FINAL REPORT:
MANE-VU RESIDENTIAL WOOD COMBUSTION EMISSION INVENTORY

FINAL

Prepared for:

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I. INTRODUCTION

This report summarizes work conducted by E.H. Pechan & Associates, Inc. (Pechan) in the development of a 2002 emissions inventory for the Mid-Atlantic-Northeast Visibility Union (MANE-VU) for residential wood combustion (RWC). RWC contributes to regional haze in Class I areas in the MANE-VU region; there is also large uncertainty in the emission estimates for this source category because the emissions are calculated using a top-down methodology. The Emission Inventory Improvement Program (EIIP) suggests using a survey method for collecting activity data on RWC.

In order to improve the RWC inventory for MANE-VU, a survey was developed and implemented in the region. The survey results were converted to emissions per survey response, and were then used to develop an emissions model for the source category. This report and the supporting technical memoranda describe the survey methods, results, and analysis used in the MANE-VU region. Members of MANE-VU include: Connecticut (CT), Delaware (DE), the District of Columbia (DC), Maine (ME), Maryland (MD), Massachusetts (MA), New Hampshire (NH), New Jersey (NJ), New York (NY), Pennsylvania (PA), the Penobscot Indian Nation, Rhode Island (RI), the St. Regis Mohawk Tribe, and Vermont (VT).

For indoor wood burning equipment, the survey was designed to obtain information on equipment type. Indoor equipment includes fireplaces, woodstoves (both conventional and certified), furnace/boilers and pellet stoves. However, due to concerns regarding the loss of statistical precision in estimating equipment level emissions, estimates at the equipment level were not made. Emissions were estimated at a more general level: outdoor and indoor equipment. Outdoor equipment includes barbeques, fireplaces, fire pits, and chimineas. Outdoor wood burning equipment has never been included in the National Emissions Inventory (NEI) or other known State and local inventories. This is the first regional survey to obtain data on this source category. Also, note that the NEI estimates for indoor wood burning equipment do not include furnace/boilers or pellet stoves.

Section II of this report provides an overview of the technical memoranda developed during this project. Also, important changes that were made during the course of the project and that may not have been reflected in the technical memoranda are noted. Section III contains a summary of the results of the project and Section IV contains conclusions and recommendations.

II. PROJECT BACKGROUND

During this project, Pechan prepared six technical memoranda (TM) to document different phases of the project. The reader should consult these documents, located on the Mid-Atlantic/Northeast Visibility Union (MANE-VU) website www.mane-vu.org or on the Mid-Atlantic Regional Air Management Association's (MARAMA's) website www.marama.org for details on each component of the project. The technical memoranda and important follow-up notes are as follows:

- TM#1- *MANE-VU Residential Wood Combustion EI Project: Sample Frame Development* – this TM described the development of the sample frame to be used during the project. Note that the sample frame had incorrect values of the number of homes in the MANE-VU Region. This issue was resolved prior to data analysis and inventory development. The correct values are shown in Table 1 below. The total number of MANE-VU single-family households was 12,660,767 and the total number of multi-family units was 12,265,129;

- TM#2 - *MANE-VU Residential Wood Combustion EI Project: Format for Activity Data in the Wood Consumption Model* – This TM described the data formats for developing the wood consumption model from the survey data, including temporal profiles. Note that for indoor equipment, most of the methods were not used since equipment-specific consumption estimates were not used to develop emission estimates (instead, the general linear model presented in TM#5 was used);

- TM#3 - *MANE-VU Residential Wood Combustion EI Project: Pilot Survey and Final Survey Instrument* – This TM provided the results of the pilot survey and the final survey instrument (questionnaire) for the survey);

- TM#4 - *Results of MANE-VU Residential Wood Combustion Activity Survey* – This TM provided statistical summaries of the survey results;

- TM#5 - *MANE-VU Residential Wood Combustion Survey Data Analysis and Emission Inventory Inputs* – this TM provided a description of the methods used to analyze the survey data, the development of activity variables to estimate emissions from indoor and outdoor equipment, and the emission factors to be applied. It was during the review of this TM that a different method was developed to estimate emissions for indoor equipment based on emission estimates constructed from each survey response (instead of estimating equipment level activity, which was originally envisioned for this project). This new method avoided the lowering of statistical precision (error) in the extrapolation of survey data, since individual responses were not divided into multiple equipment types. A description of the development of the general linear model for estimating emissions from indoor equipment was incorporated into the final TM. Outdoor equipment emissions were estimated using a user fraction (UF) and annual consumption (AC) estimate developed from the survey data; and

- TM#6 - *MANE-VU Residential Wood Combustion Emission Inventory* – this TM provided the results of the emission inventory constructed from the number of households in the 2000 Census (no adjustments to reflect 2002 housing changes were

made) and the activity variables and emission factors documented in TM#5. During a review of the draft TM#6, reviewers questioned the wood density value used by Pechan to construct the activity variables in TM#5 (2.1 tons/cord; based on the high end of the range reported for oak species). Pechan reviewed the primary types of wood reported by the survey respondents. Oak/hickory was the most popular choice provided in the survey and very little softwood (e.g., pine, hemlock) was reported. The next most popular choice was "other hardwood". Pechan developed a weighted estimate of wood density from the survey responses of 1.8 tons/cord that was used to scale the emission estimates by a factor of 0.86 (1.8/2.1). The scaled emission estimates were not reflected in TM#6, but are presented in Tables 2 and 3 below.

Also, during final quality assurance of the inventory following delivery of TM#6, Pechan discovered an error in the way in which the number of single-family homes had been computed from the 2000 Census. This error was fixed and the revised emission estimates are reflected in Tables 2 and 3 below.

Table 1. Sample Frame Used for This Study

Geographic Zone	Urban		Suburban		Rural-Forested		Rural Non-Forested	
	Single-Family	Other	Single-Family	Other	Single-Family	Other	Single-Family	Other
High HDD (≥7,000)	1,178,820	1,204,400	1,180,227	712,126	1,731,503	551,816	148,831	39,644
Medium HDD (5,500 – 6,500)	2,182,715	2,352,660	1,164,057	403,774	570,276	136,037	102,585	23,948
Low HDD (≤5000)	3,164,407	6,354,442	767,322	380,050	230,929	47,609	239,095	58,623

III. RESULTS

Tables 2 and 3 provide state-level emission summaries of RWC criteria pollutant emissions for indoor and outdoor equipment, respectively. The DC Department of Health does not believe that outdoor RWC activity occurs within DC due to an outdoor wood burning ban.

Tables 4 and 5 provide state-level emission summaries for several selected TAPs for indoor and outdoor equipment, respectively. These TAP species were not selected based on any specific criteria (e.g. toxicity). The selected TAPs simply represent a cross-section of the types of species estimated during this project (also note that emission estimates for several metals were made; see TM#5 for information on all of the TAPs for which emissions estimates were made). Figures 1 through 5 are $PM_{2.5}$ emissions density plots of the indoor equipment emissions for the MANE-VU States. Figure 6 shows a similar emissions density plot for the entire MANE-VU region.

Temporal allocation profiles were also developed for this project using the residential wood survey data. Profiles were first developed for each sample group. Activity (for outdoor equipment) or emissions (for indoor equipment) for each respondent was divided among the different temporal units (e.g., diurnal, weekly, monthly), based on their response to the temporal survey questions. For example, if a respondent reported only burning wood on weekdays, the activity value divided by 5 was assigned to each weekday, with zero activity assigned to Saturday and Sunday. For the diurnal profiles, the survey data indicated whether respondents burned wood in the morning, evening, or both. Since it is unlikely that emissions take place only in the morning and evening hours, activity was allocated to the entire 24-hour period by assigning 75% of morning activity to the hours of 6 a.m. to 12 p.m. and 25% of the morning activity to the hours 12 midnight to 6 p.m. The hours of 6 p.m. to 12 noon were assigned 75% of the evening activity; and 25% of the evening activity went to the hours 12 midnight to 6 a.m.

