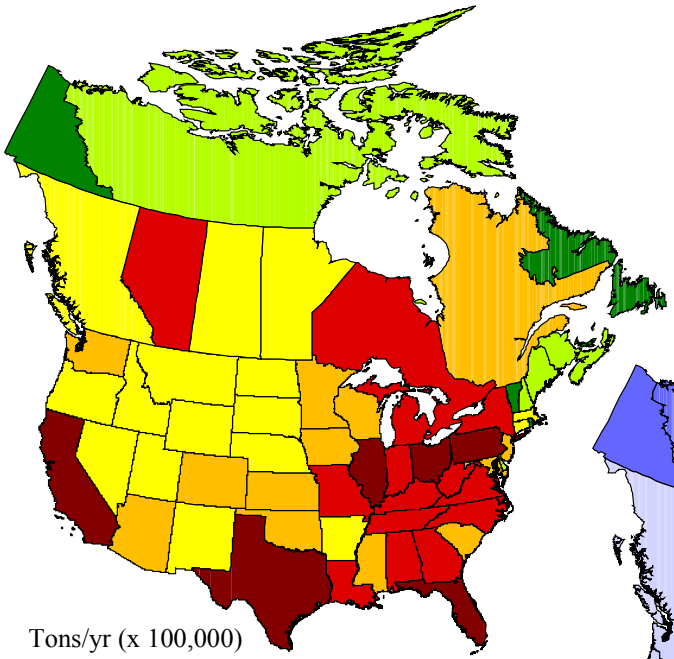
Tons
- 10,000 - 20,000
- 20,000 - 40,000
- 40,000 - 60,000
- 60,000 - 150,000

Large (>10,000 tons/yr) power plants
built between 1962 and 1977



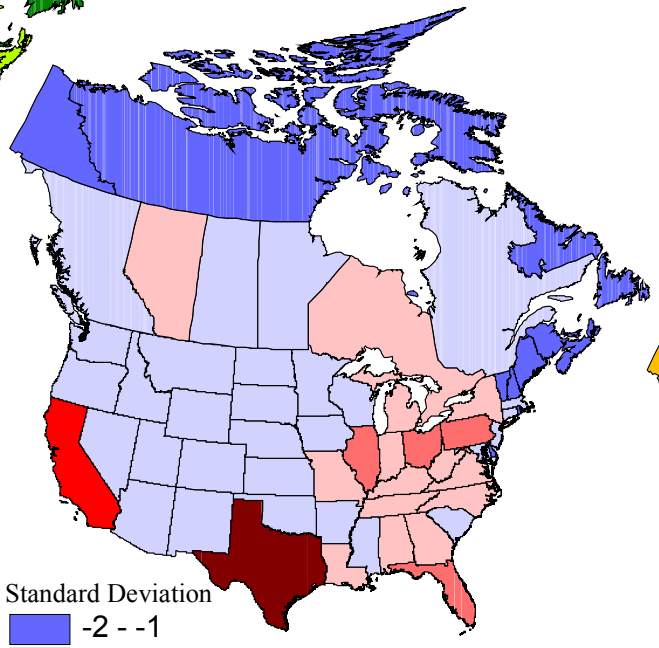
Source: 1996 Net Inventory

Figure 5. Annual Nitrogen Oxides Emissions



Tons/yr (x 100,000)

