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Natural and anthropogenic methane sources in New England

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Abstract

We have recently completed a methane emissions inventory for the New England region. Methane emissions were calculated to be 0.91 $Tg\,yr^{-1}$, with wetlands and landfills dominating all other sources. Wetlands are estimated to produce 0.33 $Tg\,CH_4\,yr^{-1}$, of which 74% come from Maine. Active landfills emit an estimated 0.28 $Tg\,CH_4\,yr^{-1}$, 60% of which are generated from twelve landfills. Although uncertainty in the estimate is greater, emissions from closed landfills are on the same order of magnitude as active landfills and wetlands; 0.25 $Tg\,CH_4\,yr^{-1}$. Sources of moderate magnitude include ruminant animals (0.05 $Tg\,CH_4\,yr^{-1}$) and residential wood combustion (0.03 $Tg\,CH_4\,yr^{-1}$). Motor vehicles, natural gas, and wastewater treatment make only minor contributions. New England is heavily forested and the soil uptake of atmospheric methane in upland forests, 0.06 $Tg\,CH_4\,yr^{-1}$, decreases emissions from soils by about 18%. Although uncertainties remain, our estimates indicate that even in a highly urbanized region such as New England, natural sources of methane make the single greatest contribution to total emissions, with state totals varying between 8% (Massachusetts) and 92% (Maine). Because emissions from only a few large landfills dominate anthropogenic sources, mitigation strategies focused on these discrete point sources should result in significant improvements in regional air quality. Current federal regulations mandate landfill gas collection at only the largest sites. Expanding recovery efforts to moderately sized landfills through either voluntary compliance or further regulations offers the best opportunity to substantially reduce atmospheric methane in New England. In the short term, however, the large contribution from closed, poorly regulated landfills may make the attribution of air quality improvements difficult. Mitigation efforts toward these landfills should also be a priority.

Keywords: Regional emissions inventory; Methane

1. Introduction

The potential for global warming and its widespread ecological effects prompted the international community to sign the United Nations Framework Convention on Climate Change in 1992. In the spirit of that convention and to demonstrate the United States' commitment to this issue, the Clinton Administration in 1993 announced the creation of the US Climate Change Action Plan. The plan is an ambitious effort to reduce US greenhouse gas emissions to their 1990 levels by the year 2000 through public–private partnerships and the implementation of cost-effective emission reduction technologies (Clinton

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and Gore, 1993). The plan targets reductions in all significant greenhouse gases and includes measures to monitor progress toward achieving its emission reduction goals.

Methane (CH_4) is a key greenhouse gas identified in the Climate Change Action Plan. Methane reduction should be a major objective in any mitigation strategy as emissions need only be reduced 10–15% to stabilize the global atmospheric burden, while carbon dioxide emissions would have to be reduced 60–80% to achieve stabilization (Houghton et al., 1992). Since fossil fuel energy, the primary source of increasing atmospheric carbon dioxide, is critical to the functioning of industrial society, it is unlikely that reductions of this magnitude would be possible in the near term. In addition, methane has a relatively short lifetime in the atmosphere in comparison to CO_2 (Houghton et al., 1992), and therefore stabilizing or reducing emissions will have a more rapid effect on mitigating the risks of potential climate change and achieving the Clinton Administration's objective of reducing emissions to their 1990 levels. Finally, methane is an energy resource and its recovery can be economically viable. Recovery efforts, particularly from coal mines and landfills, have been hindered in the past by an array of institutional, regulatory, and financial barriers, which are addressed in the Climate Change Action Plan.

The most comprehensive assessment of global sources of atmospheric methane and their future dynamics has been conducted by the United Nation's Intergovernmental Panel on Climate Change (IPCC). The IPCC data suggest that human activities are now responsible for approximately 70% of global methane emissions (Houghton et al., 1996). To fulfill requirements set forth in the Clean Air Act Amendments of 1990, the US Environmental Protection Agency issued a series of reports in the early 1990s estimating current US methane emissions and projecting future emissions. The EPA calculates that 25–30 Tg CH_4 ($1\ Tg = 10^{12}\ g$) is released annually from anthropogenic sources in the US, the majority of which are from landfills and domesticated livestock (EPA, 1993).

While source estimates at a national scale provide general guidelines for assessing mitigation alternatives, significant regional variability exists. Estimates of source magnitudes on a regional or site-specific scale allow both more focused and efficient mitigation strategies by exploiting this variability. In addition, since emissions from some sources are influenced by climate variables, more accurate, regional-specific emissions models should result in improved national estimates. A regional inventory is also relatively easy to update periodically, a critical step in assessing progress toward achieving the goals of the Climate Change Action Plan. Identification of regionally important sources may also stimulate new initiatives in the private sector in areas such as landfill gas recovery and wastewater sludge management.

This paper reports the development and results of an emissions inventory for methane sources in New England. The New England region is small enough geographically so that relevant socioeconomic data can be gathered fairly quickly, yet its population density is high enough to require a substantial urban infrastructure. All major sources of methane, with the exception of coal mining and rice agriculture, are present in the region.

2. Methodology

We have calculated annual methane emissions for all counties in the six New England states of Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine referenced to the early 1990s. Sources included in the inventory were wetlands, landfills, ruminant animals, residential wood combustion, fossil fuel combustion and use, and wastewater treatment. We have also included the uptake or sink of methane in relatively well-drained soils. Data sources included published EPA emission factors, census population statistics, climate databases, environmental habitat inventories, source modeling, and directed surveys.