Once a fraction of the total activity was assigned to each temporal unit for each survey response, the temporal unit activity was summed across all respondents in that sample group. (i.e., survey frame cell; sample groups used for the temporal profiles are the same as those use to develop model parameters.) The resulting activity values were used to calculate activity fractions (i.e., activity for Monday was divided by the sum of activity for Monday through Sunday). The resulting profiles were then assigned to each census tract based on the sample group (survey frame cell).

To produce county-level temporal profiles, the same process used to go from response level profiles to group-level profiles was used to go from group profiles to county profiles. Activity or emissions for each census tract were assigned to each temporal unit based on the tract level temporal profiles. These values were then summed across all tracts in the county and normalized to give activity fractions.

Table 2. 2002 RWC Criteria Pollutant Emissions from Indoor Equipment (tons/yr)

State	Criteria Air Pollutant						
	CO	VOC	PM_{10}	$PM_{2.5}$	NO_X	NH_3	SO_2
Connecticut	61,903	38,031	8,062	8,062	787	446	115
Delaware	8,290	5,210	1,116	1,116	112	60	15
District of Columbia	1,655	1,211	223	223	27	12	3
Maine	97,150	57,547	12,227	12,227	1,239	702	180
Maryland	56,108	34,841	7,500	7,500	699	405	99
Massachusetts	98,316	60,645	12,847	12,847	1,269	709	184
New Hampshire	61,754	36,875	7,751	7,751	795	446	116
New Jersey	67,230	43,570	8,931	8,931	870	484	121
New York	313,978	190,091	40,043	40,043	4,125	2,266	585
Pennsylvania	302,786	183,173	39,169	39,169	3,826	2,185	556
Rhode Island	15,606	9,814	2,053	2,053	200	113	29
Vermont	46,062	27,904	5,771	5,771	591	332	85
Totals	**1,130,838**	**688,912**	**145,693**	**145,693**	**14,539**	**8,160**	**2,088**

Table 3. 2002 RWC Criteria Pollutant Emissions from Outdoor Equipment (tons/yr)

State	Criteria Air Pollutant						
	CO	VOC	PM_{10}	$PM_{2.5}$	NO_X	SO_2	NH_3
Connecticut	3,349	3,037	459	459	34	5	24
Delaware	818	742	112	112	8	1	6
District of Columbia[a]	536	486	73	73	6	1	4
Maine	2,503	2,269	343	343	26	4	18
Maryland	5,067	4,593	694	694	52	8	36
Massachusetts	6,146	5,572	842	842	63	10	44
New Hampshire	1,960	1,777	268	268	20	3	14
New Jersey	7,081	6,419	970	970	73	11	50
New York	18,737	16,987	2,567	2,567	193	30	134
Pennsylvania	14,108	12,790	1,933	1,933	145	22	101
Rhode Island	976	885	134	134	10	2	7
Vermont	1,132	1,026	155	155	12	2	8
Totals	**62,414**	**56,583**	**8,549**	**8,549**	**642**	**99**	**445**

[a] DC Department of Health does not believe that outdoor wood burning occurs within DC due to a local ban.

Table 4. 2002 Selected RWC TAP Emissions from Indoor Equipment (tons/yr)

State	Toxic Air Pollutant						
	1,3-Butadiene	2,3,7,8-TCDD[a]	Acet-aldehyde	Form-aldehyde	16-PAH	Benzene	Toluene
Connecticut	50	5.06E-08	283	251	189	251	188
Delaware	6	5.88E-09	37	34	25	29	24
District of Columbia	1	1.29E-09	8	7	5	6	5
Maine	78	7.87E-08	444	396	297	390	308
Maryland	39	3.91E-08	249	228	170	194	174
Massachusetts	82	8.22E-08	451	399	300	407	312
New Hampshire	52	5.21E-08	284	251	189	258	196
New Jersey	50	5.04E-08	302	273	204	250	210
New York	257	2.58E-07	1,440	1,279	960	1,279	997
Pennsylvania	238	2.40E-07	1,375	1,230	923	1,188	954
Rhode Island	12	1.22E-08	71	63	47	60	49
Vermont	37	3.72E-08	210	187	141	184	146
Totals	**902**	**9.08E-07**	**5,152**	**4,599**	**3,450**	**4,496**	**3,573**

[a] TCDD – tetrachlorodibenzo-p-dioxin.

Table 5. 2002 Selected RWC TAP Emissions from Outdoor Equipment (tons/yr)

State	Toxic Air Pollutant						
	1,3-Butadiene	2,3,7,8-TCDD[a]	Acet-aldehyde	Form-aldehyde	16-PAH	Benzene	Toluene
Connecticut	1.8	1.76E-09	13.7	13.0	9.7	8.8	9.7
Delaware	0.4	4.31E-10	3.3	3.2	2.4	2.1	2.4
District of Columbia[b]	0.3	2.82E-10	2.2	2.1	1.5	1.4	1.5
Maine	1.3	1.32E-09	10.2	9.7	7.2	6.5	7.2
Maryland	2.7	2.67E-09	20.7	19.7	14.6	13.2	14.6
Massachusetts	3.2	3.24E-09	25.1	23.8	17.8	16.1	17.8
New Hampshire	1.0	1.03E-09	8.0	7.6	5.7	5.1	5.7
New Jersey	3.7	3.73E-09	28.9	27.5	20.5	18.5	20.5
New York	9.9	9.87E-09	76.4	72.7	54.1	49.0	54.1
Pennsylvania	7.4	7.43E-09	57.5	54.7	40.8	36.9	40.8
Rhode Island	0.5	5.14E-10	4.0	3.8	2.8	2.6	2.8
Vermont	0.6	5.96E-10	4.6	4.4	3.3	3.0	3.3
Totals	**33**	**3.29E-08**	**254**	**242**	**180**	**163**	**180**

[a] TCDD – tetrachlorodibenzo-p-dioxin.
[b] DC Department of Health does not believe that outdoor wood burning occurs within DC due to a local ban.

Table 6. Example Monthly Temporal Allocation Profiles for DE

FIPSST	FIPSCNTY	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April
Indoor Equipment													
10	001	0.0478	0.0130	0.0028	0.0028	0.0195	0.0768	0.1453	0.1886	0.1919	0.1623	0.1051	0.0441
10	003	0.0385	0.0105	0.0016	0.0016	0.0148	0.0629	0.1372	0.2133	0.2123	0.1781	0.0948	0.0344
10	005	0.0482	0.0131	0.0031	0.0031	0.0201	0.0781	0.1463	0.1862	0.1893	0.1604	0.1067	0.0455
Outdoor Equipment													
10	001	0.1199	0.1666	0.2025	0.1792	0.1293	0.0533	0.0289	0.0203	0.0184	0.0199	0.0315	0.0303
10	003	0.1327	0.1674	0.2027	0.1724	0.1329	0.0407	0.0269	0.0173	0.0152	0.0181	0.0394	0.0344
10	005	0.1157	0.1664	0.2026	0.1816	0.1282	0.0574	0.0295	0.0213	0.0194	0.0204	0.0288	0.0289

Table 7. Example Weekly Temporal Allocation Profiles for DE

FIPSST	FIPSCNTY	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Indoor Equipment								
10	001	0.1163	0.1163	0.1163	0.1163	0.1163	0.2093	0.2093
10	001	0.1095	0.1095	0.1095	0.1095	0.1095	0.2262	0.2262
10	001	0.1175	0.1175	0.1175	0.1175	0.1175	0.2061	0.2061
Outdoor Equipment								
10	001	0.0509	0.0509	0.0509	0.0509	0.0509	0.3728	0.3728
10	001	0.0517	0.0517	0.0517	0.0517	0.0517	0.3707	0.3707
10	001	0.0506	0.0506	0.0506	0.0506	0.0506	0.3735	0.3735