- 0 - 0.5
- 0.5 - 1
- 1 - 3
- 3 - 5
- 5-10
- 10-30

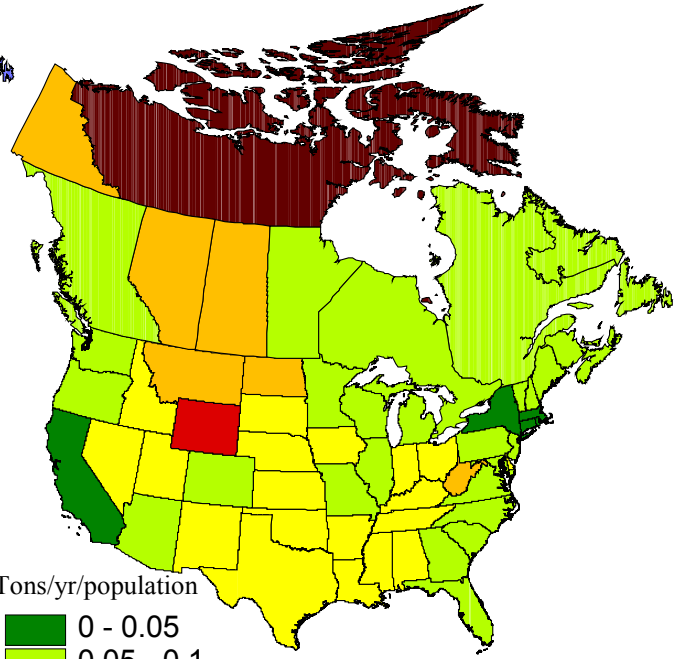


Standard Deviation

- -2 - -1
- -1 - 0
- 0 - 1
- 1 - 2
- 2 - 3
- > 3

U.S. Mean ~ 500,000 tons/yr
SD = 404,200 tons/yr

Based on US statewide average emissions

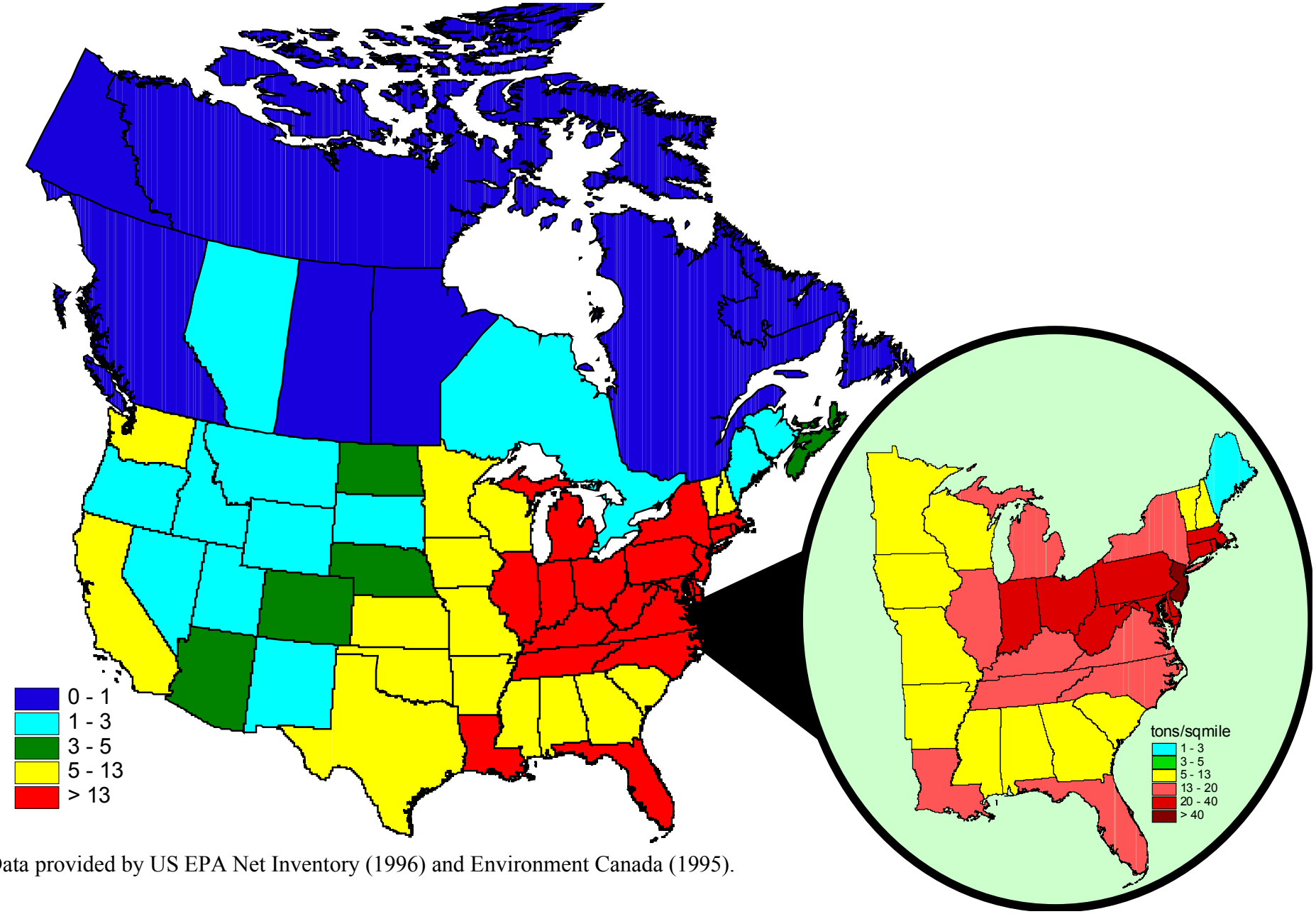


Tons/yr/population

- 0 - 0.05
- 0.05 - 0.1
- 0.1 - 0.2
- 0.2 - 0.5
- 0.5 - 1
- 1 - 2

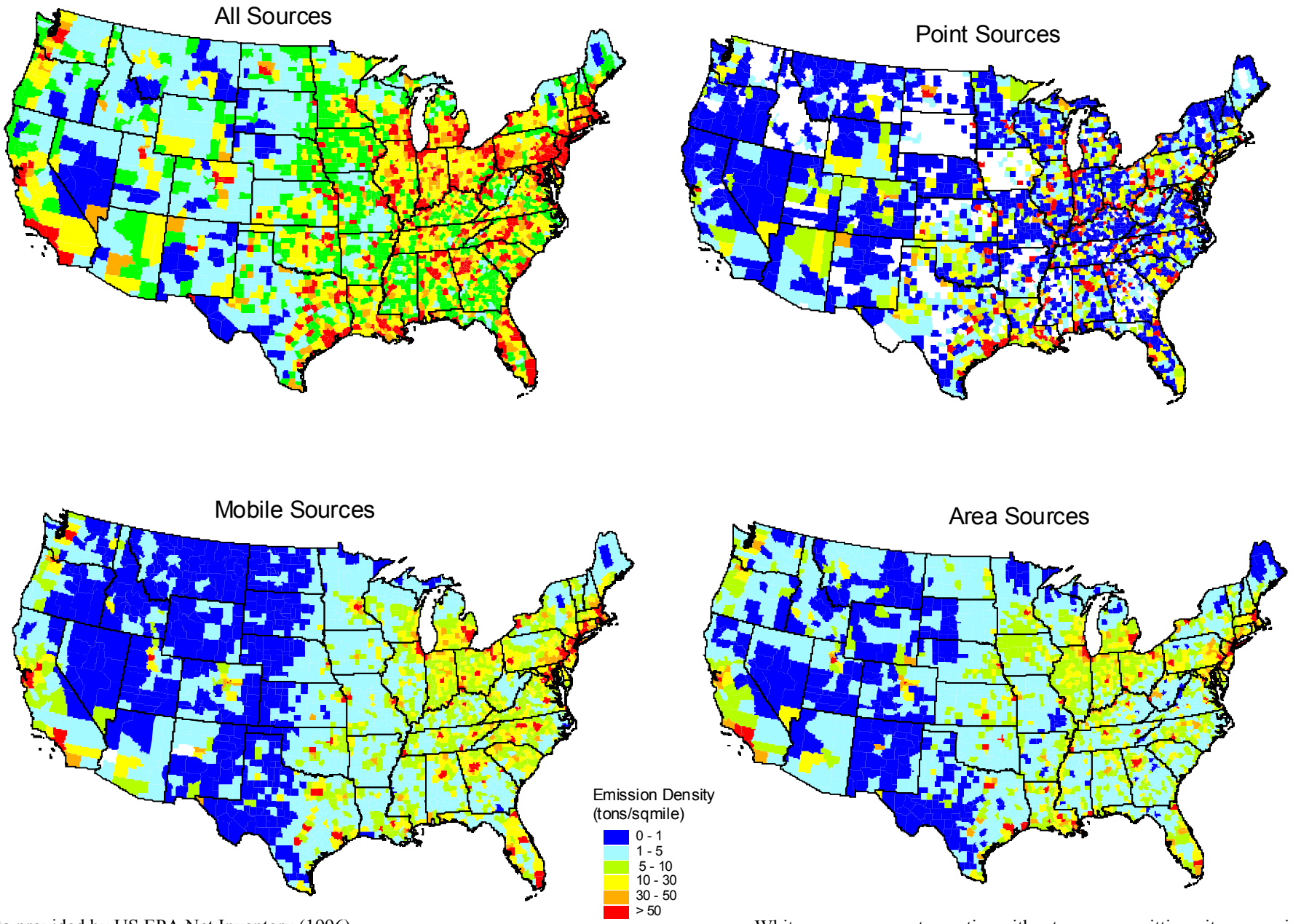
Data provided by US EPA Net Inventory (1996) and Environment Canada (1995).

Figure 6. Density Map of Nitrogen Oxides Emissions



Data provided by US EPA Net Inventory (1996) and Environment Canada (1995).

Figure 7. 1996 Nitrogen Oxides Emissions (by County)

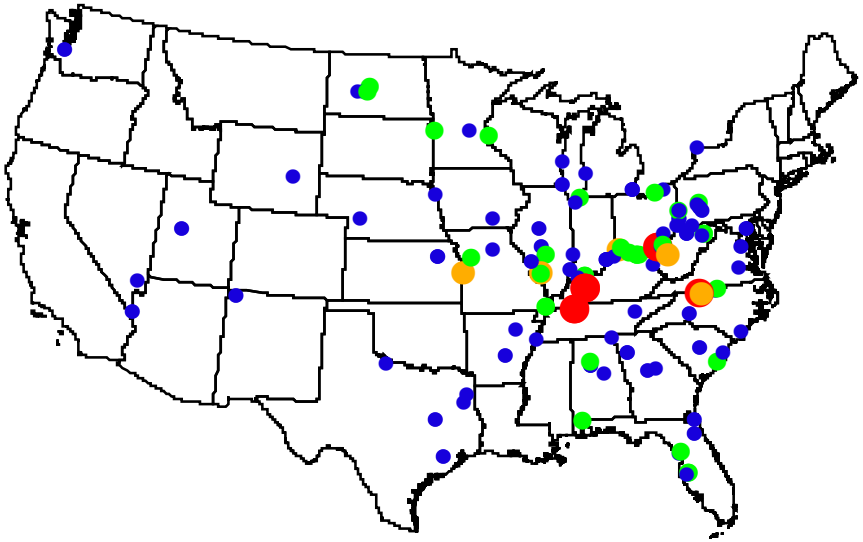


Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting nitrogen oxide.

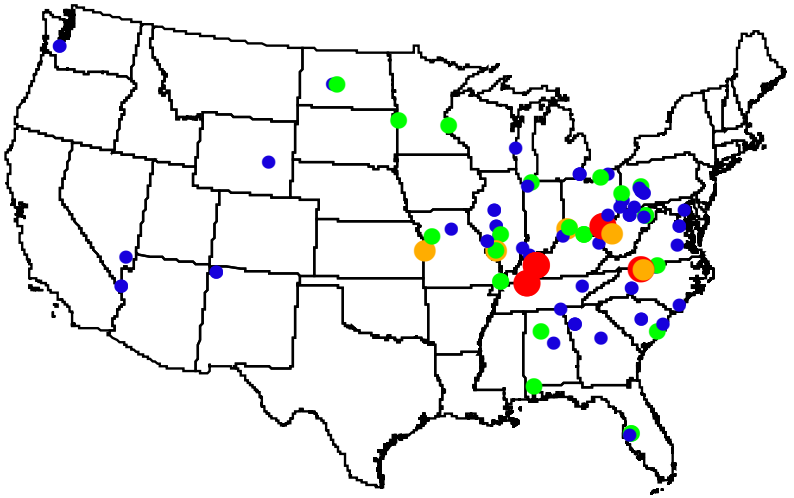
Figure 8. 1996 Nitrogen Oxide Emissions From Large Potential BART Eligible Point Sources With Stack Heights Over 50 Meters

Large (>10,000 tons/yr) sources from
26 BART Eligible Source Categories



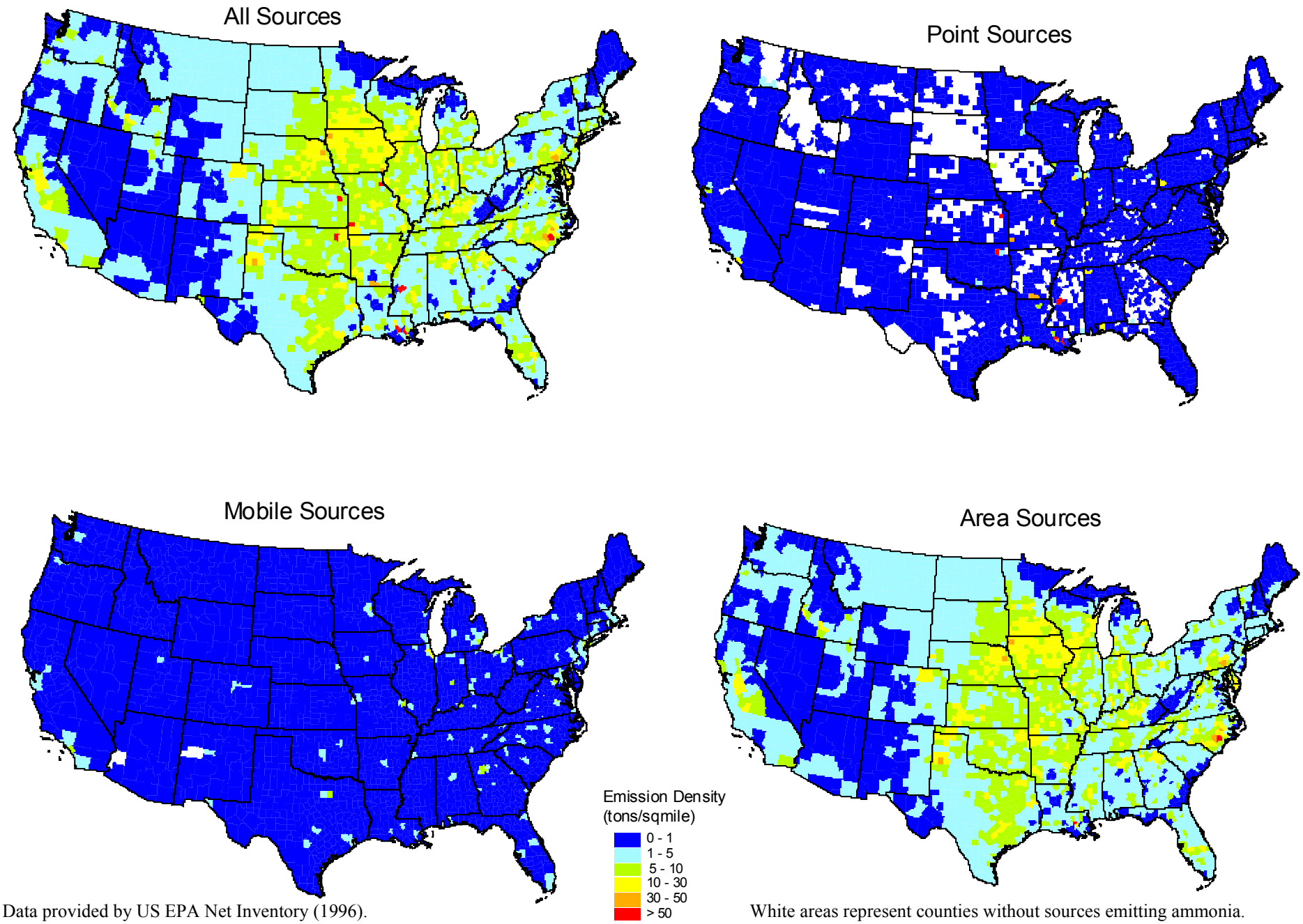
Tons
- 10,000 - 15,000
- 15,000 - 25,000
- 25,000 - 40,000
- > 40,000