2.1. Wetlands and soils

2.1.1. Wetlands

Methane emissions from natural wetlands in the region were calculated as a function of habitat-specific unit area flux, area, and emission season and were calculated on a county scale, the smallest scale available for habitat area characterization. Flux data in the literature is commonly reported as an average value over the warm emission period (Bartlett and Harriss, 1993). Literature flux values reported from wetlands in the general northeast region of the US were grouped and averaged by the wetland habitat classification types used for the National Wetlands Inventory (NWI), a nation-wide mapping effort currently underway by the Fish and Wildlife Service (Wilen and Bates, 1995). The most recent estimates of wetland areas on a county basis were obtained from the six New England states. Data quality on area estimates varied. Habitat areas in Connecticut, Rhode Island, and Massachusetts have been mapped quite recently as part of the NWI (Metzler and Tiner, 1992; Tiner, 1989, 1992). Wetlands in New Hampshire were recently mapped, but not as a part of the NWI, so habitat types differ. Wetlands in Maine, which contain the majority of wetlands in the region, have not been completely characterized recently; mapping under the NWI is currently underway. Wetlands in Vermont have been recently characterized under the NWI, but only broad habitat areas are currently available on a county basis. Based on a more detailed characterization for the entire state, the broad wetland classes were broken down within each county. All area data were normalized to the NWI habitat types.

Because climate is a major control on natural methane emissions and varies widely over our area of interest, climate data (30 year monthly average temperatures) from 155 sites in the New England section of the National Oceanic and Atmospheric Administration (NOAA) air temperature network were obtained and used to determine the seasonality of emissions. The seasonal pattern of methane release from all wetlands was scaled to patterns observed by researchers at UNH at a long-term flux measurement site in New Hampshire (Frolking and Crill, 1994; Melloh and Crill, 1996). Three years of data at the site indicate that over 90% of the annual flux occurs when air temperatures are above 10°C. The length of the emission season (temperatures above 10°C) varied from 107 days (Coos County, New Hampshire) to 183 days (Suffolk and Hampden Counties, Massachusetts). Ten per cent of the warm season flux was added to derive a total annual flux to account for emissions during the cold season.

2.1.2. Upland soils

A variety of reports in the literature have noted that atmospheric methane is consumed in the near surface of relatively dry upland soils (e.g. Crill, 1991; Castro et al., 1995). Although uptake rates are quite low, nearly two orders of magnitude less than typical emission rates from wetlands, because upland soils constitute the vast majority of the land surface, this natural sink of methane needs to be included in our inventory. Research on soil uptake rates suggests that disturbance of natural forest soil profiles generally decreases uptake rates significantly (Keller et al., 1990; Castro et al., 1995; Mosier et al., 1991, 1996). We obtained data on forest areas on a county basis from the US Forestry Service Forest Inventory and Analysis (FIA) project (Griffith and Alerich, 1996; Frieswyk and Malley, 1985a, b; Dickson and McAfee, 1988a–c). State inventories are revised periodically and data date from 1983 (Vermont and New Hampshire), 1985 (Massachusetts, Rhode Island, and Connecticut), and 1995 (Maine). Because of concern about including areas of forested swamp as both sources and sinks and because methane consumption occurs only in relatively well-drained soils, we subtracted the areas of forest growing on very poorly drained land from total forest areas. Data on land areas under agricultural use (cropland, pasture, rangeland, and orchards) were obtained from the 1992 agricultural census (Bureau of the Census, 1994). Since consumption rates are reduced in these soils due to the effects of soil compaction and fertilizer application, we assumed that rates were only 20% (cropland) or 30% (pasture, rangeland, and orchards) of that in undisturbed forests. A large proportion of the work on soil methane uptake has been carried out in the New England region and indicates that forest type (deciduous, evergreen) does not significantly affect rates. We therefore used a simple average for data reported in the region and applied it to all forests.

Although soil methane consumption occurs during the warm season, it appears to be largely controlled by rates of methane diffusion into the soil rather than temperature, except during a relatively brief period in the spring (Crill, 1991). We used a multi-year data set from New Hampshire reported in Crill (1991) to determine the period over which uptake takes place and assumed that it occurred at a "warm season" constant rate over this period. This season, the time when the NOAA air temperature network 30 yr monthly average temperature rises above freezing through the time when the average monthly minimum falls below freezing, varied from 214 days (northern Vermont, New Hampshire, and Maine) to 306 days (Barnstable, Dukes, and Nantucket counties, MA).

2.2. Landfills

Landfills are the largest anthropogenic methane source in the US, estimated to release 8.1–11.8 Tg CH_4 in 1990 (EPA, 1993). Because there have been relatively few field measurements of landfill methane and those in the literature indicate high spatial and temporal variability (Bogner and Spokas, 1993; Czepiel et al., 1996), most emissions estimates have instead been based on modeling. Methane production is estimated based on such factors as the quantity and organic content of the refuse, depth of burial, temperature and moisture content of the soil.

We obtained operating values for landfills in each state from the state environmental agencies. Maine does not collect the required data. Data were obtained individually from the landfills in operation in 1994. Since this coincided with the imposition of more stringent Resource Conservation and Recovery Act (RCRA) requirements, the number of landfills we surveyed in Maine was much lower than that of the other states. The sites included in our study were those municipal solid waste (MSW) landfills operating in the early 1990s which account for more than 90% of the total waste landfilled in each state. We excluded industrial landfills from our analysis since they are thought to contribute only 5–10% of all methane emissions (EPA, 1993). In all, we surveyed 92 landfills in New England with a size distribution (in tons per year waste received) from 1500 (Greenville, ME) to 711 000 (Plainville, MA) metric tons. As for other regions, most states' municipal waste is landfilled at only a few high volume sites (Fig. 1), an observation important in determining a mitigation strategy for landfill methane.

