

Airborne particulates and asthma: a Maine case study

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Maine currently has the second fastest growing asthma rate in the nation – 9.4% of the adult population has asthma and one out of eight children is affected. The factors behind this increase are poorly understood, but previous reports suggest that biologically soluble metal ions from particulate matter (PM₁₀) may play a role in asthma episodes. In an effort to study this issue, we first identified geographic and temporal trends in Maine asthma hospitalizations. Clinical data show a strong fall peak in asthma admissions with weaker peaks in January and May, and a summer low in asthma admissions. Asthma admissions are also higher in the cities than in the rural areas in Maine. We then analysed PM₁₀ collected by the Maine Department of Environmental Protection in three different Maine locations in the years 2000 and 2001, at times when clinical asthma data showed peaks and during the summer low period. We also collected soil samples in the same locations. The PM₁₀ and soils were analysed for 10 metals by acid extraction to determine total metal content and then with cell culture medium, DMEM/F12+CCS growth medium, to determine metal biosolubility. Our results showed that Mn, Cu, Pb, As, V, Ni and Al were present in the Maine PM samples. V, Ni and Pb showed seasonal variation, while the others were relatively constant throughout the year. Pb and Al did not appear to be soluble in the biological medium. There was also variation from location to location with the urban area showing the highest concentrations for most metals. Aluminium was present in the highest concentration in soil samples, followed by Mn and V. Only Cu was biologically available in soils. We determined from M/Al ratios that most of the PM₁₀ did not originate from local crustal material. *Toxicology and Industrial Health* 2005; **21**: 75–92.

Key words: *asthma; heavy metals; PM₁₀; suspended particulate matter*

Introduction

Asthma has been documented as a worldwide epidemic (Kheradmand *et al.*, 2002). It is one of the most common chronic diseases in the USA (Mannino *et al.*, 1998), with an estimated 26 million people diagnosed with asthma, an increase of 82% over the last 15 years. Asthma

has a significant impact on the US people, costing over \$12 billion annually and accounting for about 3 million lost work days and more than 10 million lost schools days (Eggleston *et al.*, 1999). Between 1970 and 1998 the death rate from asthma increased 55.6% even though the death rate from all causes combined decreased 18% (American Lung Association, 2001).

In 1996 the northeast region of the USA had the highest absolute rate of asthma as the primary diagnosis for hospitalizations. Currently, the rate of asthma occurrence in Maine is the second fastest

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growing in the nation – 9.4% of the adult population has asthma, and currently one out of eight children is affected. Maine and Connecticut show greater than 13% asthma prevalence among children (NEARC, 2004). Of the seven states with the highest asthma rates in the country, five are in New England, with nearly a million adults in the region with asthma (PPH, 2003). Yet, it is a poorly defined condition because little is known about its causes and history (Friedman *et al.*, 2001).

Different segments of the population are known to have different susceptibilities for asthma. Hospital and emergency room admissions from 1960 to 1999 show females and age 0–4 children with highest admission rates, while admission rates for black populations are consistently 3- to 4-times higher than in white populations (CDC, 1998; 2002). Psychosocial factors, such as exercise and stress, and socioeconomic factors such as poverty and single motherhood contribute significantly to asthma incidence and its variability (Kimes, Ullah *et al.*, 2004).

Many other factors have been considered as potential asthma episode triggers. It has been suggested that these factors fall into four main categories: indoor environmental factors, outdoor environmental factors, infectious agents and psychosocial factors (Kimes *et al.*, 2004). Possible outdoor factors include air toxins, endotoxins, particulates, climate factors, pollen, mold spores or airborne eroded soils contaminated with possible irritants such as pesticides, fungicides or fertilizers. In particular, SO₂, particulates and O₃ have been shown to increase the incidence of asthma episodes (Jamason, 1997; Redd, 2002; Wilson *et al.*, 1995), and exposure to poor air quality is also correlated with increases in admissions for asthma (Chen *et al.*, 2000). Many studies have shown significant increases in incidence of acute respiratory symptoms and significant decreases in pulmonary function from ambient outdoor air pollution (Calderon-Garciduenas *et al.*, 2000; Mortimer *et al.*, 2000), and significant health effects occur at levels far below the National Ambient Air Quality Standards (Gent *et al.*, 2003; Spektor *et al.*, 1988a,b). Some environmental factors have distinct seasonal patterns (e.g., ozone, pollen) while psychosocial factors such as poverty and education are relatively constant over periods of time.