Large (>10,000 tons/yr) power plants
built between 1962 and 1977



Source: 1996 Net Inventory

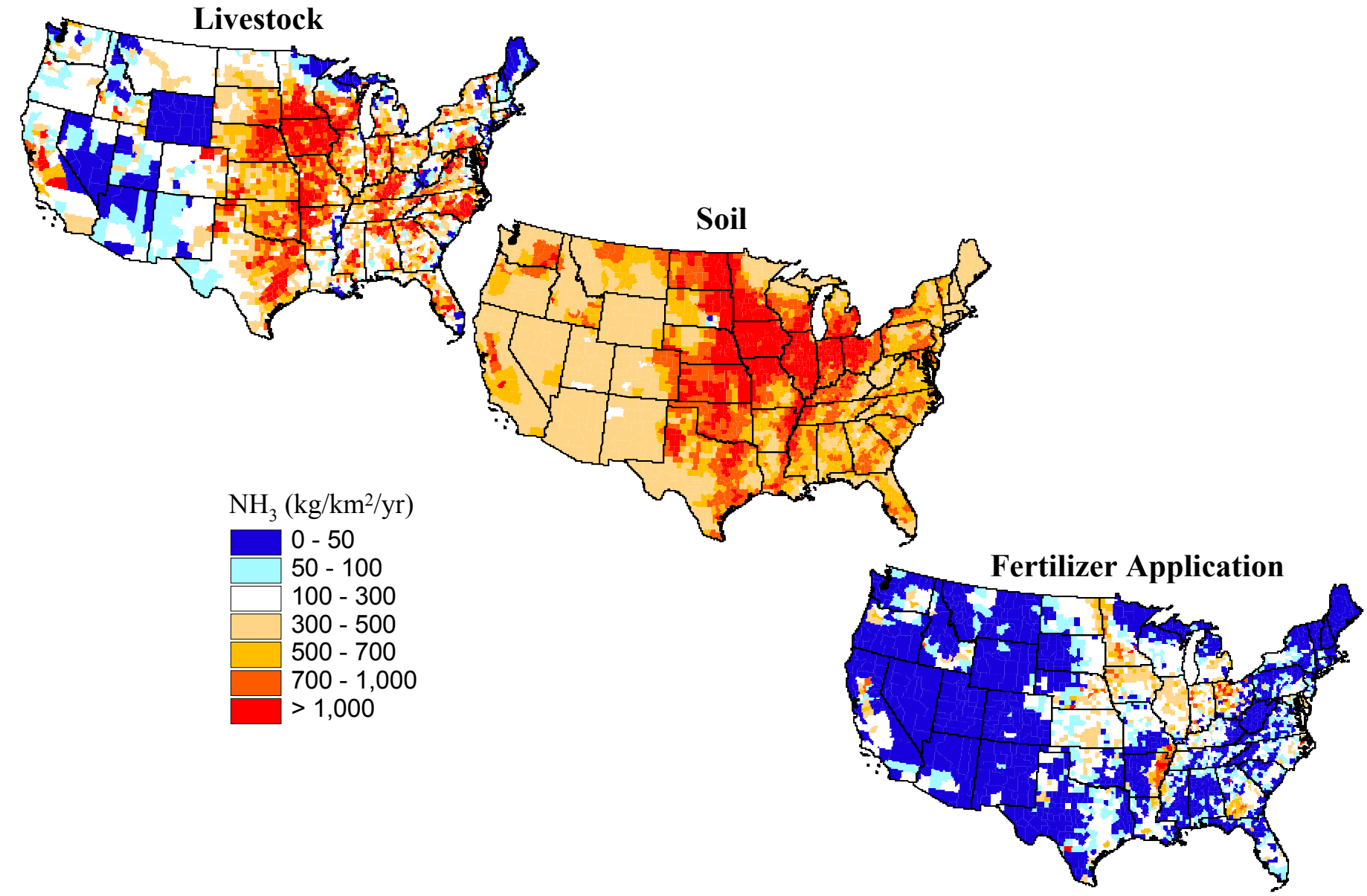
Figure 9a. 1996 Ammonia Emissions by County



Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting ammonia.

Figure 9b. 1996 Ammonia Emissions by Major Source Category



Source: CMU Inventory (Soil Emissions have large uncertainty.)

Figure 9c. Comparison of Ammonia Estimated with Net Inventory versus CMU Inventory

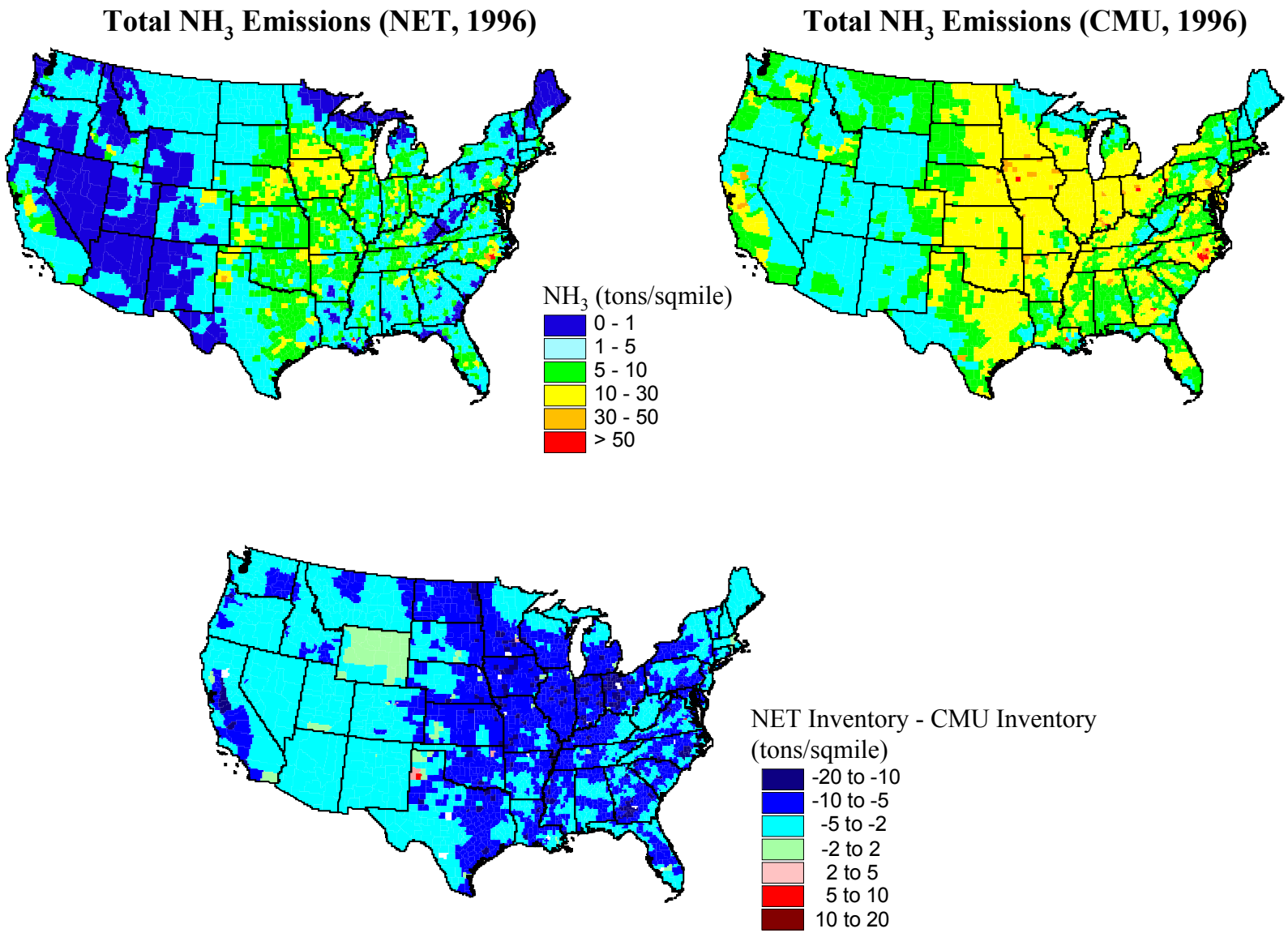
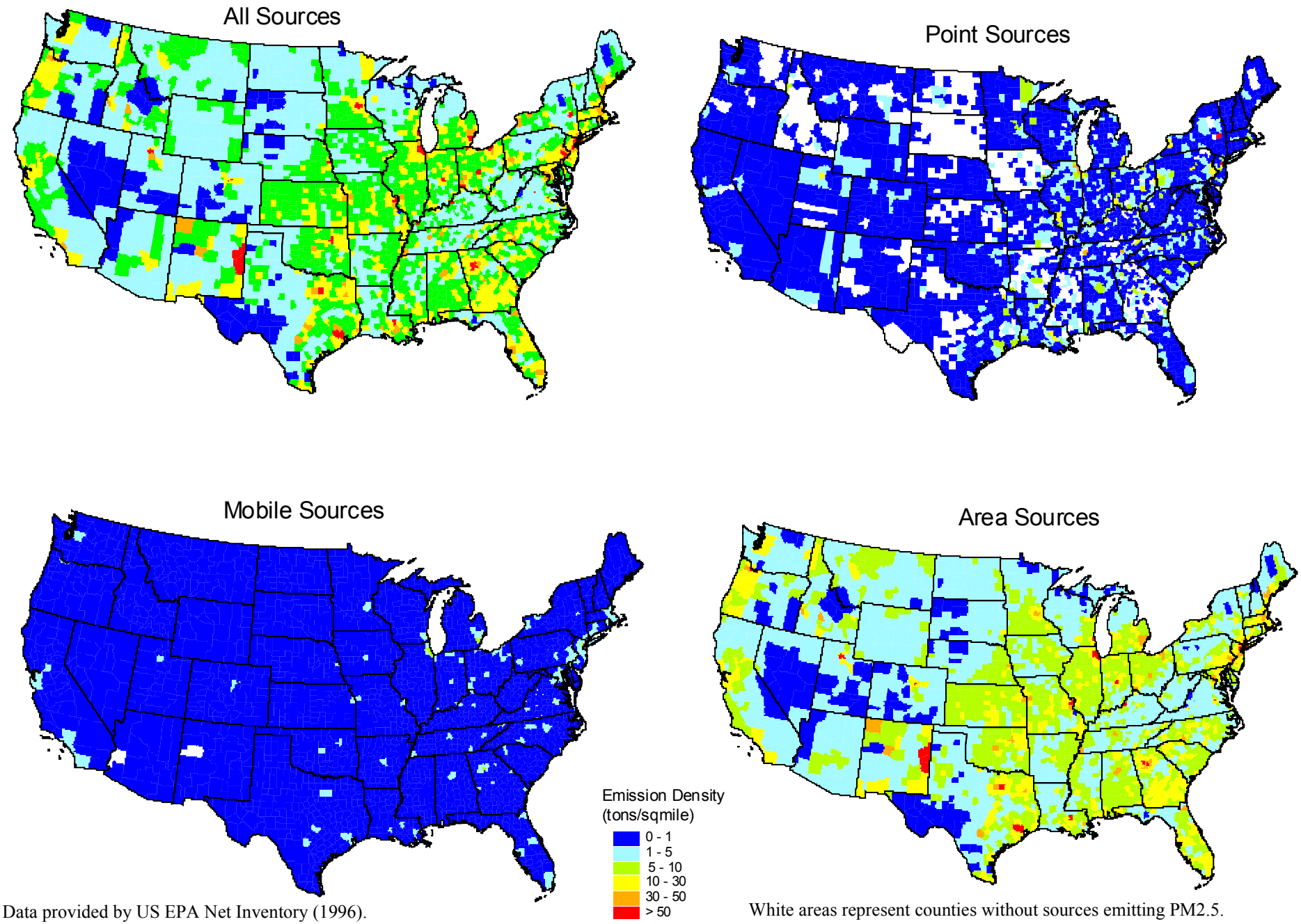