These data were used to parameterize a landfill methane emissions model based on the assumption that landfilled waste produces methane as a result of

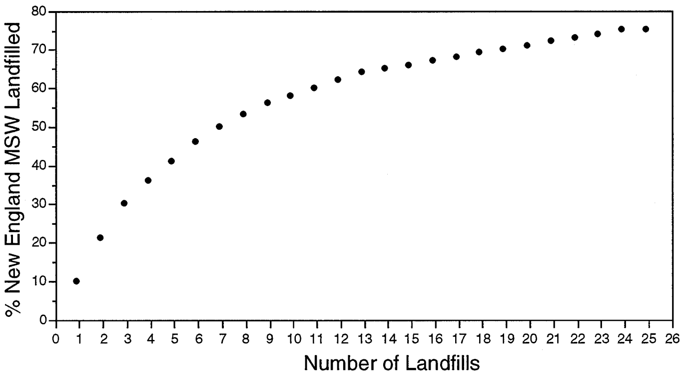

Fig. 1. Distribution of municipal solid waste among New England landfills.

biological decomposition and can be modeled by first order kinetics (Augenstein and Pacey, 1991; EMCON, 1981; Peer et al., 1992). This degradation occurs at different rates in materials with different physiochemical characteristics. Three fractional composition categories were defined to encompass the major types of degradable carbon found in MSW. The rapidly degradable fraction consists of high moisture and organic content wastes such as food and yard wastes, the moderately degradable fraction consists of more slowly degradable wastes such as paper products, and the slowly degradable fraction consists of wastes with the least available organic content such as wood, leather, and plastics. The methane produced from a batch of waste was calculated as the sum of methane produced from each fractional waste category by the equation

$$E = (M f_{\mathrm{T}} Y f_{\mathrm{m}}) \exp(L^{-1} t)$$

where E is annual methane production, M is the total waste batch mass, f_{T} is waste category fraction being considered (by wet weight), Y is the ultimate methane yield, f_{m} is the fractional dry weight of the waste, L is the generation time constant, and t is the time. The ultimate methane yield is the total quantity of methane that will be produced by a unit mass of waste during its degradation lifetime, while the generation time describes the time during which the waste mass will generate significant methane. Our ultimate yield values and generation time constants were adopted from the EMCON MGM model and were based on observed field gas recovery rates and estimates of waste organic composition (Augenstein and Pacey, 1991). The model assumes that for each annual waste batch, a constant fraction of organic material is degraded per unit time resulting in peak methane generation, after a specific lag time during which no methane is produced, followed by an exponential decrease in methane production. The waste landfilled in years prior to the year for which landfilled mass is known is estimated as a function of regional population statistics. The contribution of each annual waste batch is summed to yield the total present methane production.

There are currently six landfills in New England which have landfill gas collection systems (GAA, 1991). We modified our estimates from these landfills to reflect the reduction in atmospheric emissions at these sites. We assumed an 80% collection efficiency, based on our field experience with landfill operations in New England (Czepiel and Mosher, unpublished data).

While a landfill can produce methane sixty or more years after its closure, most methane is emitted within a thirty year period (Peer et al., 1992). There are, however, very few reliable data on closed landfills. Closure dates, waste-in-place estimates, even the location of the landfills themselves are all relatively uncertain. Massachusetts and Connecticut did provide a listing of inactive landfills in their states. Closure dates were known for slightly more than half of the landfills in Massachusetts and almost 90% of the landfills in Connecticut. Closure dates were estimated for the remaining sites by assuming that closure dates by decade were distributed similarly to those of the landfills where closure dates were known. We further assumed that the size distribution of closed landfills paralleled that of currently operating sites. Based on these assumptions, we calculated emissions from landfills in Massachusetts and Connecticut which closed from 1960 to 1992. To derive a regional estimate for emissions from closed landfills for this period, we derived an average per capita emission rate from both states and extrapolated to other states using census population statistics. Although calculated emissions from closed landfills cannot be allocated to a county basis and are clearly more uncertain than open landfills, they are an important source of methane in the short term and have typically been ignored in previous studies.

2.3. Ruminants

Direct methane emissions from ruminant animals in the US are thought to contribute about 21% of the anthropogenic methane released to the atmosphere each year; the vast majority from beef cattle and dairy cows (EPA, 1993). Ruminant animal emissions are calculated based on animal populations and emission factors which include differences in age, sex, and type of animal as well as typical diets. In New England, relatively few cattle are raised for beef, and ruminant populations are primarily dairy cows and replacement heifers (EPA, 1993). Census data from 1992 on cattle populations was used to map populations and emissions to a county basis. Wild and domestic animals other than cattle such as goats, sheep, deer and moose are estimated to contribute only about 4% to national ruminant CH_4 emissions (EPA, 1993). We assumed that their contribution was insignificant in New England.

2.4. Animal manure

In addition to direct emissions of methane from domesticated livestock, methane is also released from livestock manure as it decomposes. Nationally, emissions from livestock manure are about 40% of direct livestock releases (EPA, 1993). Production and release of methane from manure is dependent on animal population sizes, their diets, manure management systems, and local climate. Our estimates for the New England region are based largely on waste management systems and emission factors reported by Safley et al. (1992) and updated by the EPA (1993). These authors calculate emission factors for a wide variety of domestic livestock (cattle and cows, swine, chickens and turkeys, horses, sheep, and goats) and estimate emissions on a state basis. We have used their emission factors in combination with 1992 census data on cattle and cows to update and allocate population figures to a county basis. Because Safley et al. (1992) calculate that the majority of emissions in New England (58–96%) come from cattle and cow manure, we distributed other livestock populations in proportion to those of cattle and cows and assumed that their populations varied in parallel with them.

2.5. Fuel combustion

Methane is also emitted to the atmosphere from the incomplete combustion of fossil and biomass fuels, or as a byproduct of the combustion process itself. Methane is emitted from both stationary sources; oil, coal, wood or natural gas fired equipment, and mobile combustion sources such as highway vehicles, aircraft, and railroad transportation. The EPA estimates <2.0 Tg CH_4 are emitted annually in the US from fuel combustion, mostly from stationary sources (EPA, 1993). Residential wood combustion is the largest emission source, estimated to release 0.52 Tg of CH_4 annually. This estimate is not derived from measured emissions but rather uses emissions of non-methane volatile organic compounds (VOCs) and the ratio of methane to non-methane VOCs and, as such, is considered highly uncertain.