Large pollution events of organic dust have been shown to cause sudden epidemics in asthma events (D'Amato, 2000), and correlations between hospital admissions and particulate matter in specific locations have been demonstrated (Claiborn *et al.*, 2002; Lin *et al.*, 2002; Ostro *et al.*, 2001; Stieb *et al.*, 2000; Tolbert *et al.*, 2000).

Furthermore, epidemiological studies in a number of regions show a strong correlation between asthma incidence and particulate matter with a particle size of less than 10 µm (PM₁₀) (Brunekreef *et al.*, 1995; Koren, 1995; Leaderer and Beckett, 1997; Peden, 2001; Stieb *et al.*, 2000). In addition, particles 10 µm and smaller represent the most chemically active part of the soil and thus have the potential to carry heavy metals, pesticides and spores from microbes, as well as nutrients for plant growth (Shinn, 2000). Because the average person inhales about 20 m³ of air/day, and an average Maine resident inhales about 1 mg of PM₁₀ daily (ALA, 2002), it is understandable that the intimate contact with the surrounding atmosphere means residents are highly susceptible to airborne pollutants (Holgate, 1995).

Therefore, the objective of this research was to assess the dynamics of Maine's asthma history and to examine PM₁₀ as a potential environmental trigger for asthma episodes in Maine. Specific goals are:

- 1) to identify geographic trends and temporal trends in Maine asthma hospitalizations by age, gender and race; and
- 2) to begin to identify the origins of the PM₁₀ by collecting and analysing PM₁₀, and comparing results with similar analyses of local erodible soils.

Methods

Clinical

Clinical data sets were collected from the Maine Health Data Organization (MHDO). This nonprofit organization collects all admissions records from all Maine hospitals for both inpatient (IP) and emergency department admissions. We obtained IP records from 1980 to 2001, and Outpatient (ER) records from 2000 and 2001.

We analysed admissions where the principle diagnosis was asthma, classified as ICD9 code 493xx, by the *International Classification of Disease*, ninth revision. The database also contained up to 10 secondary ICD9 codes, however the principle diagnosis was the only one used to mark an admission. We discarded secondary asthma admission codes, because it is likely that the patient was admitted to the hospital for urgent care other than asthma.

For each admission, the patient's age, sex, admission date and geocode were recorded. We examined admission records at a weekly interval, as the small total population in Maine results in daily admission data that are too small to be useful. Weeks start on 1 January of the respective year, and consist of seven days. Each year contains 52 weeks that make up 364 days of the year, the 365th day was added to week 52, as well as the 366th day on leap years. The correspondence between week, month and date are shown in Table 1.

Two broad age groups were analysed. The age group labelled 'paediatric' contains admissions from 0–18 year olds. The age group labelled 'adults' contains admissions from 19 years old and greater. Paediatric age groupings were defined based on the Center for Disease Control groupings used in their national statistics. The age group 0–4 represents preschool children, 5–14 represents elementary and middle schools, and 15–18 represents high school age children.

No distinctions were made between genders in this study as initial analysis showed only insignificant differences in admissions, which did not affect the major trends that are the focus of this study. In addition, racial characteristics were not included in

this study as only ~3% of the Maine population is not Caucasian. This is not to say that racial characteristics do not have significance in this study, only that their numbers are too few for analysis.

The asthma admission rate was defined as the number of admissions per 10 000 individuals. Year 2000 census populations were used to assign 2000 and 2001 admission rates. Census information was obtained from the US Census Bureau. An assumption is made that the population of an area may vary from 2000 to 2001, but the difference in change between towns is insignificant, and will insignificantly alter the major trends among the different geographic types analysed.

Geocodes, which are similar to Zip codes only more constant over time, are used in the census data sets to define the town in which the patient resides. The designation 'large' cities refer to Portland, Bangor, Lewiston, Auburn and Augusta, all with populations >18 000 people. The designation 'small' cities refers to Biddeford, Brunswick, Gorham, Orono, Presque Isle, Saco, Sanford, Scarborough, South Portland, Waterville, Westbrook and Windham, with populations between 10 000 and 18 000 people. The designation 'rest of state' refers to the state total less the asthma admissions from large and small cities combined. The 'rest of state' designation represents towns with a population of less than 10 000 people.