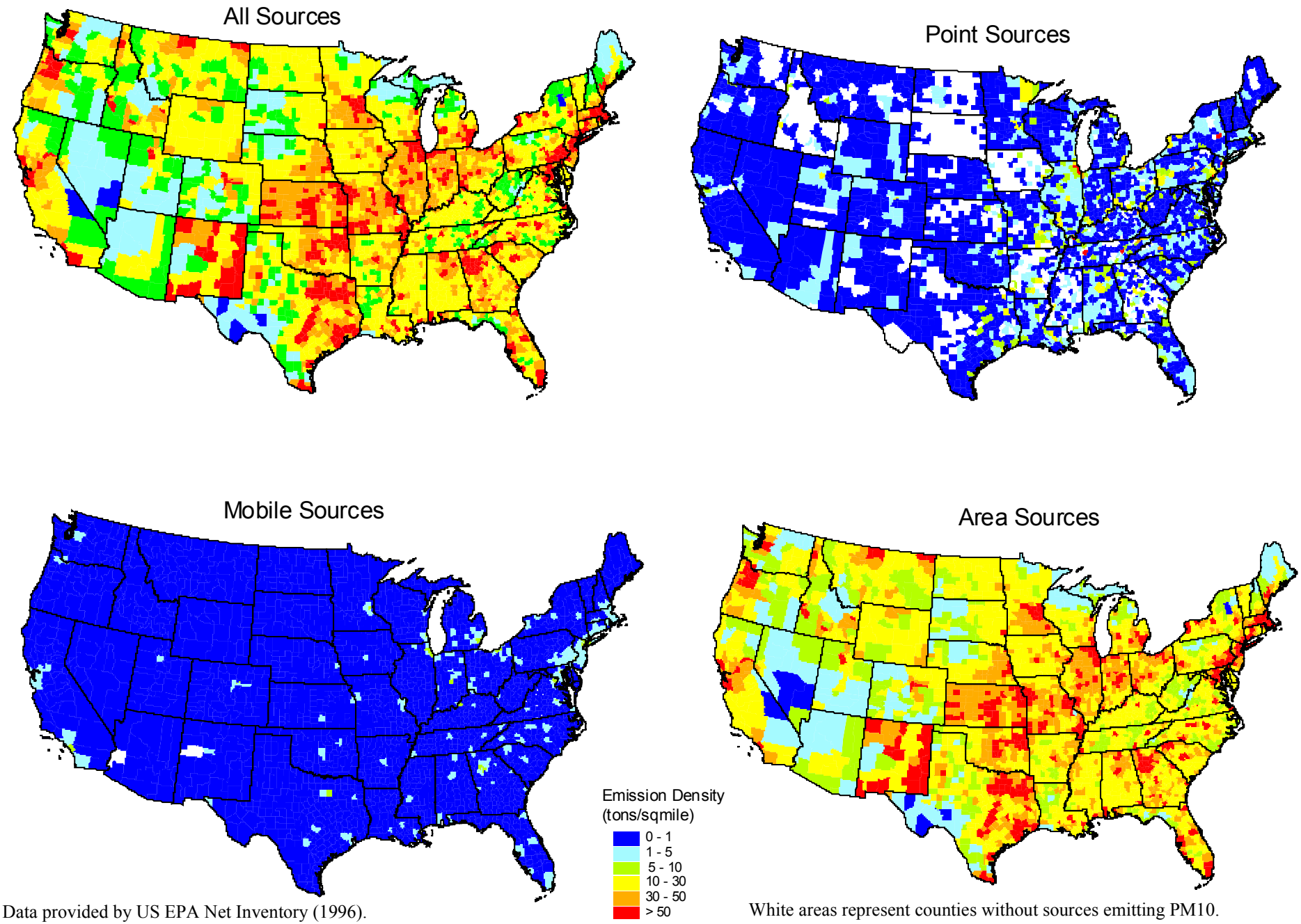
Figure 10. 1996 PM2.5 Emissions (by county)



Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting PM2.5.

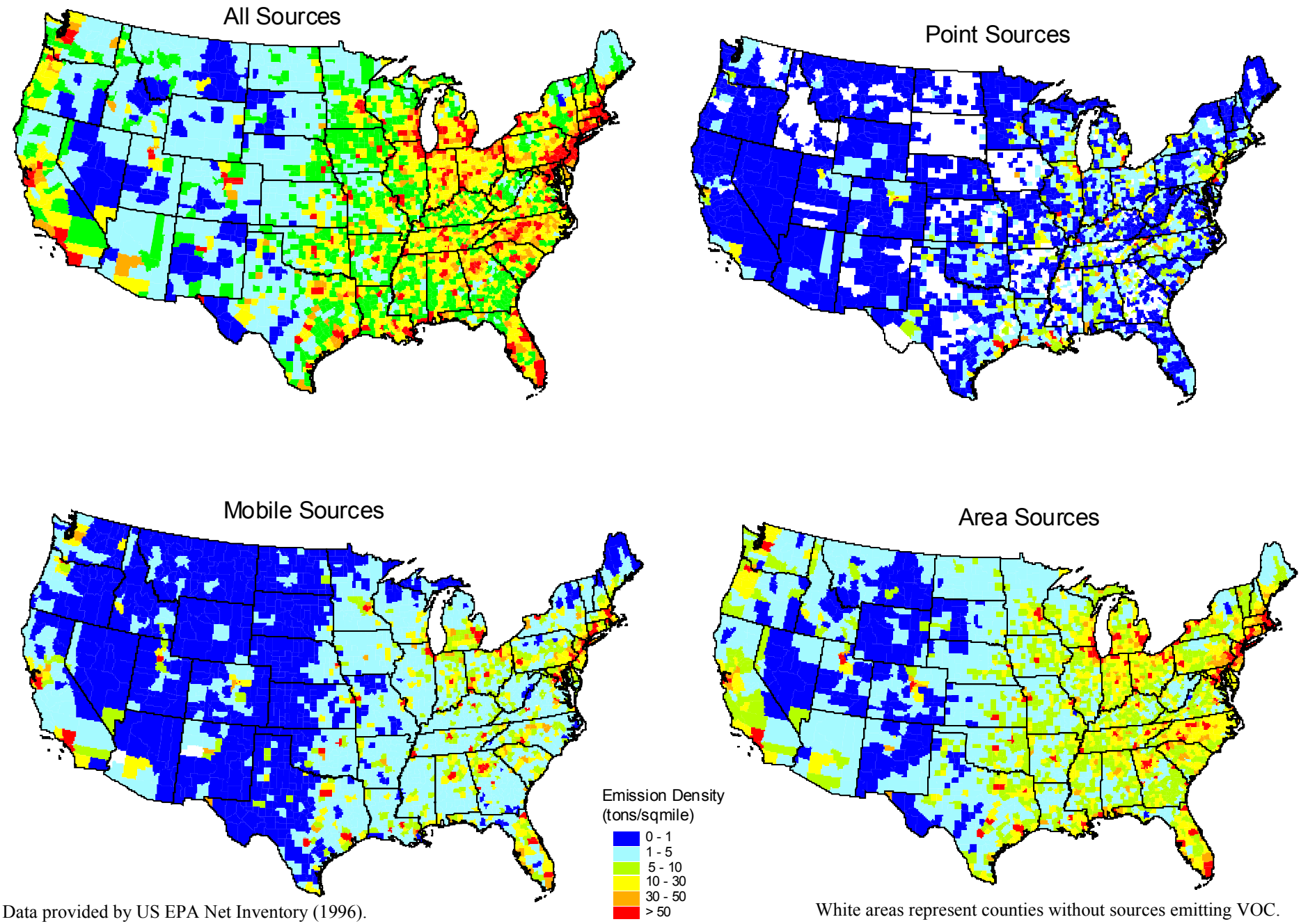
Figure 11. 1996 PM10 Emissions (by county)



Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting PM10.