While wood combustion is a relatively minor methane source in the US overall, it is of much greater significance in rural states like Maine and Vermont where it provides an average of 15% of residential heating requirements. In more urban areas such as Connecticut, Rhode Island and Massachusetts wood is the primary heat source in only 1% of households (Bureau of the Census, 1993). In New England, roughly 200 000 homes use wood as the primary heat source and an additional 900 000 homes rely on wood for supplemental heating (EIA, 1995a). Using the EPA's national emission estimate and residential energy consumption data from the Energy Information Administration (EIA, 1995a), we derived emissions estimates per household unit for both primary and secondary wood combustion and applied those emission factors to county data on residential wood use (Bureau of the Census, 1993).

Methane is also emitted from mobile combustion sources, principally highway vehicles. The EPA estimates 0.27 Tg CH_4 are emitted annually from mobile sources, 90% of which are from highway vehicles (EPA, 1993). We obtained Department of Motor Vehicle registration records from each state to estimate the number of passenger vehicles, light and heavy trucks, and motorcycles in each county, paralleling the vehicle type classification used in the EPA report. Department of Transportation highway statistics were used to calculate the average annual vehicle miles traveled by vehicle type in each of the six New England states (Federal Highway Administration, 1994). The EPA's emission factors, by vehicle type, were then used to estimate vehicle emissions (EPA, 1993).

2.6. Natural gas system leakage

Methane is the major constituent of natural gas. Methane is released to the atmosphere from all components of the natural gas system: extraction, processing, transmission, and distribution. Methane losses during the transmission of natural gas in the US are estimated to range from 0.59 to 2.06 Tg annually, about 40% of all natural gas emissions (EPA, 1993). We used the EPA's emission factor together with a pipeline atlas (PennWell, 1990) to estimate emissions in the New England region. The emission factor includes an estimate from all components of the transmission system: normal operations, fugitive emissions, routine maintenance and system upsets. We estimate there are approximately 975 miles of transmission pipeline running throughout New England. For our purposes, only emissions from the transmission of natural gas were considered since there are no production sites in New England and estimating emissions from transmission lines through distribution systems to residential, commercial and industrial end-users requires pipeline length and location data that are difficult to obtain. This should not be a significant error since distribution pipelines are estimated to emit only 14% of all natural gas emissions (EPA, 1993) and natural gas consumption in the region is relatively low, 600 billion cubic feet per year, about 2.8% of the US total (EIA, 1996a).

Although our calculations are based on the 1990 EPA study of anthropogenic methane emissions, a more recent joint study by the EPA and the Gas Research Institute suggests natural gas emissions are more than twice those previously estimated (EIA, 1996b). This study includes a more comprehensive inventory of equipment components and uses a more representative sample in its emissions estimates from these components (EIA, 1996b). We have recently completed a research project with Aerodyne Research Inc. (Billerica, Massachusetts) and Washington State University to quantify low-level fugitive emissions from components in the natural gas system using atmospheric tracer techniques. Identifying leaky components of the pipeline system and improving system-wide emissions factors should result in more accurate emissions estimates from this source.

2.7. Wastewater treatment plants

Methane emissions were estimated from both liquid treatment processes and the anaerobic digestion of sludge. Liquid treatment emissions were calculated from the flow data and flow based methane emission factors for primary and secondary treatment derived from recent field studies (Czepiel et al., 1993). Because data inputs were not available from the states, a questionnaire requesting the necessary data (influent or effluent flow rates, sludge production and disposal methods, and anaerobic digestion status) was sent to the treatment plants in each state comprising more than 90% of each state's design flow. The response rate to the questionnaire averaged about 50% and follow-up telephone interviews were made until at least 80% of the design flow in each state was included in our survey.

Of the 201 treatment plants surveyed, 45 use anaerobic digestion to reduce sludge volume. Most plants either flare the biogas generated from this process or use it to fuel the digestor or heat the treatment plant. Thirteen of the plants vent part of their gas, while three of the plants vent all of their biogas. Emissions could only be estimated for three of the sixteen plants (and none of the plants that vented all their biogas) since gas quantities were either not measured or metering equipment was malfunctioning at the time of our inquiry. Similarly, gas production could only be quantified for 22 of the other 29 anaerobic digestors.

Methane emitted as a result of anaerobic sludge digestion was estimated either directly from questionnaire data where biogas methane content was assumed to be 65%, or indirectly from sludge flow data, assuming a volatile solids destruction rate of 45% and a biogas conversion rate of 638 grams CH_4 per kilogram volatile solids destroyed (Metcalf and Eddy, 1991). Fugitive emissions of biogas from anaerobic digestors were not considered.

3. Results

Methane emissions from New England are calculated to be 0.91 $Tg\,yr^{-1}$ (Table 1). Our results suggest wetlands are the dominant emissions source, producing 0.33 $Tg\,CH_4$ annually, 36% of the region's total. Methane emissions from landfills, the major anthropogenic source, are of the same order of magnitude as those from wetlands, but are distributed differently and less diffusely. Wetlands emissions are concentrated in eastern New England, particularly northern Maine. Maine is calculated to emit 0.24 $Tg\,CH_4\,yr^{-1}$, 74% of the total from this source and a quarter of all methane emissions in the region. Wetlands are also the major emissions source in New Hampshire, estimated to release 0.03 $Tg\,CH_4\,yr^{-1}$, almost half of all emissions from that state. County estimates of wetlands emissions are presented in Fig. 2.

We calculate 0.28 $Tg\,CH_4$ is emitted annually from active landfills in New England. This estimate is 31% of the total emitted from all sources and is the largest anthropogenic source in the region. Emissions are concentrated in urban southern New England, particularly Massachusetts (Fig. 3). Most landfill methane is emitted from only a few sites. The three largest emission sources are calculated to release 35% of all landfill methane; the twelve largest sources produce an estimated 60% of all emissions. We estimate 0.07 $Tg\,CH_4$ is recovered annually by landfill gas collection systems in New England. Point source estimates of active landfill emissions are provided in Fig. 4.