Soil and PM₁₀ collection

Soil samples were collected from surface horizons according to standard methods (Soil Survey Staff, 1993). Samples were collected from Portland,

Table 1. Corresponding week, month and date of the year.

Week	Month/dates	Week	Month/dates	Week	Month/dates	Week	Month/dates
1	Jan 1–7	14	Apr 2–8	27	Jul 2–8	40	Sep 31–Oct 7
2	Jan 8–14	15	Apr 9–15	28	Jul 9–15	40	Oct 8–14
3	Jan 15–21	16	Apr 16–22	29	Jul 16–22	42	Oct 15–21
4	Jan 22–28	17	Apr 23–29	30	Jul 23–29	43	Oct 22–28
5	Jan 29–Feb 4	18	Apr 30–May 6	31	Jul 30–Aug 5	44	Oct 29–Nov 4
6	Feb 5–11	19	May 7–13	32	Aug 6–12	45	Nov 5–11
7	Feb 12–18	20	May 14–20	33	Aug 13–19	46	Nov 12–18
8	Feb 19–25	21	May 21–27	34	Aug 20–26	47	Nov 19–25
9	Feb 26–Mar 4	22	May 28–Jun 3	35	Aug 27–Sep 2	48	Nov 26–Dec 2
10	Mar 5–11	23	Jun 4–10	36	Sep 3–9	49	Dec 3–9
11	Mar 12–18	24	Jun 11–17	37	Sep 10–16	50	Dec 10–16
12	Mar 19–25	25	Jun 18–24	38	Sep 17–23	51	Dec 17–23
13	Mar 26–Apr 1	26	Jun 25–Jul 1	39	Sep 24–30	52	Dec 24–31

Bridgeton and Presque Isle during September, 2003 (Figure 1). Portland was chosen because it is the largest city in Maine, while Bridgeton and Presque Isle were chosen to represent rural areas in south-western and northern Maine. Samples were air dried and stored in sterile sample bags at room temperature until ready for analyses. Samples were ground and passed through a 2-mm sieve prior to analysis.

PM₁₀ filters were obtained from Maine Department of Environmental Protection (DEP), which operates collection sites in Portland, Bridgeton and Presque Isle. The Maine DEP archives filters containing PM₁₀ and was willing to provide the recorded weights of the PM₁₀ on the filters and samples of filters requested for specific dates. The dates were chosen to correspond with peaks in asthma admissions identified from previous years (January, May and September), or with the summer low in asthma admission (July). Filters containing PM₁₀ were sectioned as described in EPA Compen-

dium Method 3.1. Soil samples were weighed and then treated similarly to the PM₁₀ samples.

Acid extraction procedure

This procedure closely follows the EPA Compendium Method IO-3.1 (EPA, 1999). A soil sample that weighed between 0.5 and 1.0 g, or a filter section was placed in a 150-mL beaker and 10.0 mL of extracting acid added. The extracting acid was 2.0 M in HCl and 0.9 M in HNO₃. The resulting solution was covered with a watch glass and gently refluxed in the hood for half an hour with DI water added when necessary to prevent the solution from evaporating to dryness. After removing from the heat and allowing the solution to cool, enough DI water was added to return the volume to approximately 10 mL and the solution was transferred to a 25-mL volumetric flask. The remaining sample in the beaker had 10 mL of DI water added to it and was allowed to sit for half an hour. At that point the wash solution was also transferred to the 25-mL volumetric flask and the volume made up to 25 mL with DI water rinses from the sample beaker. The transfer of particles does not matter, as after mixing the solution in the volumetric flask, the solution was syringe filtered to an acid-washed 15-mL capped centrifuge tube. The tube was marked with the date and sample information and stored for analysis on a Perkin Elmer Optima 2000 Inductively Coupled Plasma Emission Spectrometer (ICP-AES, Shelton, CT, USA).