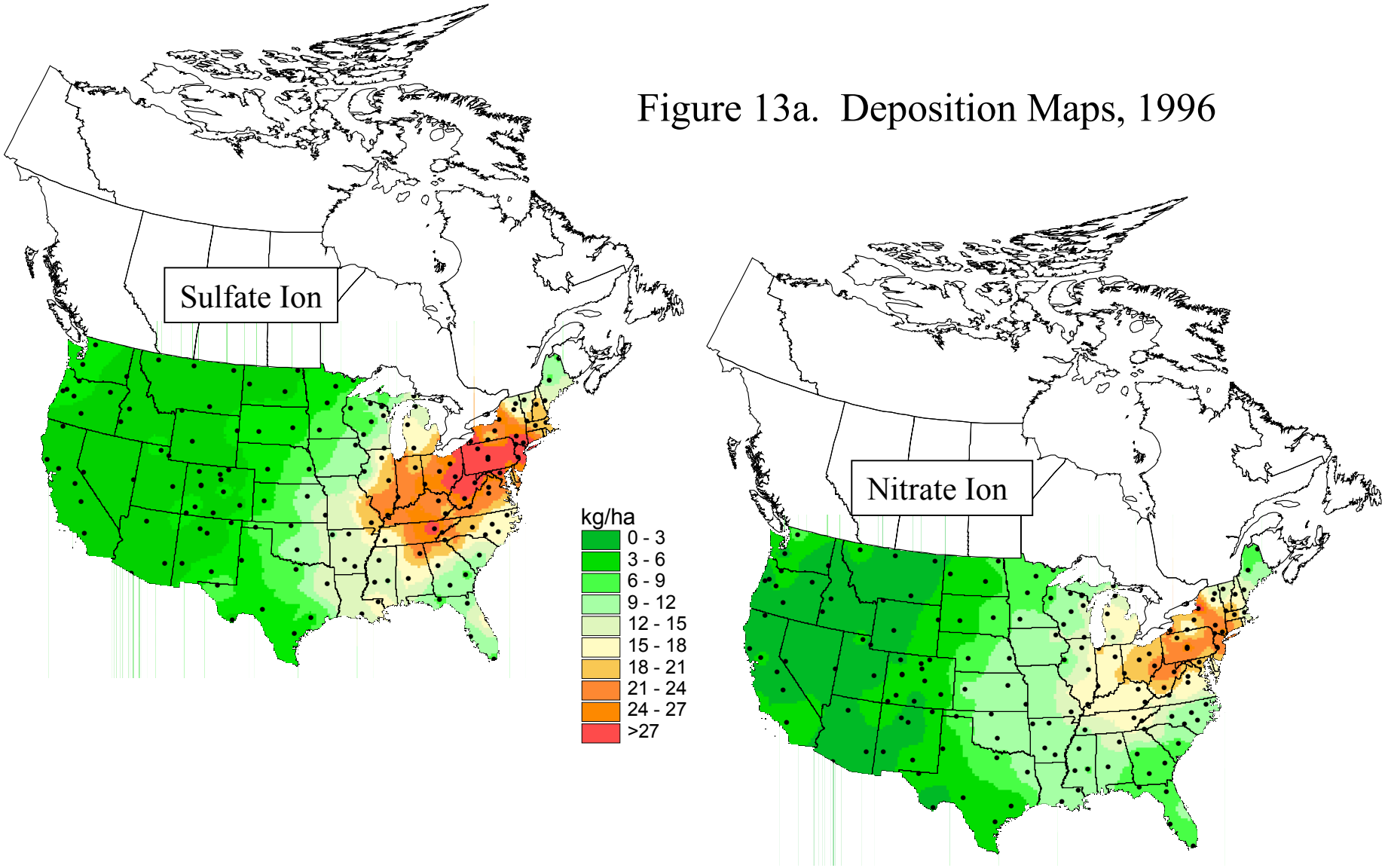
Figure 12. 1996 VOC Emissions (by county)



Data provided by US EPA Net Inventory (1996).

White areas represent counties without sources emitting VOC.

Figure 13a. Deposition Maps, 1996



Date provided by National Atmospheric Deposition Program
http://nadp.sws.uiuc.edu

Figure 13b. Deposition Maps, 1996

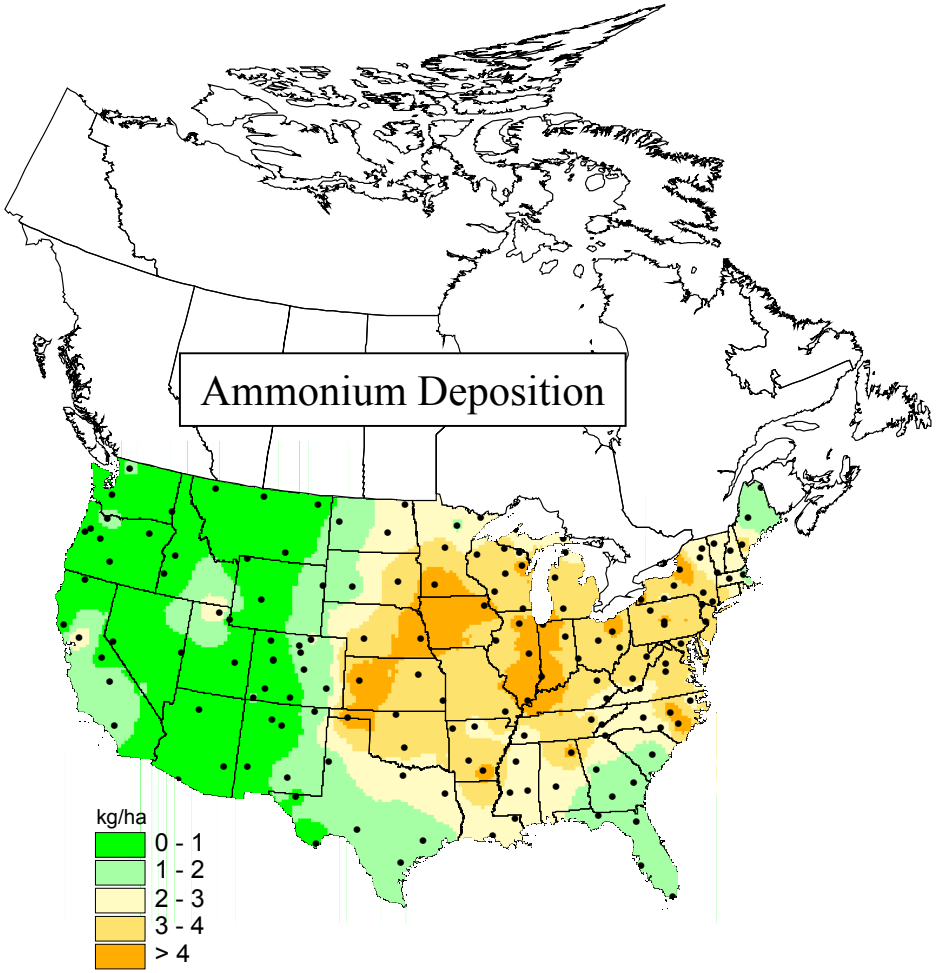
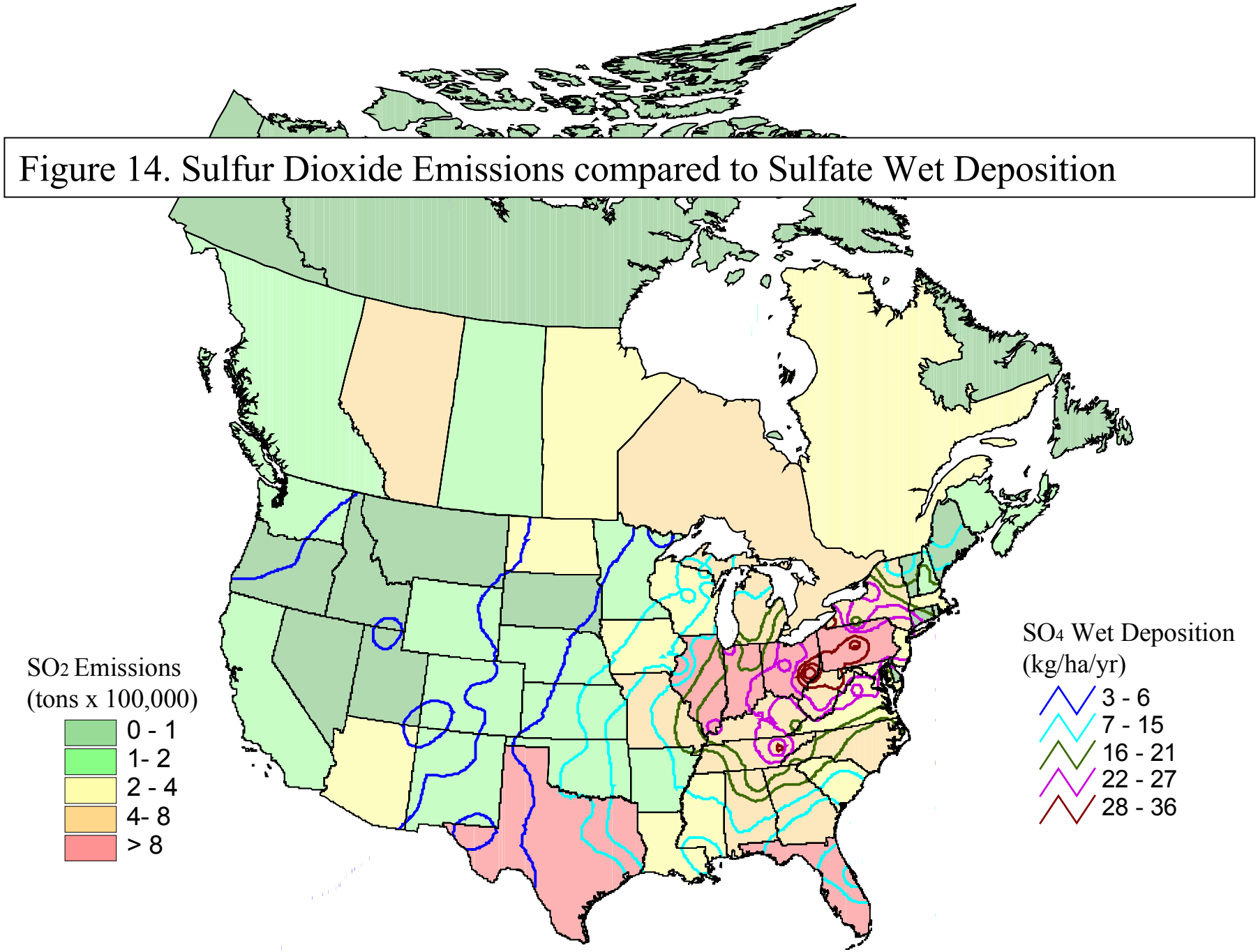


Figure 14. Sulfur Dioxide Emissions compared to Sulfate Wet Deposition



Sources: 1996 Net Inventory for the U.S. emissions, 1995 Canadian inventory, NADP

Figure 15. Location of IMPROVE Sites.