Our results indicate methane emissions from closed landfills may be on the same order of magnitude as wetlands and active landfills. In Massachusetts, we estimate 0.15 $Tg\,CH_4\,yr^{-1}$ is released from closed landfills, roughly 75% of that from active sites (Table 1). We estimate 0.05 $Tg\,CH_4\,yr^{-1}$ is emitted from closed landfills in Connecticut. Over half of the 576 closed landfills in Massachusetts and Connecticut were closed since 1980 and thus remain a prime emission source. If past waste disposal practices in other New England states resemble these two states, a regional estimate for methane emissions from closed landfills would be 0.25 $Tg\,CH_4\,yr^{-1}$.

Ruminant animals are calculated to release 0.05 Tg $CH_4\,yr^{-1}$. Half of all ruminant emissions are from Vermont where dairy populations are relatively high; three

Table 1
New England methane emissions: state estimates (10^9 g CH_4 yr^{-1})

State	Wetlands	Active landfills	Closed landfills	Ruminants	Residential wood combustion	Motor vehicles	Manure	Natural gas	Wastewater treatment	Soils	Total
Connecticut	10.6	27.9	50.9	7.0	3.0	2.4	2.8	1.0	0.2	− 3.7	102.0
Maine	239.7	4.9	24.9	9.4	10.0	1.4	2.0	0.1	0.0	− 30.6	261.8
Massachussets	31.4	206.1	154.1	6.5	5.0	4.8	1.3	1.9	0.3	− 5.6	405.8
New Hampshire	27.6	21.6	9.1	4.3	5.6	1.3	0.7	0.2	0.0	− 8.8	61.6
Rhode Island	3.4	6.6	9.0	0.5	0.8	0.7	0.1	0.1	0.1	− 0.7	20.8
Vermont	12.8	12.8	4.9	25.1	5.4	0.7	3.9	0.2	0.0	− 8.0	58.0
New England	325.5	279.9	252.9	52.9	29.9	11.2	10.8	3.5	0.6	− 57.4	909.9

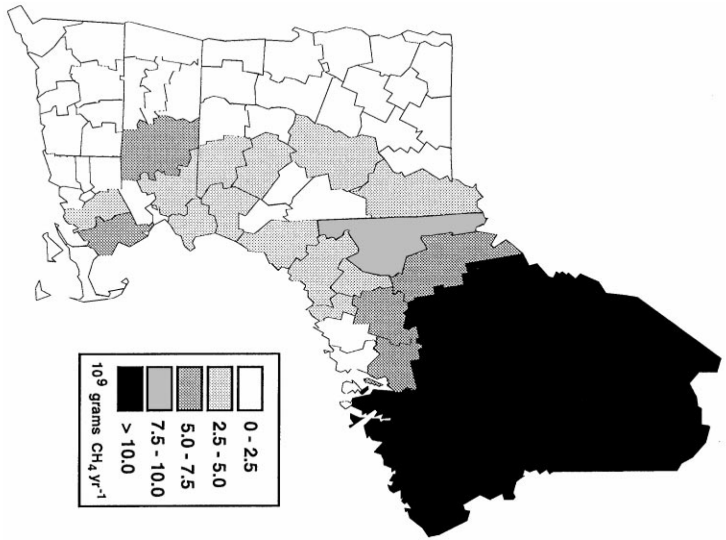

Fig. 2. Methane emissions from natural wetlands.

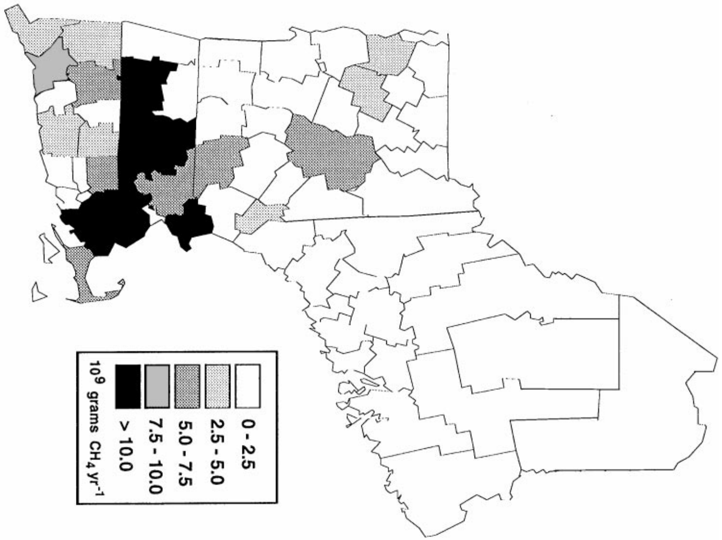

Fig. 3. Methane emissions from active landfills.