Table 8. Example Daily Temporal Allocation Profiles for DE

FIPSST	FIPSCNTY	*Indoor Equipment*											
		0100	**0200**	**0300**	**0400**	**0500**	**0600**	**0700**	**0800**	**0900**	**1000**	**1100**	**1200**
10	001	0.0303	0.0303	0.0303	0.0303	0.0303	0.0340	0.0340	0.0340	0.0340	0.0340	0.0340	0.0113
10	003	0.0319	0.0319	0.0319	0.0319	0.0319	0.0292	0.0292	0.0292	0.0292	0.0292	0.0292	0.0097
10	005	0.0301	0.0301	0.0301	0.0301	0.0301	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0115
FIPSST	**FIPSCNTY**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**2400**
10	001	0.0113	0.0113	0.0113	0.0113	0.0113	0.0910	0.0910	0.0910	0.0910	0.0910	0.0910	0.0303
10	003	0.0097	0.0097	0.0097	0.0097	0.0097	0.0958	0.0958	0.0958	0.0958	0.0958	0.0958	0.0319
10	005	0.0115	0.0115	0.0115	0.0115	0.0115	0.0904	0.0904	0.0904	0.0904	0.0904	0.0904	0.0301
FIPSST	**FIPSCNTY**	*Outdoor Equipment*											
		0100	**0200**	**0300**	**0400**	**0500**	**0600**	**0700**	**0800**	**0900**	**1000**	**1100**	**1200**
10	001	0.0351	0.0351	0.0351	0.0351	0.0351	0.0197	0.0197	0.0197	0.0197	0.0197	0.0197	0.0066
10	003	0.0350	0.0350	0.0350	0.0350	0.0350	0.0199	0.0199	0.0199	0.0199	0.0199	0.0199	0.0066
10	005	0.0351	0.0351	0.0351	0.0351	0.0351	0.0196	0.0196	0.0196	0.0196	0.0196	0.0196	0.0065
FIPSST	**FIPSCNTY**	**1300**	**1400**	**1500**	**1600**	**1700**	**1800**	**1900**	**2000**	**2100**	**2200**	**2300**	**2400**
10	001	0.0066	0.0066	0.0066	0.0066	0.0066	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.0351
10	003	0.0066	0.0066	0.0066	0.0066	0.0066	0.1051	0.1051	0.1051	0.1051	0.1051	0.1051	0.0350
10	005	0.0065	0.0065	0.0065	0.0065	0.0065	0.1054	0.1054	0.1054	0.1054	0.1054	0.1054	0.0351

Figure 1. 2002 $PM_{2.5}$ Emissions Density Map for Indoor Equipment (ME, NH, VT)

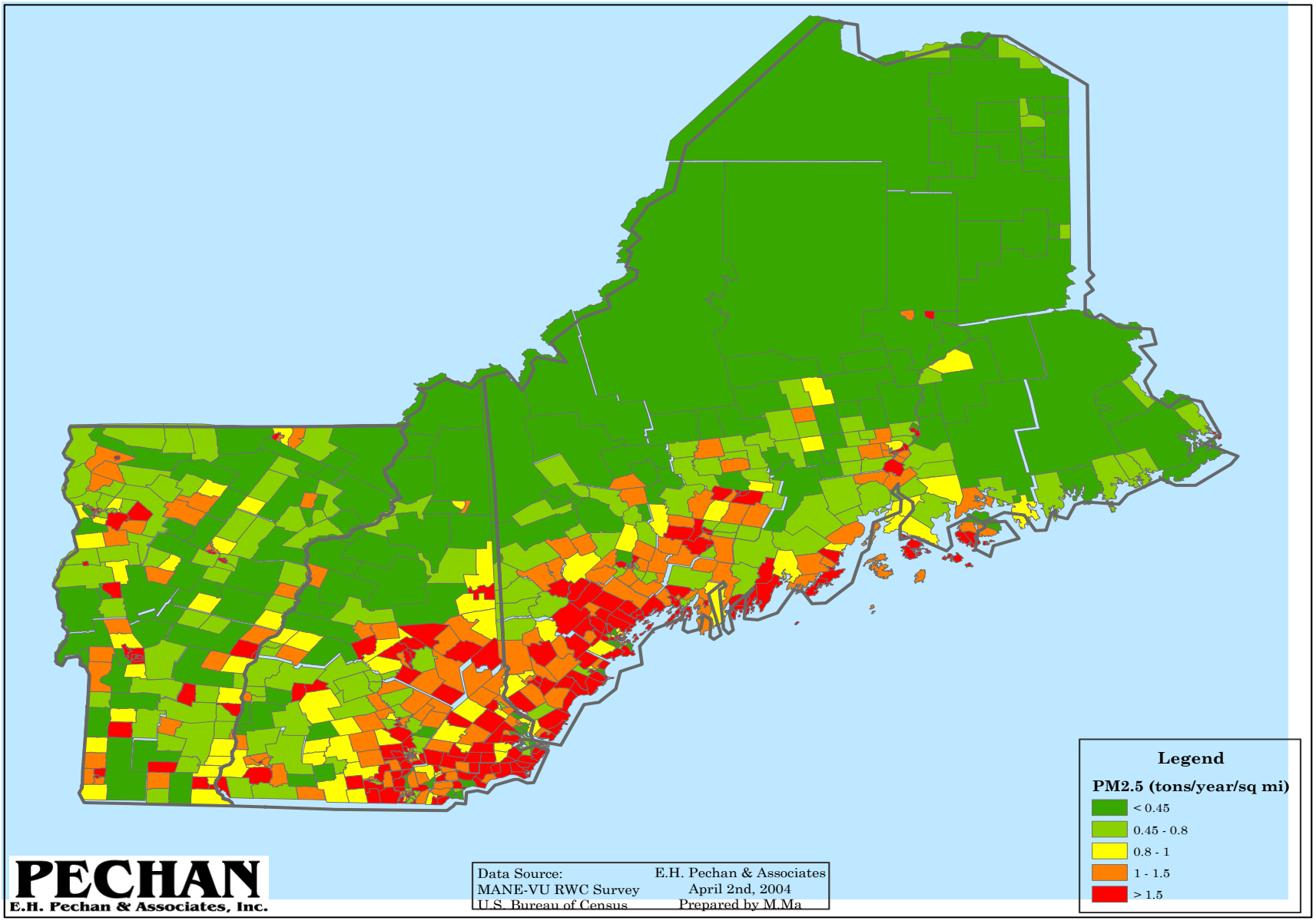


Figure 2. 2002 PM2.5 Emissions Density Map for Indoor Equipment (MA, CT, RI)