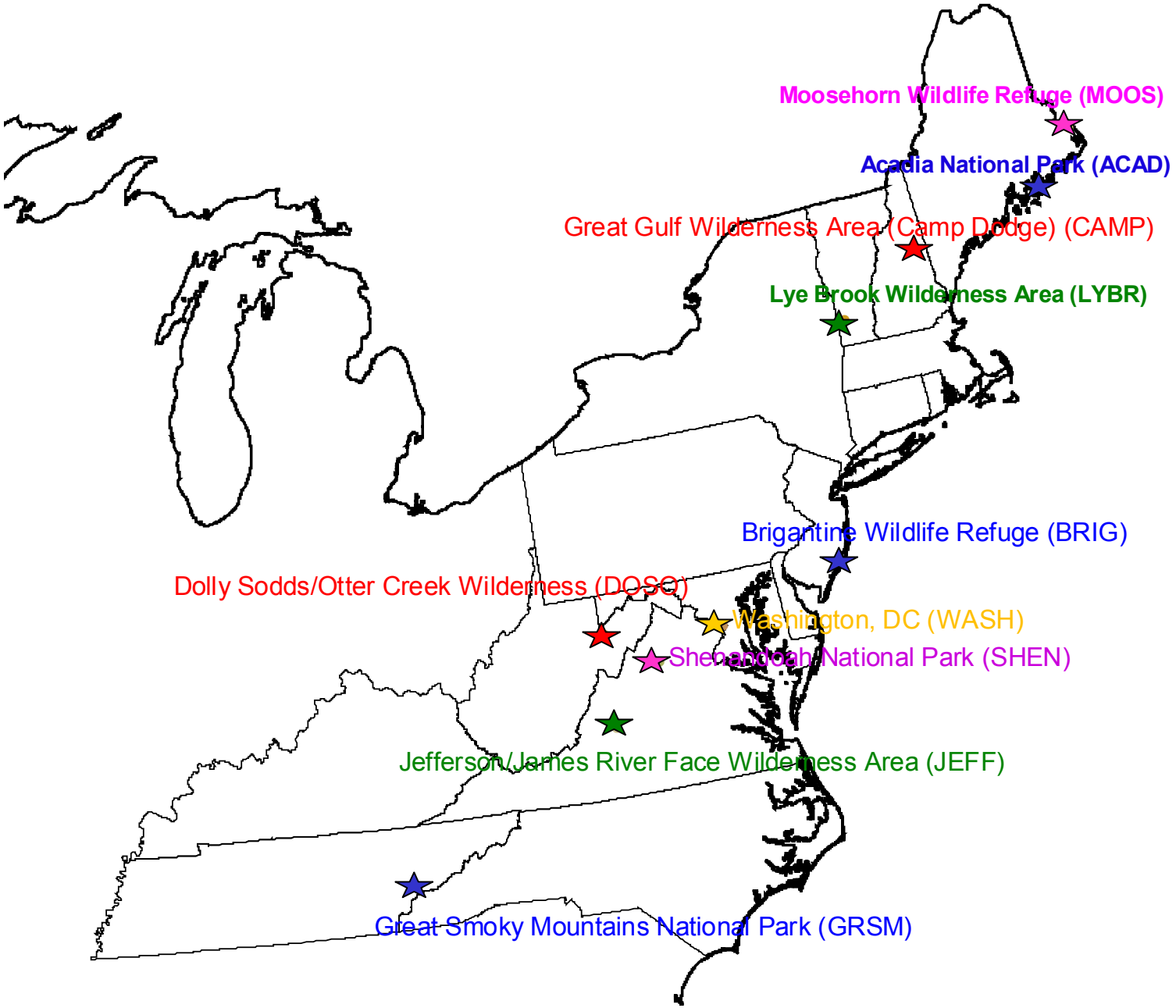
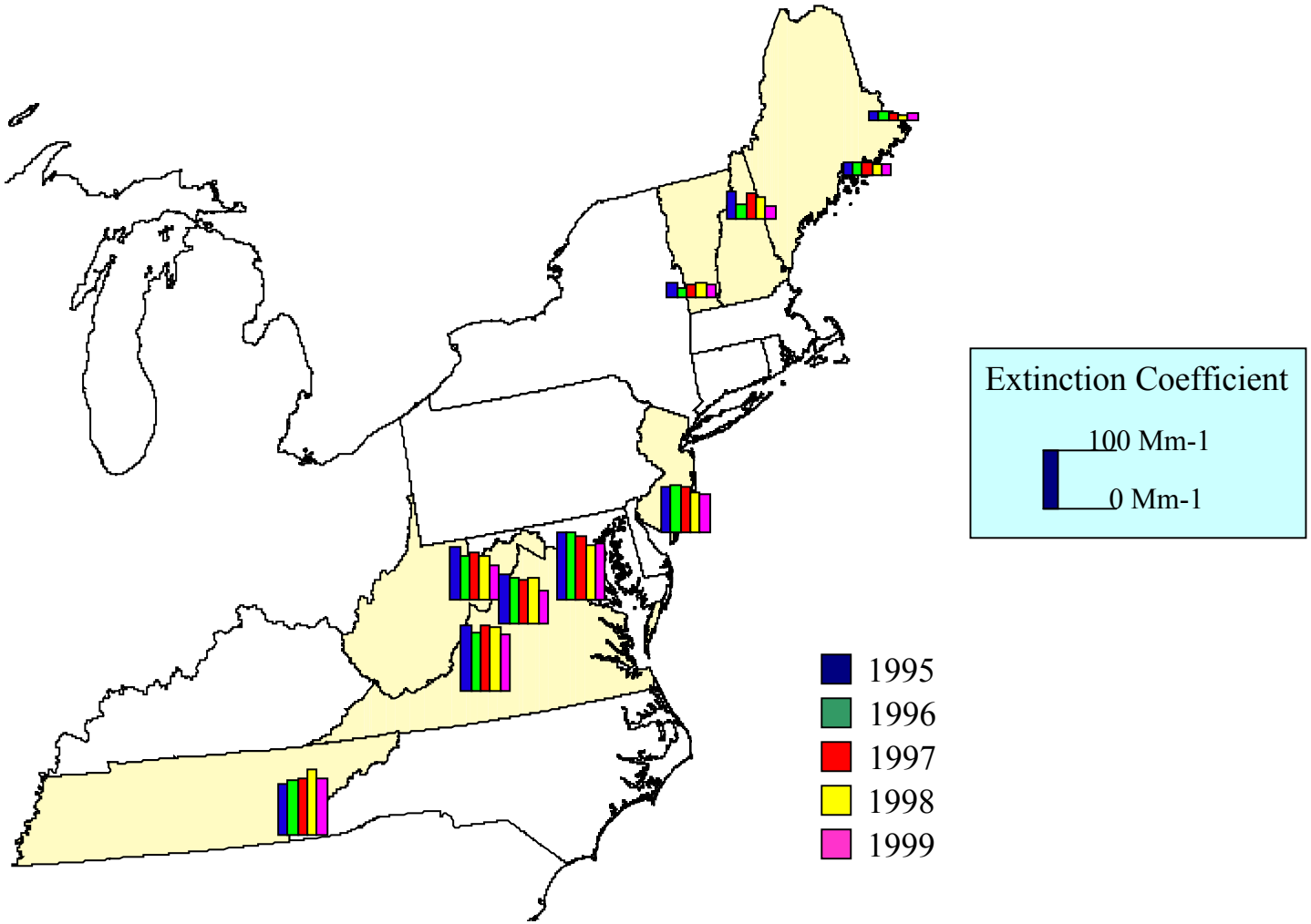
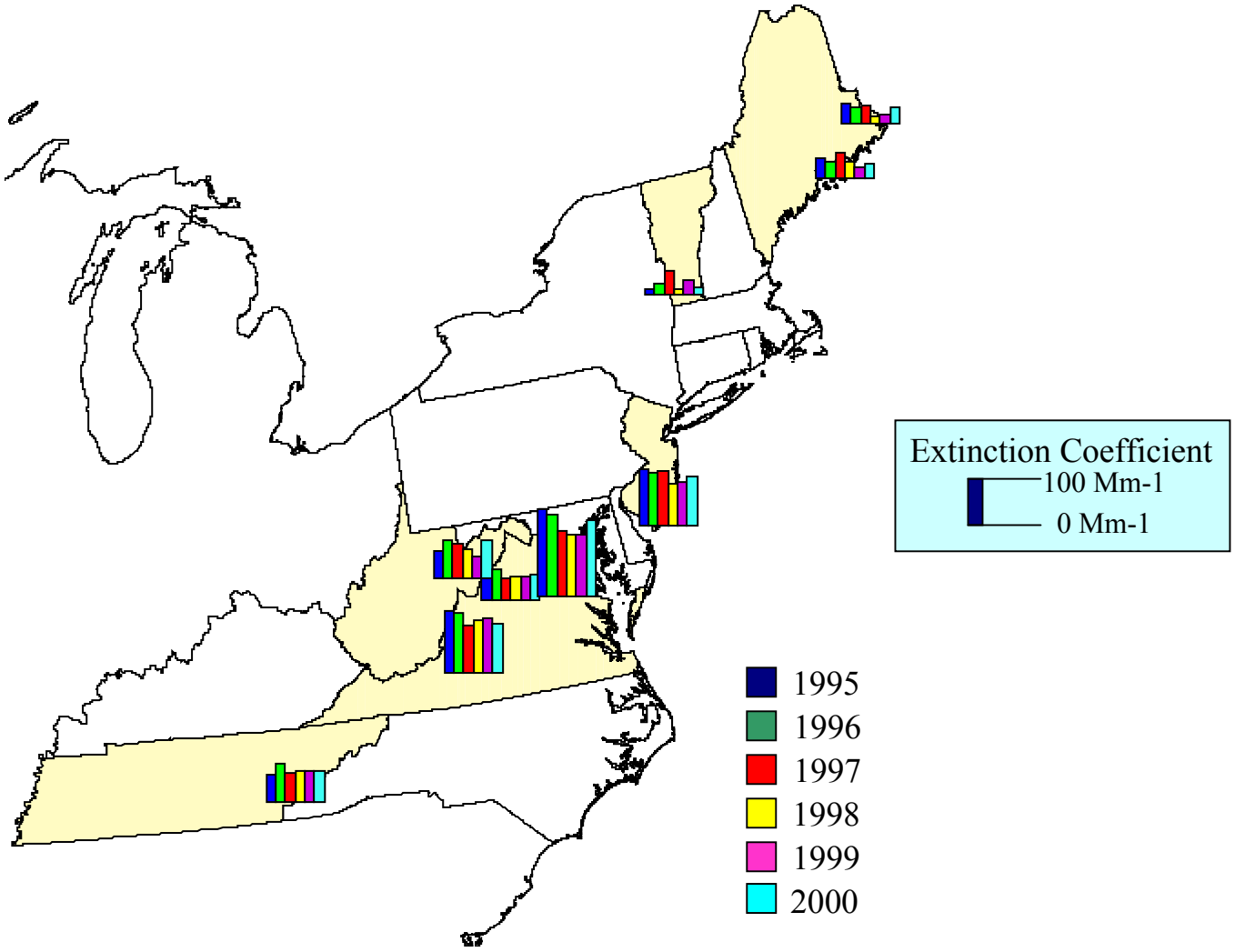


Figure 16. Annual Extinction Coefficient from 1995 to 1999 for the MANE-VU Region