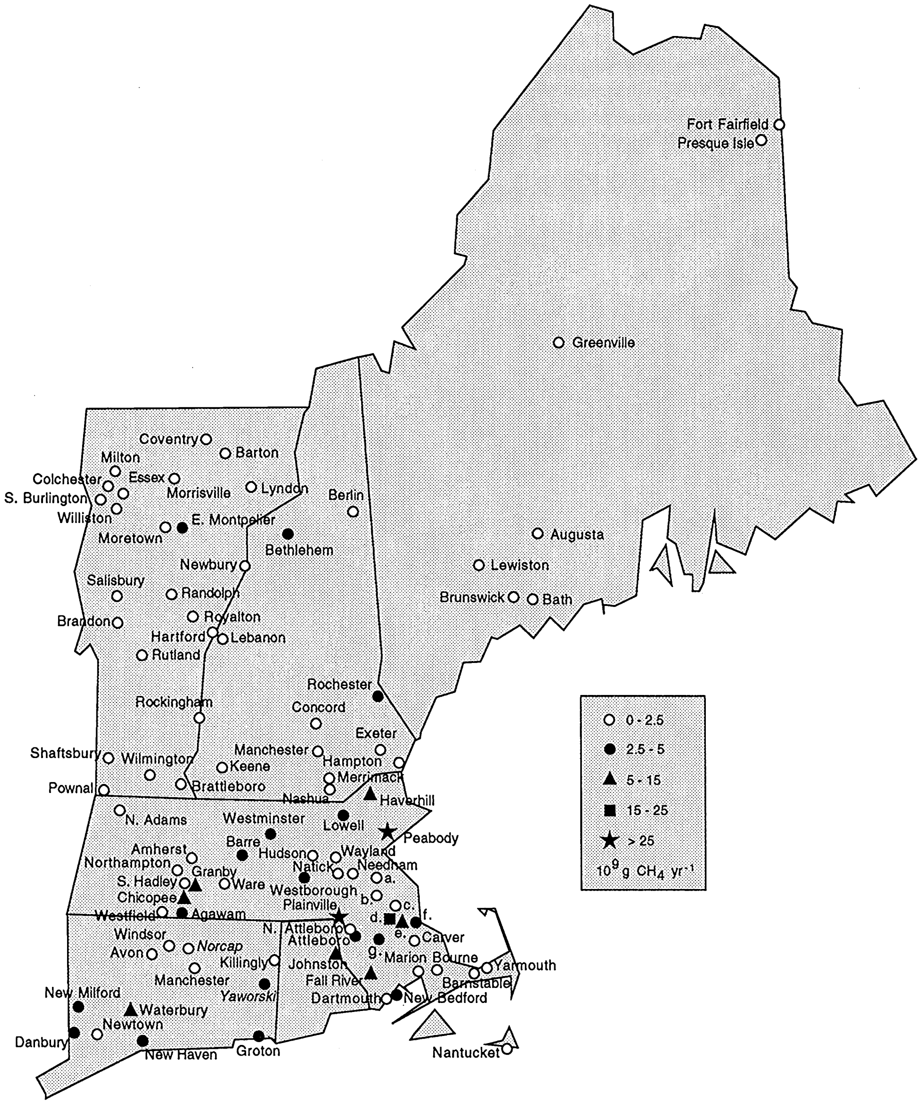

Fig. 4. Point source emissions from active landfills. CT, MA, NH, and VT tonnage data from the state DEP offices. Rhode Island data from the R.I. Solid Waste Management Corp. Tonnage data for Maine from Maine landfills. Landfill gas collection data from Governmental Advisory Associates Inc. Includes those landfills comprising >90% of the total tonnage landfilled in each state. Assumes 10% oxidation in the soil cover. (a) Milton, (b) Randolph, (c) Rockland, (d) East Bridgewater, (e) Halifax, (f) Plymouth, (g) Taunton. Landfill gas collection sites: Brattleboro, VT; Johnston, RI; Manchester, NH; Nashua, NH; New Milford, CT; Rochester, NH.

counties in that state produce 28% of all regional emissions. The states of Maine and Connecticut emit another 30% of the ruminant total. We estimate 0.01 Tg CH_4 is released annually from animal manure, the vast majority (94%) from dairy cattle and chickens (caged laying hens). Residential wood combustion, more prevalent in rural northern New England, is estimated to emit 0.03 Tg $CH_4\,yr^{-1}$. Maine produces a third of all regional emissions; New Hampshire and Vermont provide an additional 37%. In all, wetlands, landfills, ruminant animals, and wood combustion emit 98% of all regional methane. County estimates of methane emissions from all sources are provided in Fig. 5.

Fossil fuels do not appear to be a significant methane source, owing largely to the relatively small use of natural gas, low automobile emissions, and absence of coal mining in the region. We estimate natural gas emissions to be 0.003 Tg $CH_4\,yr^{-1}$, while motor vehicles release 0.011 Tg of methane annually. Connecticut and Massachusetts, the most populous states, emit over 60% of the

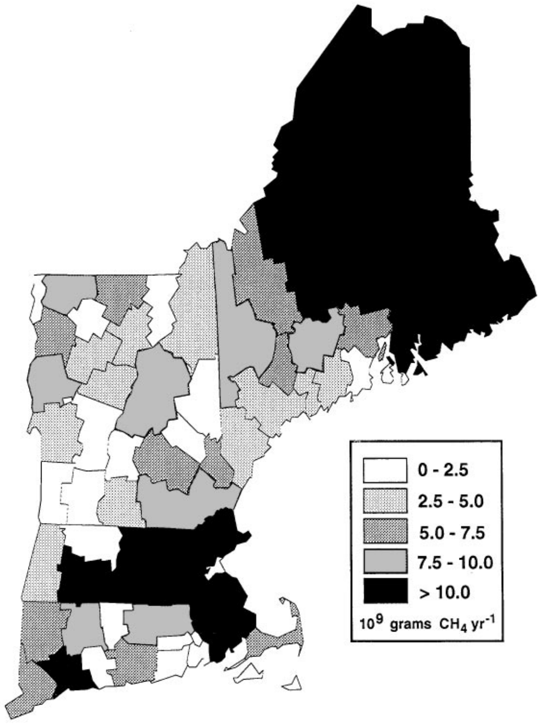

Fig. 5. New England methane emissions. (Excludes closed landfills which cannot be allocated on a country basis).

region's total from each of these sources. Wastewater treatment plants, the smallest methane source, release 0.63×10^9 g CH_4 yr^{-1}. Of this, about 0.12×10^9 g CH_4 is emitted from the biogas produced from anaerobic digestion.