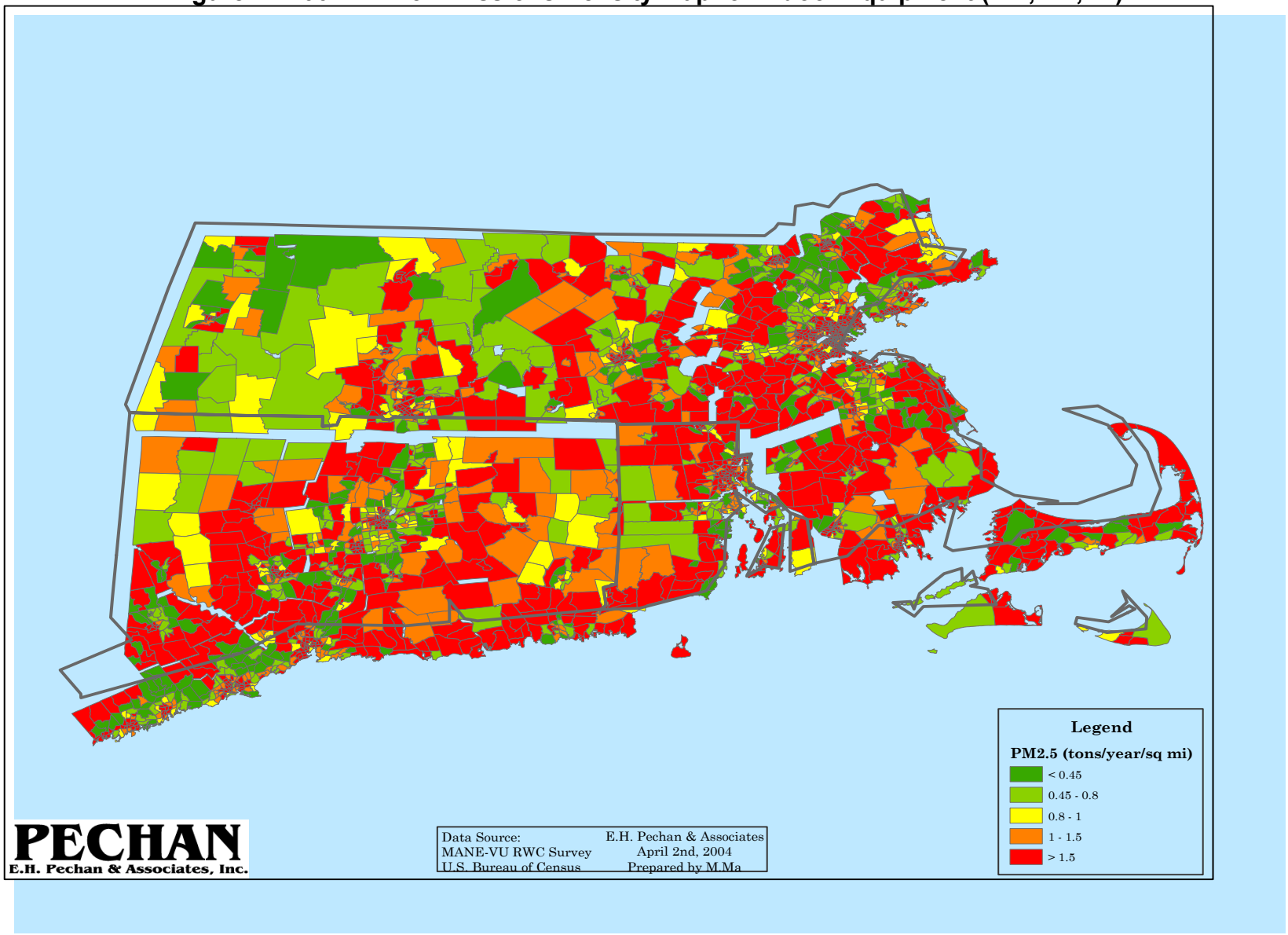


Figure 3. 2002 $PM_{2.5}$ Emissions Density Map for Indoor Equipment (NY)

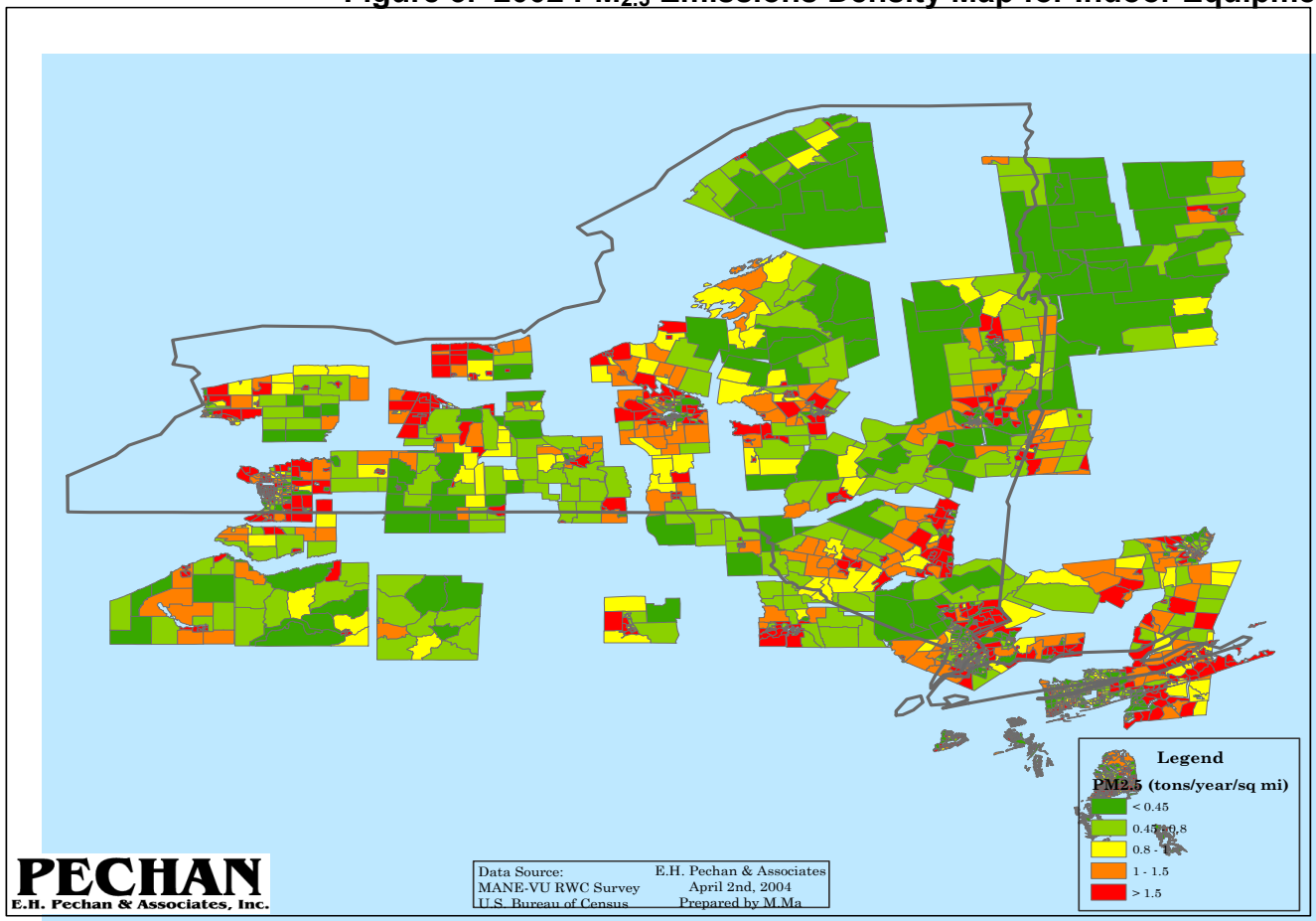


Figure 4. 2002 PM2.5 Emissions Density Map for Indoor Equipment (PA, NJ)