Biological extraction procedure

This procedure was very similar to the acid extraction procedure. In this procedure the soil samples of similar sizes or filter sections were placed in 150-mL beakers and 10 mL of cell culture medium added. The cell culture medium consisted of DMEM/F12 medium plus 15% Cosmic Calf Serum, 1% antibiotic, 1% L-glutamate and 0.1% sodium pyruvate. The solution was covered with a watch glass and heated at 37°C for 24 hours. After cooling, the solution was transferred to a 25-mL volumetric flask and 10 mL of DI water added to the sample in the beaker. The wash solution was allowed to sit at 37°C for half an hour and then it too was transferred to the 25-mL beaker and DI water rinses of the sample were used to bring the

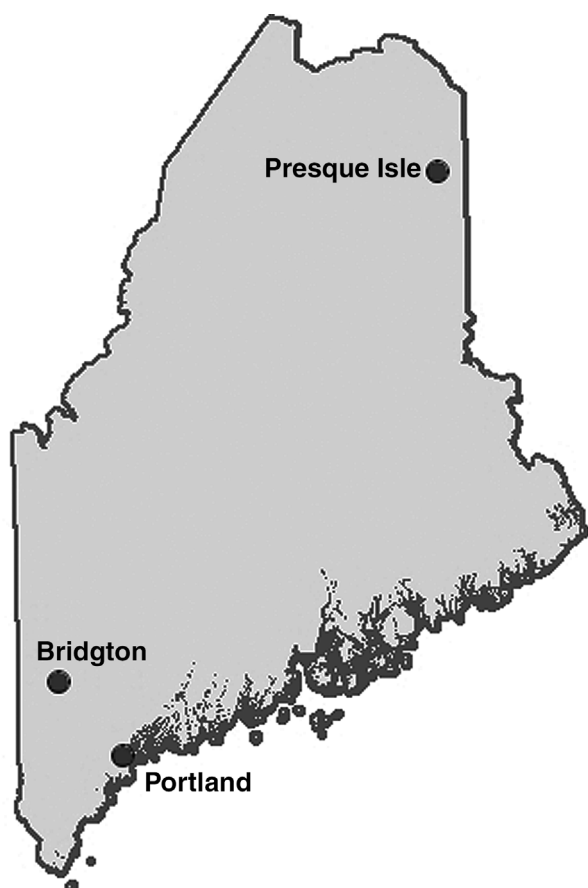


Figure 1. Sample collection locations.

solution to 25 mL. After thoroughly mixing the solution, it was syringe filtered through a 20- μ m filter into an acid washed 15-mL capped centrifuge tube. The tube was marked with the date and sample information and stored in the refrigerator until it was analysed by ICP-AES.

Accuracy assurances for analyses

Standard solutions for metal analyses were made from certified Reference Standards of 1000 ± 1 ppm purchased from Fisher Scientific Co (Suwanne, Georgia, USA) and diluted to specified concentrations with 2% trace metal-free HNO_3 . Empty filters were extracted by both acid and biological extraction procedures and the results were subtracted from the corresponding metal analyses. The cell culture medium was also analysed for metals and biological extractions of PM_{10} and soil analyses were corrected for the metals found in the medium. In order to check the accuracy of the acid extraction procedure, replicate samples of NIST Refer-

ence Material 1648 were analysed by this procedure and the results compared to the analysis provided with the reference material. Further controls included a matrix spike where a blank filter was treated with 1 mL of the highest concentration of each metal standard and then taken through the acid extraction procedure and analysed as a sample. An Internal Calibration Verification Standard (ICVS) was a fourth standard for each metal with a known concentration which was approximately an average of the highest and lowest standard for that metal. The ICVS was analysed as a sample.

Result

State populations

Maine's weekly paediatric ER and hospital asthma admissions for 2000 and 2001 are shown in Figure 2(a,b). The figures show how admissions are elevated from the beginning of the year to late