The New England region is heavily wooded and the magnitude of this sink significantly decreases emissions of methane from soils by about 18%. The soil uptake of atmospheric methane, 0.06 Tg CH_4 yr^{-1} (Table 1), is relatively large in comparison to several of the sources in our inventory. It is larger, for example, than emissions from ruminants, manure, fossil fuels, and wastewater treatment. Uptake in forests (56.5×10^9 g CH_4 yr^{-1}; 98% of the regional total) dominates that from other land uses due to both their much smaller areas and lower consumption rates, a consequence of fertilizer use and changes in soil structure. Uptake in agricultural soils varies somewhat between states, ranging from less than 1% of the sink in New Hampshire and Maine, the most heavily forested states, up to 19% in Rhode Island. Overall, forests in Maine dominate uptake in the region, comprising 53% of the regional sink. The magnitude of the soil sink has increased significantly over the last 150 yr as large areas of land formerly cleared for agriculture have reverted to forest. In New Hampshire, for example, forests have increased from covering $<48\%$ of the state in the mid-1800's to the present 87% cover. The amount of land reverting to forest stabilized only in 1960 (Frieswyk and Malley, 1985a). Based on Forest Service estimates of forest cover at present and in the 1850's, we estimate that the magnitude of the soil sink for methane has been increased by 17×10^9 grams CH_4 yr^{-1} (30%) over the last 150 years.

4. Uncertainties

While carbon dioxide emissions from several sources, notably fossil fuel combustion, can generally be estimated with a relatively high degree of accuracy from commercial transaction statistics, methane emissions estimates are more uncertain. Uncertainties stem from two sources—a lack of available, verifiable data on inputs to emissions (as is the case with wood combustion and waste going to landfills) and an imperfect understanding of the many controls that regulate emission (as in landfills and wetlands). Landfills illustrate this point. Most landfill emission estimates are based on models. Our MEUS model calculates landfill emissions based on a series of factors: current annual disposal rates, a population-adjusted assumption about historical disposal rates, and assumptions about the organic composition of the waste stream, methane generation time horizon, depth of burial and soil oxidation rates. Each of these model inputs has an associated uncertainty which cannot easily be quantified but which increases the overall uncertainty of the emissions estimate. These data and process constraints make rigorous uncertainty estimates difficult and highly unreliable. Waste disposal rates, for example, are rarely reported; they are typically estimated from the tipping fees received by the landfill or remaining landfill capacity. Similarly, few records exist of prior years tonnage statistics. Estimating these earlier figures based on current population statistics will likely be in error, particularly in view of recent trends in waste management such as increased recycling and the greater regionalization of landfills. Assumptions made about the physiochemical characteristics of the landfill, waste stream, and soil cover are reasonable, but ignore variability between landfills. Since other methane sources typically have comparable uncertainties associated with their data sources and methodologies, we have elected not to attempt to bound these uncertainties in this report. Given the magnitude of the source strength of landfills and wetlands in our inventory, we do not believe this omission affects the results of our study.

5. Comparisons with other inventories

The Environmental Protection Agency has provided funding over the last few years to compile state inventories of anthropogenic greenhouse gas emissions. The inventories use a standardized protocol comparable to that of the national inventories required by the United Nations' Framework Convention on Climate Change. Four of the six New England states are participating in this project and two states, Maine and Vermont, have completed their inventories (Vermont Department of Public Service, 1994; Simmons, 1995). Overall, our results compare reasonably well with the Maine and Vermont reports. Vermont's landfill emissions estimate is 0.012 Tg CH_4 yr^{-1}, 90% of our estimate. Maine's landfill estimate is an order of magnitude higher than ours, 0.034 Tg CH_4 yr^{-1} compared to 0.005 Tg CH_4 yr^{-1}. This difference appears to be due to the use of different landfill tonnage figures. Maine estimates 468 000 t of municipal solid waste were landfilled statewide in 1991. Our estimate, based on telephone inquiries to the landfill operators in the state, assumes 100 000 t were landfilled in 1994. This dramatic decrease is likely the result of higher recycling and incineration rates (Maine Waste Management Agency, 1993) in 1994. If we use the Maine 1991 tonnage figure our model estimate would be 0.024 Tg CH_4 yr^{-1}.

Ruminant emissions from both states and manure estimates from Maine are within 10% of our figures, a result of the use of similar animal populations and emissions factors used to derive these estimates. Vermont's manure estimate is 0.45×10^9 g CH_4 yr^{-1}, an order of magnitude lower than our emissions estimate. This difference appears to be due to differences in assumptions about the waste management systems used in that state. Vermont has assumed that 29% of dairy manure is pastured, and thus a relatively small emissions source. According to Safley (1992), no dairy manure is pasture managed in the United States and this 29% of dairy manure in Vermont is liquid slurried, ideally suited for methane production. This difference in waste management systems illustrates the sensitivity of releases to moisture and climate. Maine calculates 1.19×10^9 g CH_4 is emitted annually from residential wood combustion, about 12% of our estimate. Although our methodologies are quite different, both have a high degree of uncertainty. More research is clearly needed to improve emissions estimates from this source.

Comparing our results with US estimates yields some interesting observations. Although active landfill emissions make up 36% of all anthropogenic emissions for the United States (EPA, 1995), they are 73% of the total for New England. This regional difference is largely the result of smaller energy sector emissions and relatively small ruminant populations in New England. Residential wood combustion appears to make a larger contribution to emissions in New England, (8 vs 2% nationally (EPA, 1995)). These source magnitude differences between regional and national studies underscore the importance of using local to regional scale inventories to determine an effective and efficient methane mitigation strategy. In New England, for example, controlling emissions from both open and closed landfills of large to moderate size will be the most effective strategy to reduce anthropogenic inputs. Mitigation plans aimed at other sources will have, at best, second order effects.

6. Emission trends

New England landfills the smallest percentage of its waste stream of all regions in the United States, largely the result of its highest incineration rates (Biocycle, 1996). Recycling rates currently average about 27% (Biocycle, 1996) and are targeted to increase over the next few years. Population growth is expected to increase at an annual rate of about 0.8% through the year 2010; slightly lagging the US projected rate of 1% (Bureau of Economic Analysis, 1995). Higher recycling rates and moderate population growth should therefore limit growth in the quantity of waste landfilled through 2010. Assuming landfill trends in New England parallel those of the rest of the United States, a reasonable projection is no change from current disposal levels (EPA, 1996).