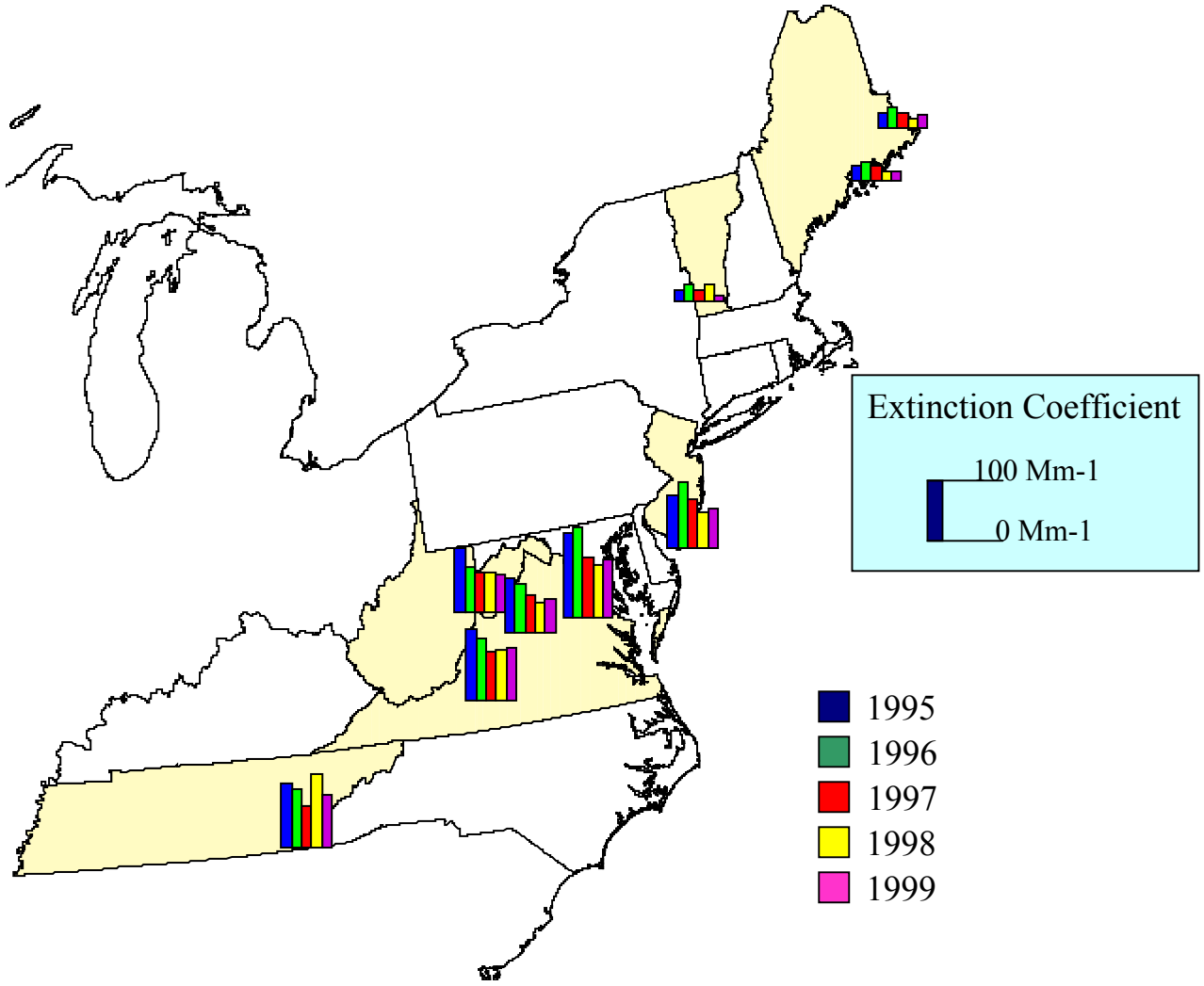
Source: IMPROVE

Figure 17. Average Extinction Coefficient in Winter from 1995 to 2000 for the MANE-VU Region



Source: IMPROVE

Figure 18. Average Extinction Coefficient in Spring from 1995 to 1999 for the MANE-VU Region



Source: IMPROVE

Figure 19. Average Extinction Coefficient in Summer from 1995 to 1999 for the MANE-VU Region

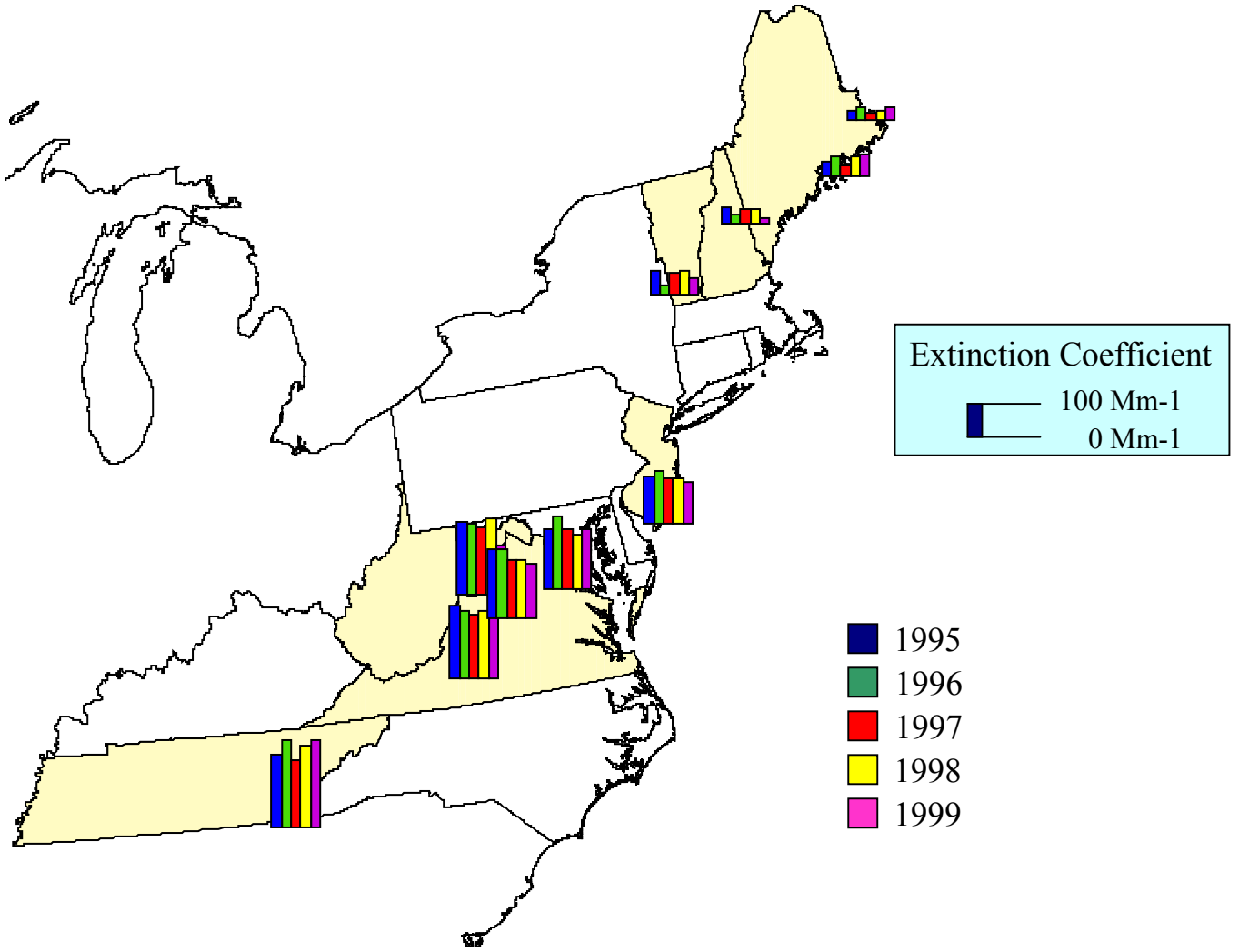


Figure 20. Average Extinction Coefficient in Fall from 1995 to 1999 for the MANE-VU Region