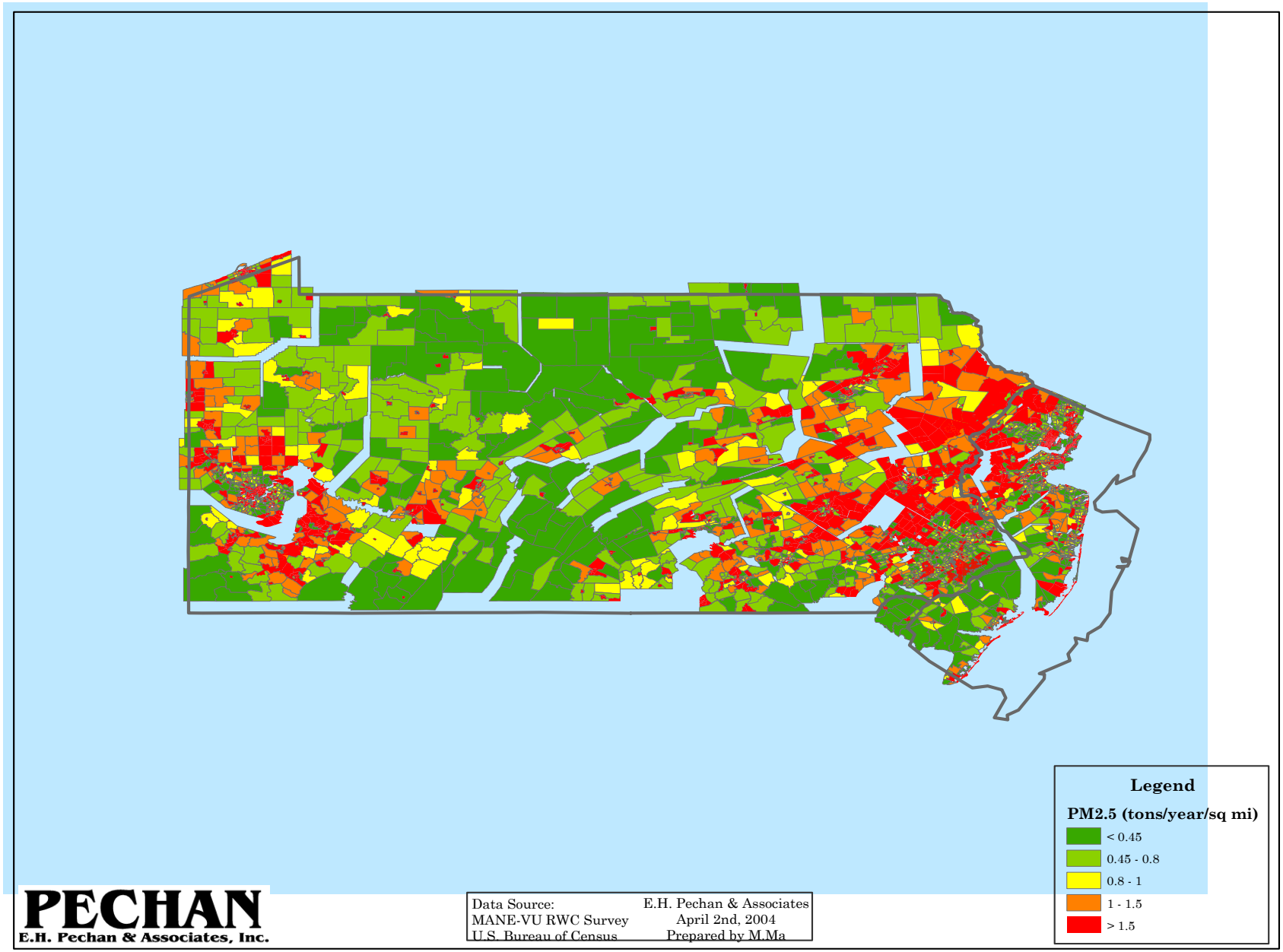


Figure 5. 2002 $PM_{2.5}$ Emissions Density Map for Indoor Equipment (MD, DE, DC)

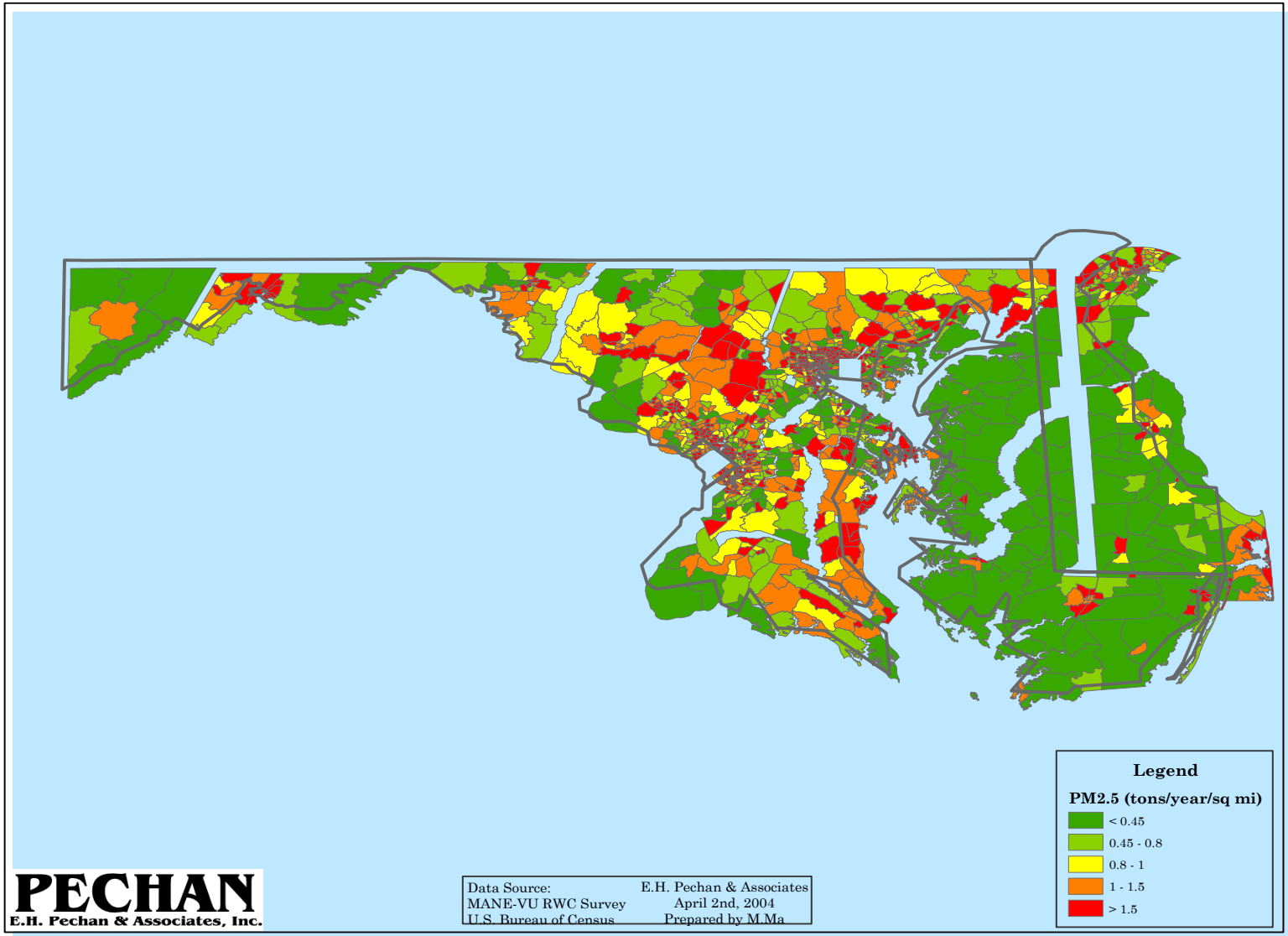


Figure 6. 2002 PM2.5 Emission Density Map for Indoor Equipment (MANE-VU Region)