Future methane emissions from landfills will be principally determined by landfill gas recovery efforts in the region. New Source Performance Standards effected in 1996 require all landfills that have received municipal solid waste since 8 November 1987 and have a design capacity equal to or greater than 2.5 million metric tons and non-methane organic compound (NMOC) emissions exceeding 50 metric tons per year to collect their landfill methane (Federal Register, 1996). This requirement is expected to reduce NMOC emissions by 53% and methane emissions by 39%. The regulation should affect about 312 US landfills (Federal Register, 1996) and at least six in New England.

Even landfills exempted from mandatory reductions are expected to increase their methane recovery efforts. Regulatory compliance with both the Clean Air Act and the Resource Conservation and Recovery Act has increased the cost of municipal waste disposal. This, coupled with the difficulty in siting new landfills has resulted in the regionalization of landfills; a trend likely to continue. Larger landfills have economies of scale which often make gas recovery efforts economically viable. To encourage methane recovery as an energy resource, the EPA has initiated a Landfill Methane Outreach Program. The program provides participants with information about the opportunities and benefits of landfill gas recovery and offers regulatory flexibility and technical assistance to promote development.

Natural gas consumption in New England has increased 38% since 1991 to a current level of 600 billion cubic feet annually (EIA, 1996a). Consumption is expected to increase over the near term, with particularly strong growth in the industrial sector, especially cogeneration (EIA, 1995b). In response to increased demand, new transmission pipelines have been proposed. The 250 mile Portland pipeline from Jay, Vermont (near the Canadian border) to Haverhill, Massachusetts will add 250 million cubic feet per day pipeline capacity to the region (EIA, 1996c) and is expected to be operational by 1998 (Bay State Gas, 1996).

Long-term projections for natural gas in the US are also quite favorable. Gas consumption is projected to increase at an annual rate of 1.7% through the year 2015 (EIA, 1996d). Natural gas is predicted to supply an increasing share of the US' energy requirements, as its reliance on nuclear power declines. Natural gas currently provides 10% of electrical generation needs, a share expected to increase to 29% by 2015 (EIA, 1996d).

While carbon emissions from motor vehicles are expected to increase in the future as a result of increased vehicle miles traveled (EIA, 1996d), methane emissions from this sector should decline (EIA, 1996b). Methane emissions are sharply reduced in passenger vehicles using emission control technology; as older vehicles are replaced with newer vehicles equipped with this technology, emissions should decrease. Methane emissions from passenger vehicles in the US fell 34% from 1988 to 1994 (EIA, 1996b) and further reductions in emissions are likely over the near term. Methane emissions from residential wood combustion should remain relatively constant over the next 20 years, since little change is projected from current consumption levels (EIA, 1996d). Wastewater treatment emissions, which are closely correlated with population growth, are expected to increase in the US at an annual rate of about 1% (EIA, 1996b).

Therefore, while landfills will remain the largest anthropogenic methane source in New England, future emissions will depend on what methane recovery efforts are undertaken in the region. Natural gas sector emissions should increase, in response to increased demand, while vehicle emissions should decline. Other sources will likely remain relatively constant.

7. Summary and policy implications

Although the New England region is highly urbanized, our results indicate natural sources of methane make the single greatest contribution to total emissions, 0.33 $Tg\,CH_4\,yr^{-1}$, with contributions varying between 8% (Massachusetts) and 92% (Maine) of state totals. Landfills are the dominant anthropogenic source, emitting 0.28 $Tg\,CH_4\,yr^{-1}$. A few large landfills emit most of the source total suggesting a mitigation strategy targeted to these sites could be highly effective and relatively simple to implement. Approximately, 157 landfills in the United States and six in New England recover or intend to recover methane (GAA, 1991). While current federal regulations mandate gas recovery at only the largest sites, expanding collection efforts to moderately sized landfills through either voluntary compliance (by promoting the benefits of gas recovery) or further regulations would significantly reduce anthropogenic emissions. We estimate a 30% reduction in landfill emissions (a 50% reduction in emissions from the region's twelve largest landfills) would result in a 0.08 $Tg\,CH_4\,yr^{-1}$ decrease in atmospheric emissions, 9% of the region's total. It should be noted, however, that the large population of closed landfills in the region complicates the impact assessment of a mitigation strategy targeted toward active sites. Since most closed landfills are exempt from recent federal regulations yet continue to emit methane over a roughly 30 yr time horizon, mitigation efforts aimed at only open landfills may result in only modest reductions in anthropogenic emissions over the short-run.

Closed landfills appear to be a significant emissions source. We calculate 0.15 $Tg\,CH_4\,yr^{-1}$ and 0.05 $Tg\,CH_4\,yr^{-1}$ is emitted from closed Massachusetts and Connecticut landfills, respectively, and an additional 0.05 Tg $CH_4\,yr^{-1}$ could result from other closed landfills in the region. A 1990–1992 field measurement survey of urban methane emissions in 13 US cities by Aerodyne Research Inc., Washington State University, and the University of New Hampshire found closed landfills were frequently the source of elevated concentration levels (McManus et al., 1994). More research is clearly needed to identify the locations of these closed landfills and improve emissions estimates from this source.

Ruminant animals and residential wood combustion are estimated to emit 0.06 and 0.03 $Tg\,CH_4\,yr^{-1}$, respectively. Wood combustion has particularly interesting policy implications, although more data are needed on wood consumption to more accurately quantify emissions from this source. Although wood emissions are an order of magnitude lower than landfills, it is one of the few other sources that may be amenable to mitigation, through a greater use of more efficient catalytic stoves.

Despite its inherent uncertainties, we believe regional inventories such as this are a useful tool for improving US estimates of atmospheric methane. The relative importance of specific methane sources depends on an array of demographic, economic, and ecosystem variables. Identifying these variables and calculating source magnitudes at a sub-national scale provides the quantitative data necessary to develop sound mitigation strategies and achieve the emissions reductions targeted in the US Climate Change Action Plan.

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