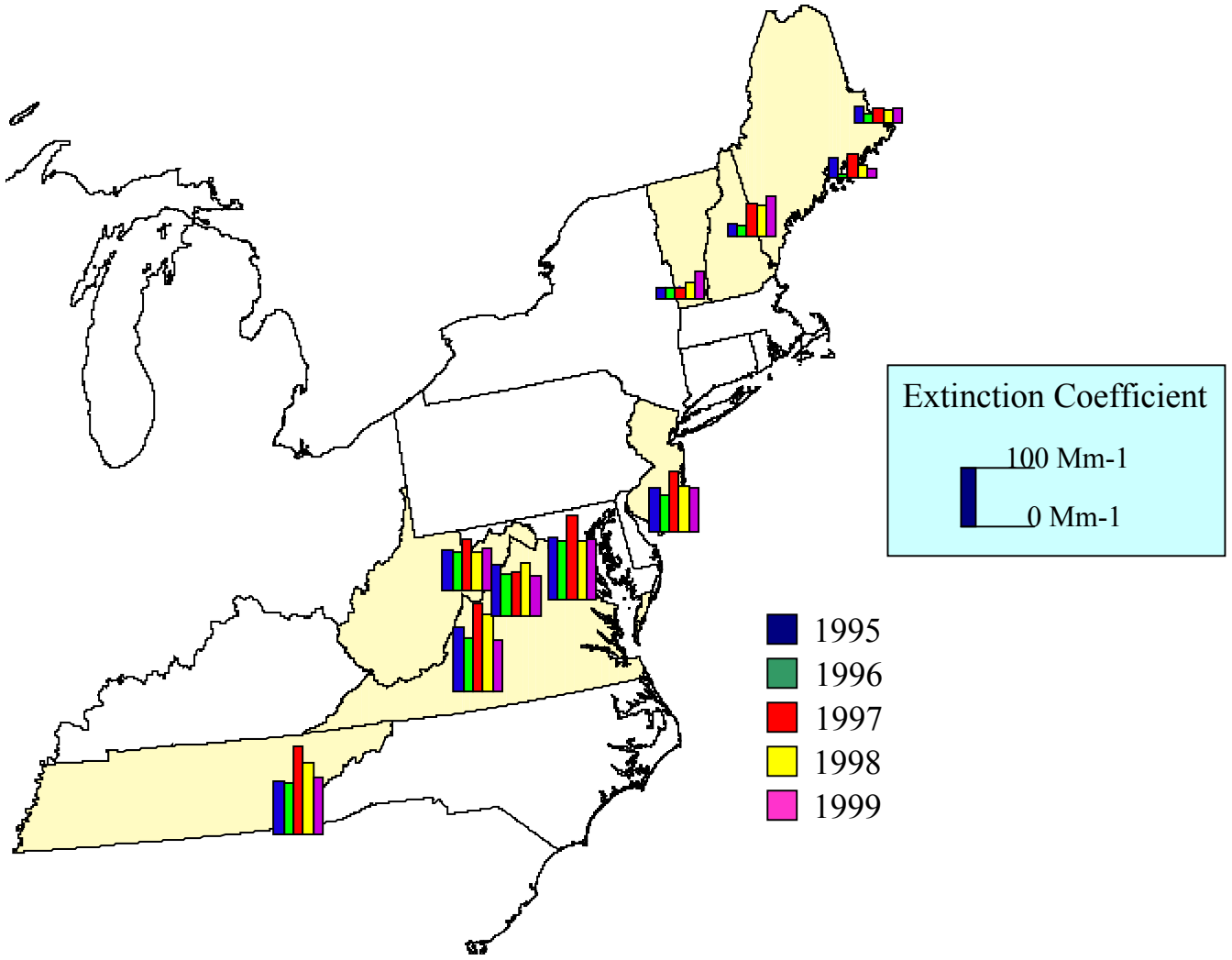
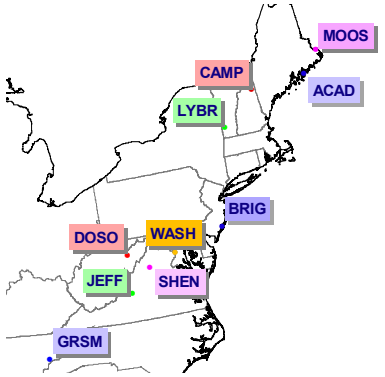
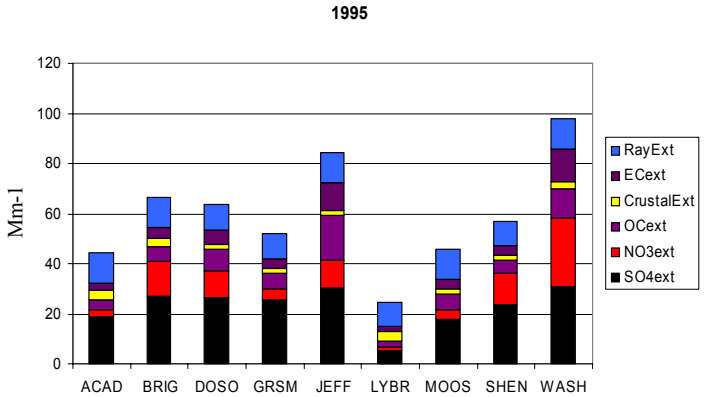
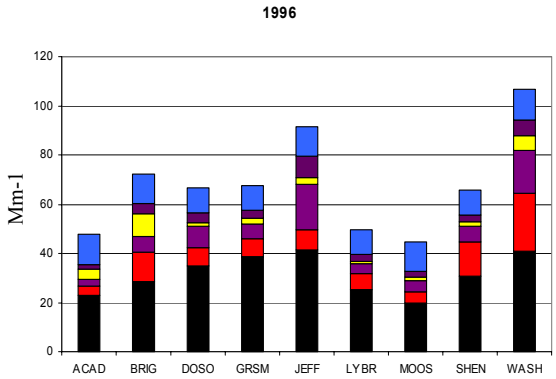
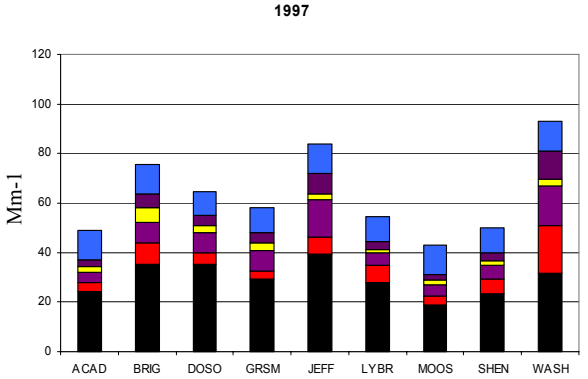


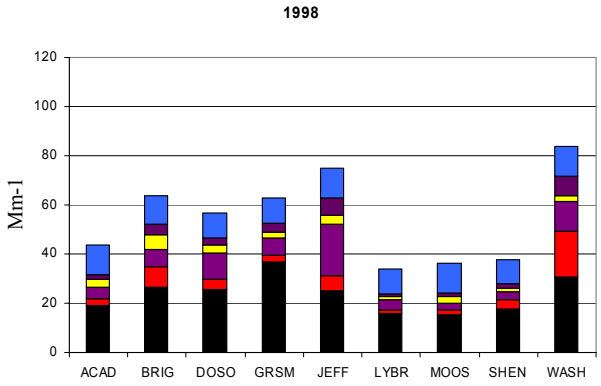
Figure 21. Total Extinction in January by Species

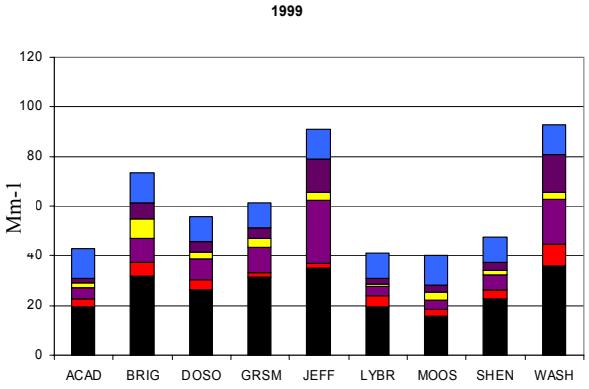


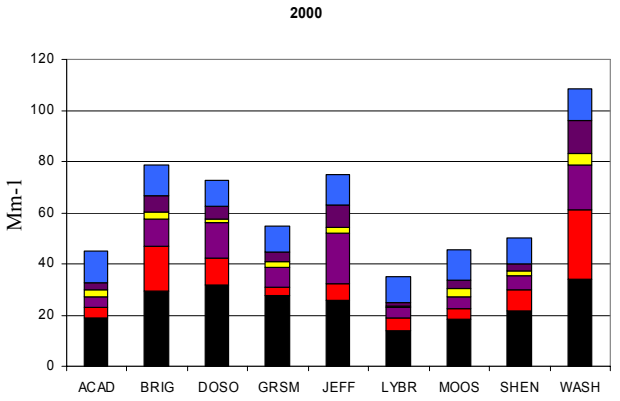






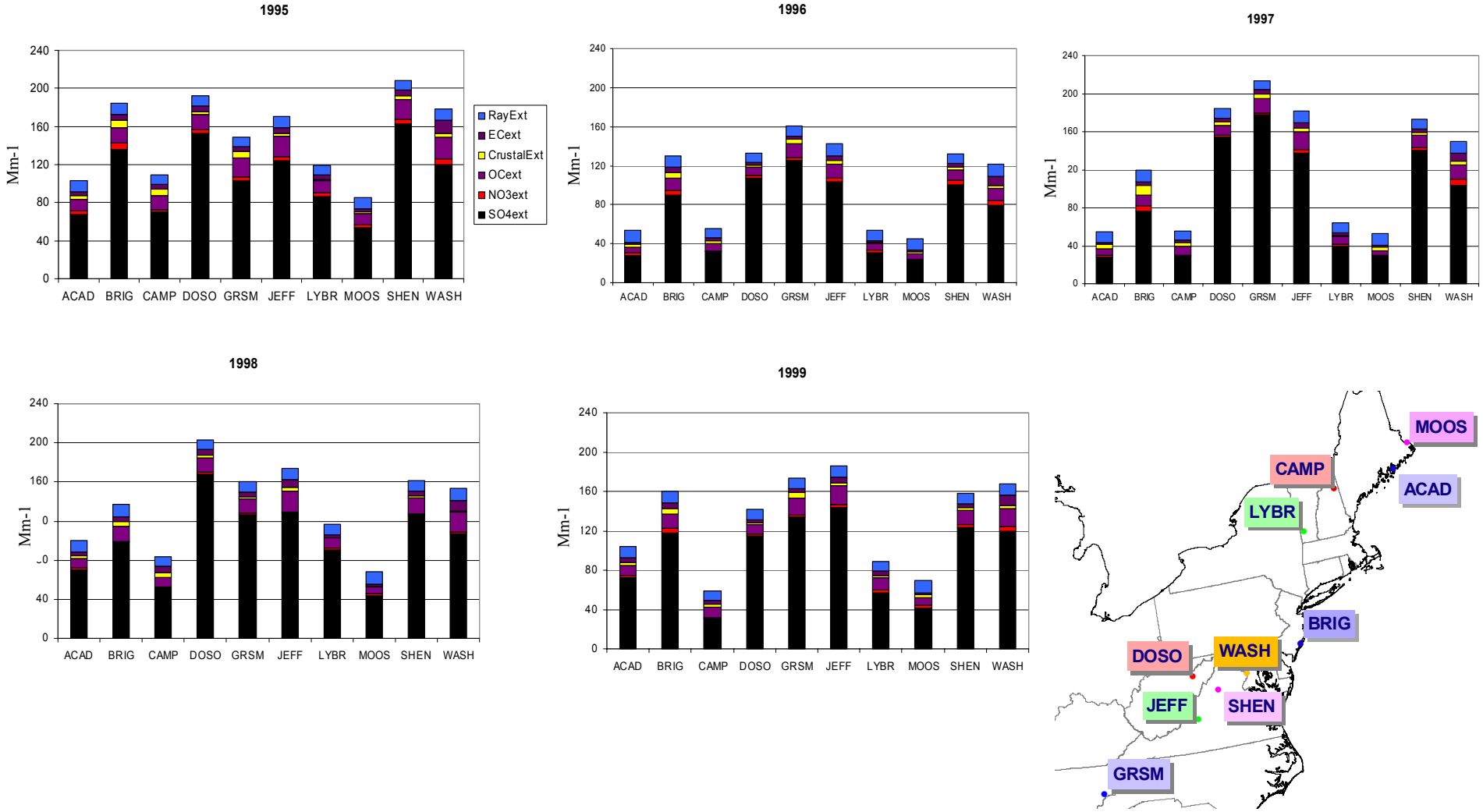






Source: IMPROVE

Figure 22. Total Extinction in July by Species



Source: IMPROVE