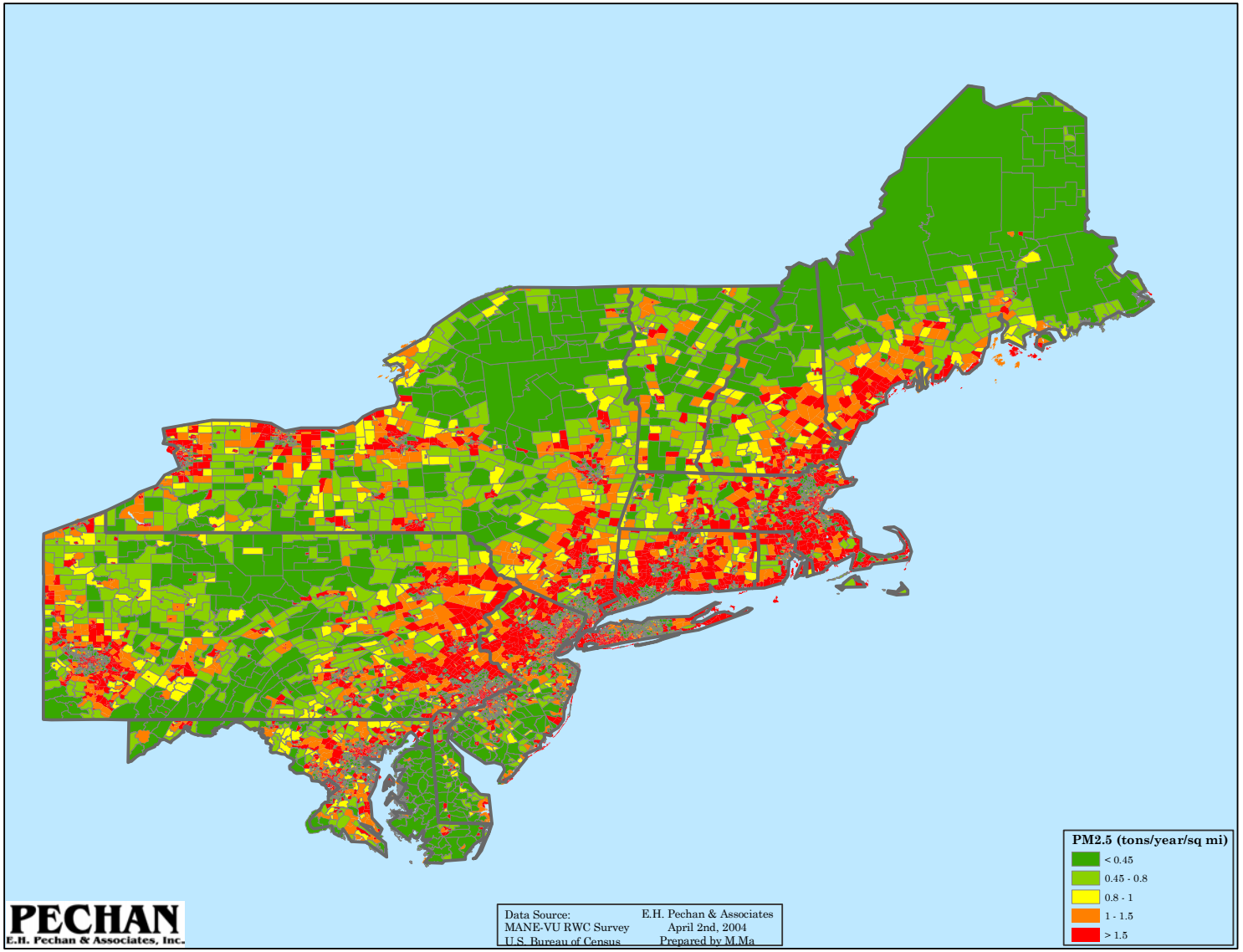


Figure 7. 2002 PM2.5 Emissions Density Map for Outdoor Equipment (ME, NH, VT)

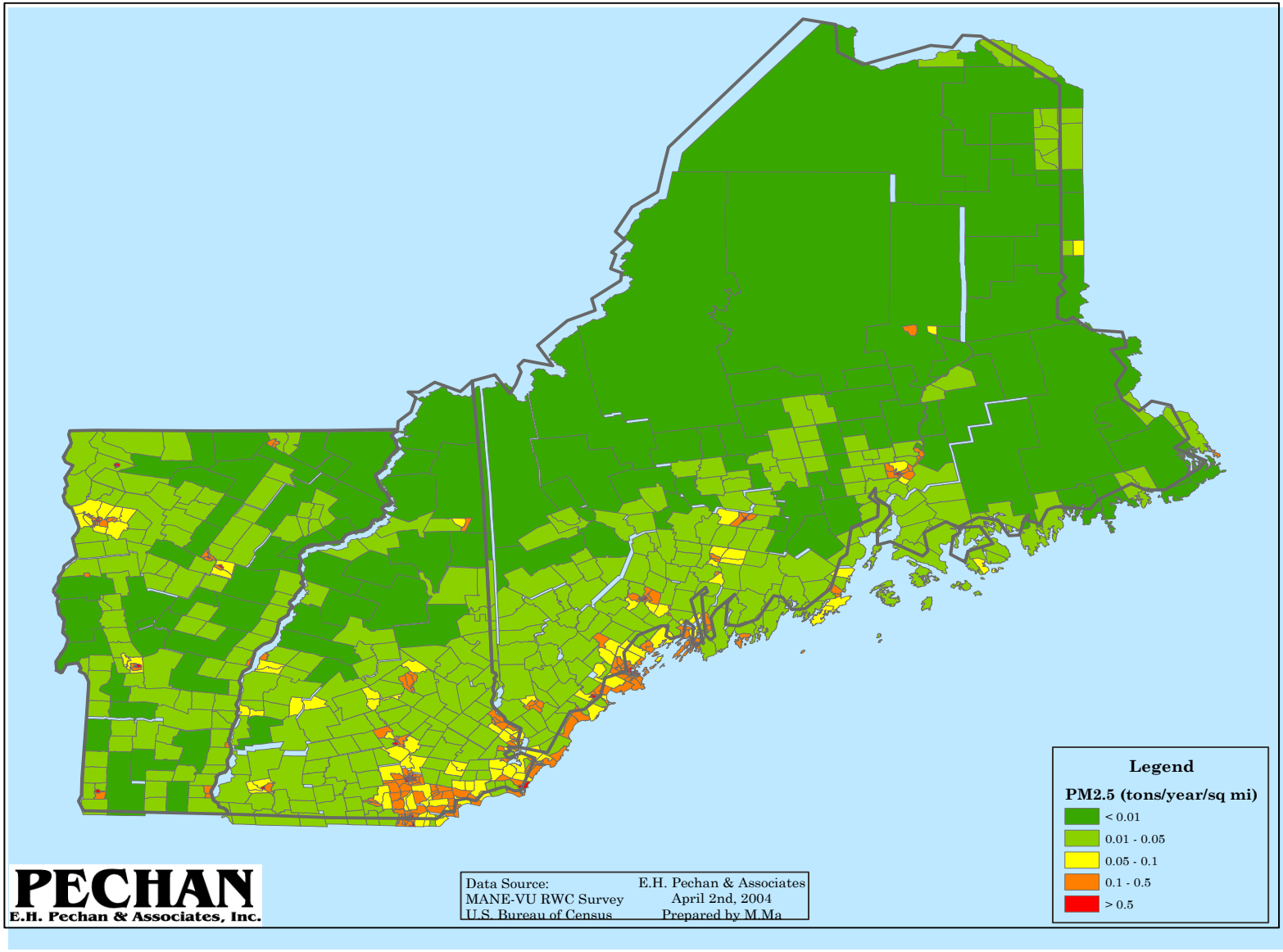


Figure 8. 2002 PM2.5 Emissions Density Map for Outdoor Equipment (MA, CT, RI)

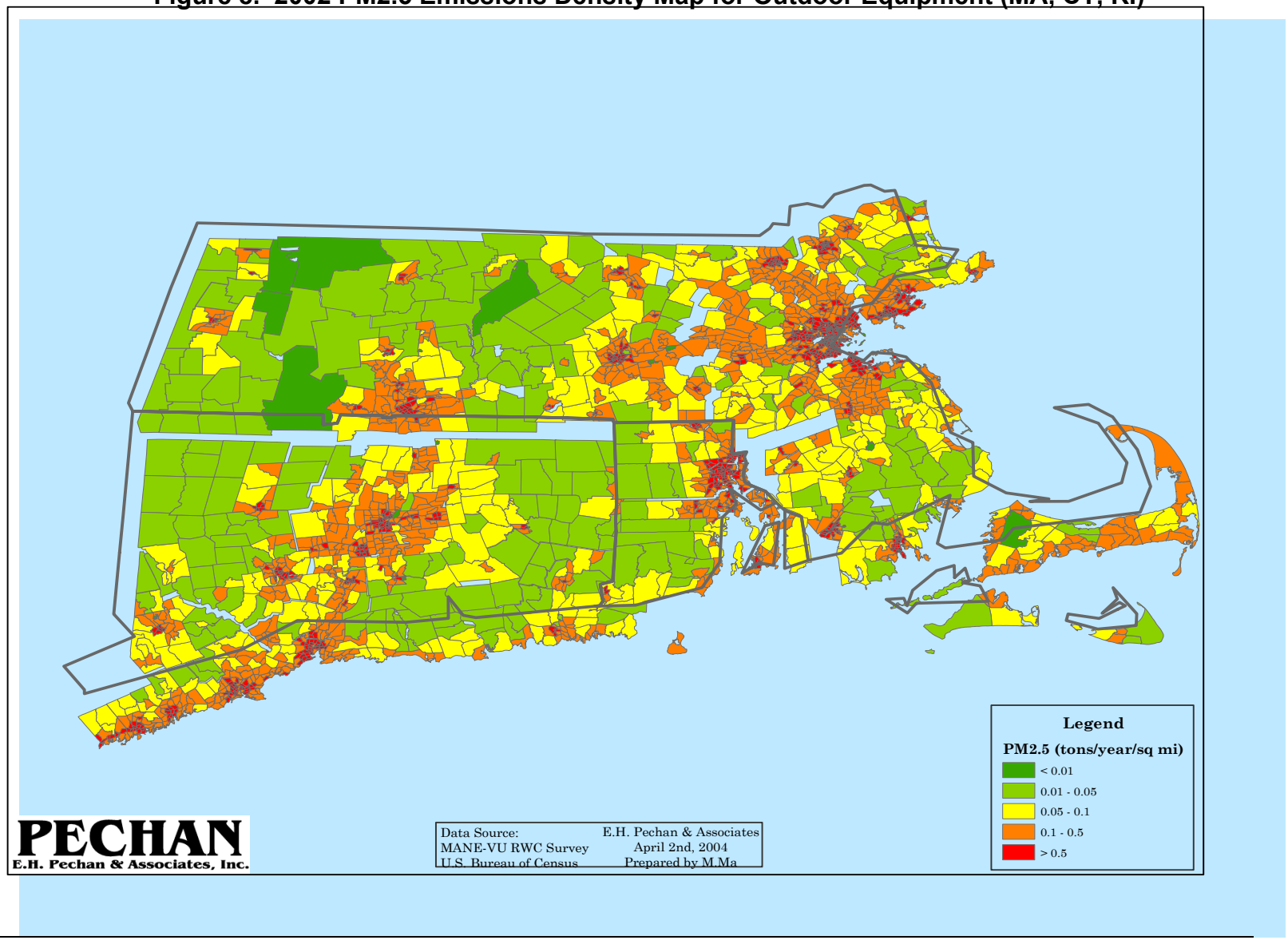


Figure 9. 2002 PM2.5 Emissions Density Map for Outdoor Equipment (NY)

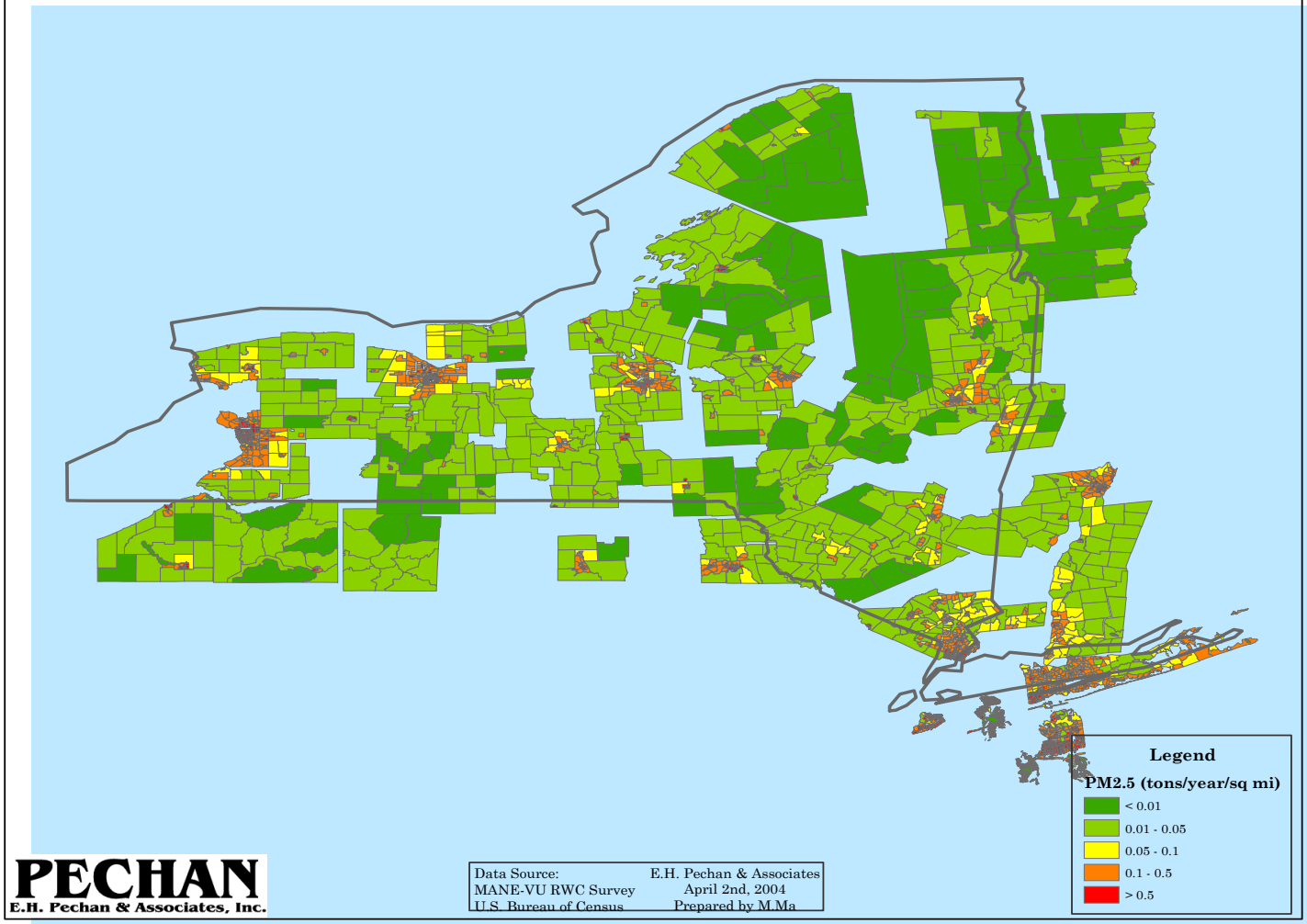


Figure 10. 2002 PM2.5 Emissions Density Map for Outdoor Equipment (PA, NJ)

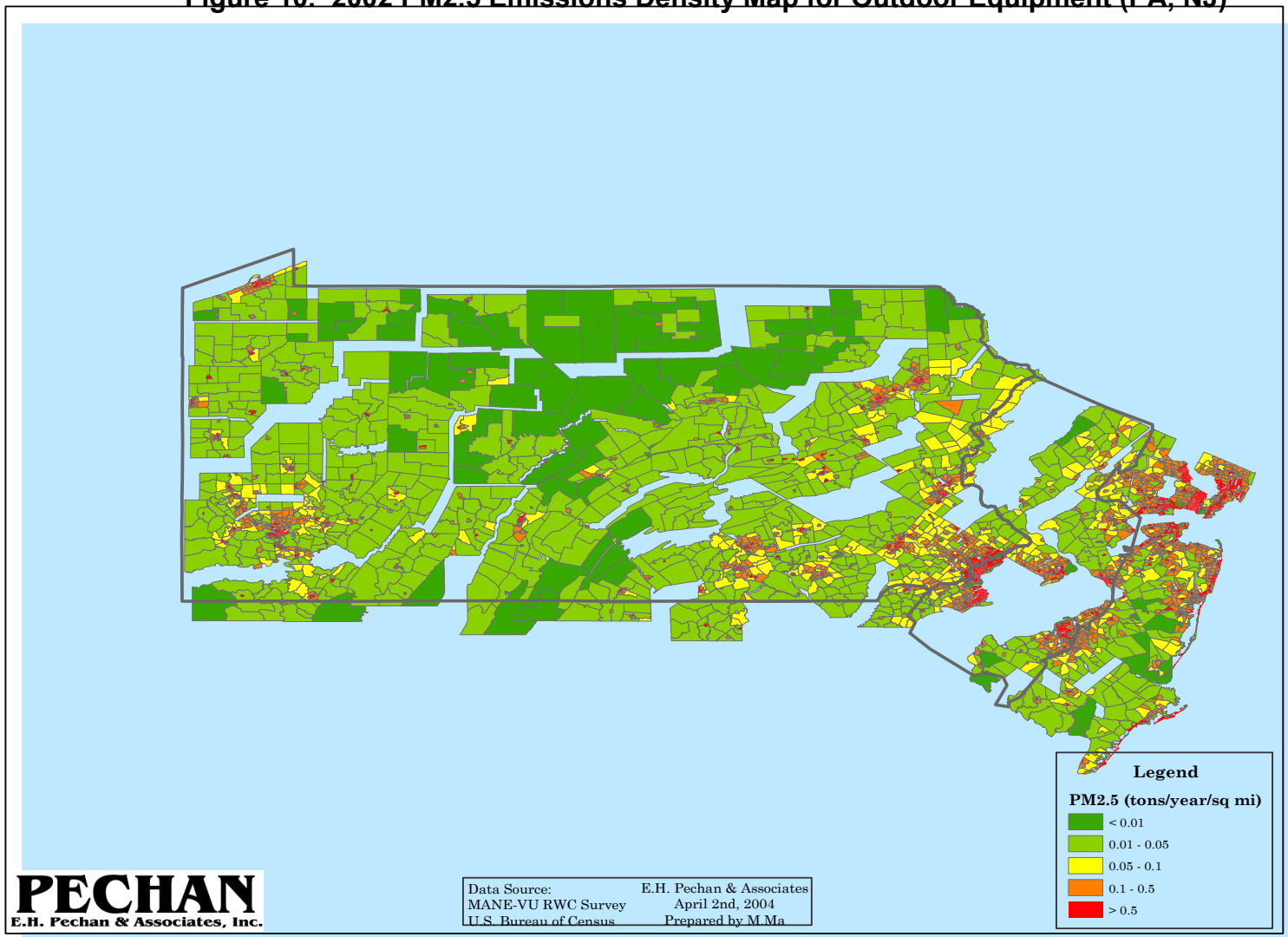
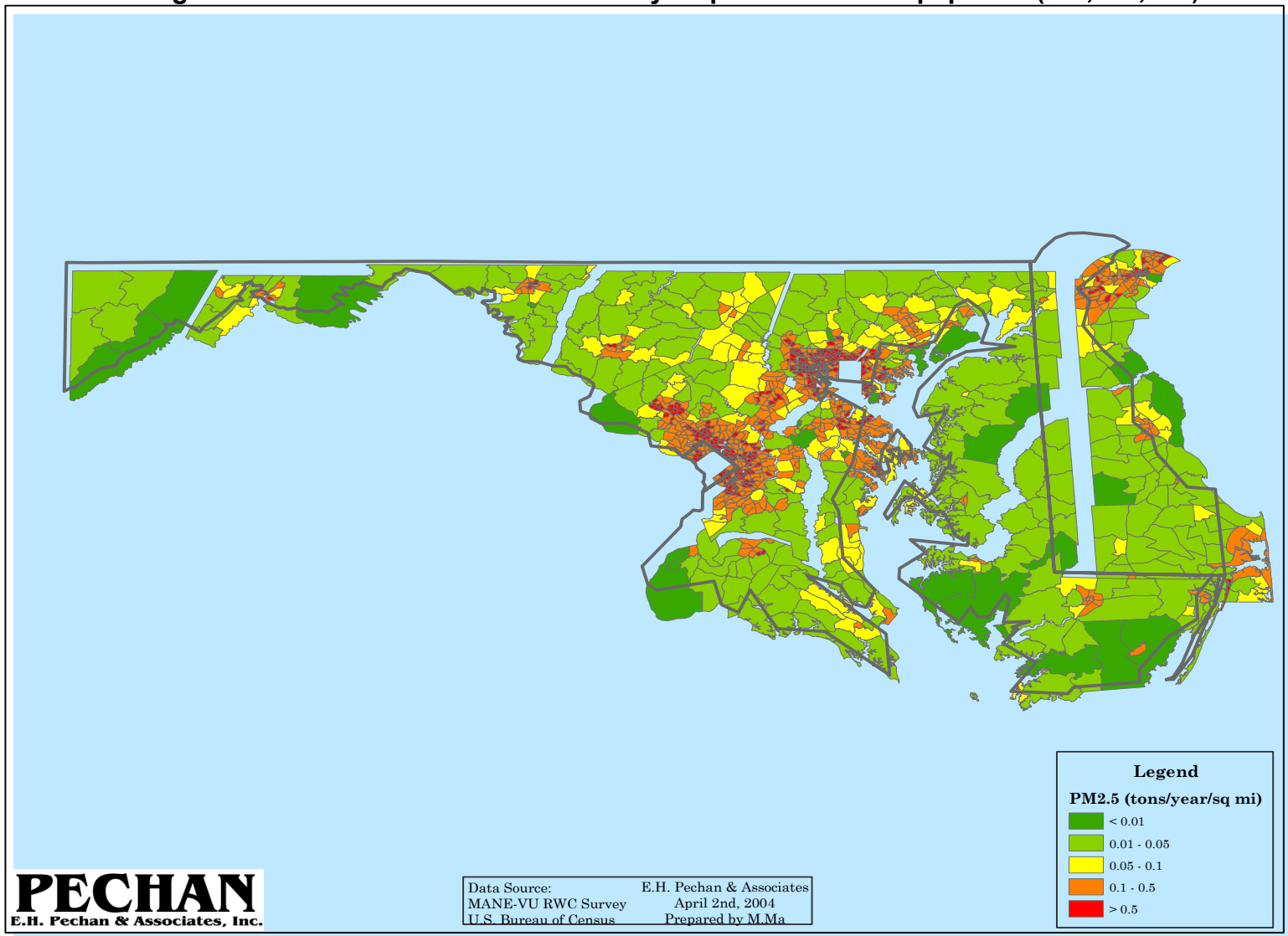


Figure 11. 2002 PM2.5 Emission Density Map for Outdoor Equipment (MD, DE, DC)



IV. CONCLUSIONS AND RECOMMENDATIONS

The emissions estimates from this survey work are approximately twice the NEI estimates for residential wood combustion. Because this survey included more indoor equipment types than the NEI (i.e., pellet stoves, wood-fired boilers/furnaces, outdoor equipment), it was expected to result in higher emissions. The higher emission estimates also portray important regional differences in RWC. These include differences in both the amount and type of wood consumed, as compared to the average U.S. household. The different wood density value applied in this study compared to the value used in the NEI accounts for some of these differences (1.8 compared to 1.2 tons/cord). The bottom-up methods applied allow for much more detailed analyses of the geographic distribution of RWC emissions. These methods appear to at least partially correct for what were believed to be previous over-allocations of RWC activity to urbanized areas.

Pechan is confident that survey methods are the best approach for developing regional RWC emission estimates. In conducting this project, several lessons were learned that may help with future surveys. Future similar surveys should strive to obtain larger sample sizes in urban areas. Based on the occurrence of wood burners found in this project, Pechan recommends an increase in the urban area sample sizes of at least a factor of 3 to 5 compared to this study. Also, the survey instrument was designed to accommodate gathering data from the most complex wood burner (e.g., those residing in rural areas that consume large quantities of wood in varying types of equipment). A simpler, scaled-down, instrument should be developed for urban areas where usage patterns are simpler and respondents have more difficulty in quantifying wood consumption. A simpler survey would allow for more cost effective gathering of larger sample sizes in urbanized areas.

The Bureau of Census has data on the number of households using wood as the primary source of heat by census tract. Future RWC survey efforts of the type conducted for this project should consider the merits of incorporating the Bureau of Census data in the survey design. For example, the survey could be constructed to ask whether wood is used as the primary source of heat or for pleasure purposes. The survey data could then be designed to characterize wood consumption for primary versus pleasure burners. Most suburban and urban wood burners are pleasure burners.