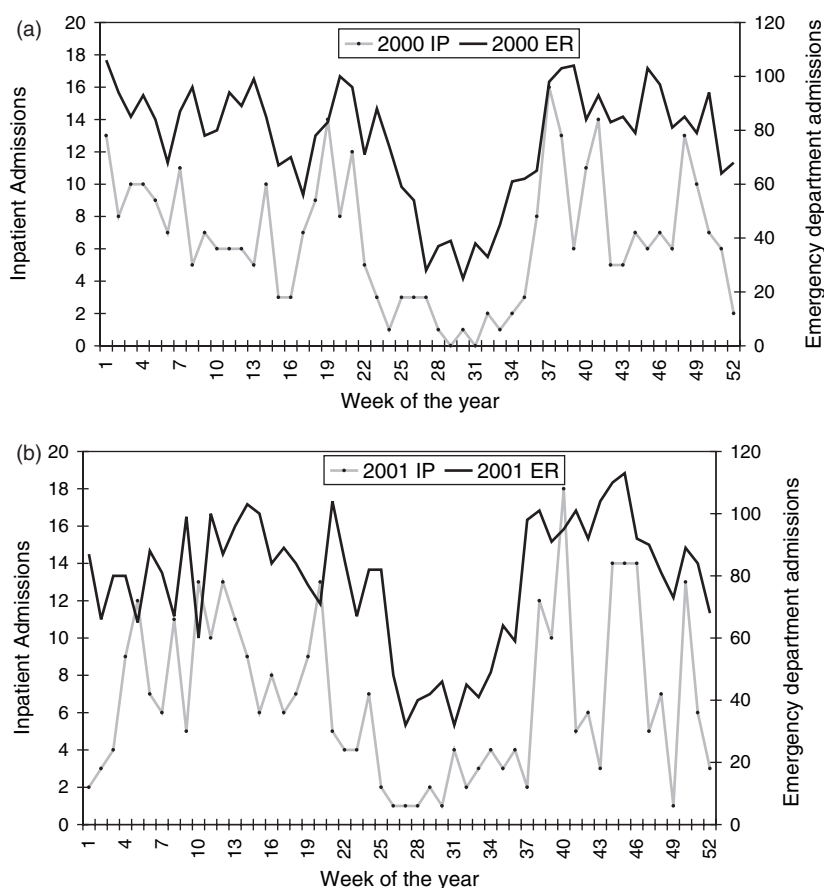


Figure 2. (a) 2000 Maine paediatric IP and ER asthma admissions. (b) 2001 Maine paediatric IP and ER asthma admissions.

spring, depressed during the summer and elevated again in the fall and for the remainder of the year. This general trend is consistent each year for hospital (IP) and ER admissions, but large variation in the peaks and troughs occur. These peaks are unique events that vary in timing and relative magnitude from year to year, consequently it is important not to average data between years, as important information can be masked. The importance of not averaging data between years is shown in Figure 3, which plots yearly data along with 22-year average data. These data show the general trends of high winter/spring and fall rates, but it is evident that long-term averages mask specific events occurring in various years.

From examining multiple years of data and generalizing trends, prominent features consistently stand out each year (Figure 3). The most notable and consistent feature each year is a summer lull in paediatric asthma admissions that ends with a dramatic fall peak. The summer lull in paediatric admissions averages eight weeks and occurs between weeks 25 (mid-June) and 33 (mid-August). The first paediatric fall peak occurs at week 38 (mid-September) with relatively little deviation in timing from year to year (s.d. = 0.8 weeks). The first fall peak is the highest peak for 14 of the 22 years of paediatric IP records; its magnitude ranges greatly from 13 admissions to 50 admissions, with an average of 24 admissions. There is no significant change in magnitude or timing of the first fall peak from 1980 to 2001. The average number of weeks it takes for the first fall peak to rise from the summer lull is four weeks and ranges from two to seven

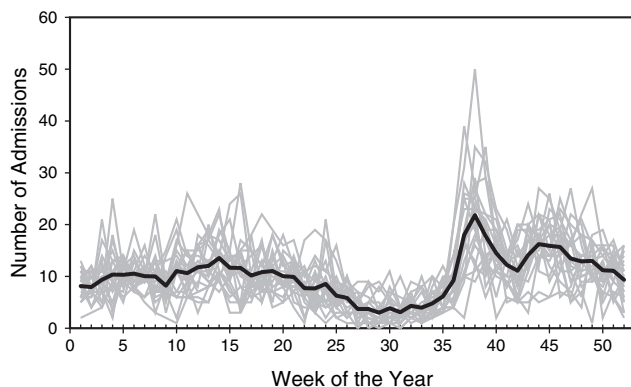


Figure 3. Maine weekly paediatric IP asthma admissions from 1980 to 2001.

weeks (Figure 3). Adult IP admissions from 1980 to 2001 have a less defined summer lull than paediatric admissions, and the first fall peak is less defined with respect to both timing and magnitude than paediatric admissions (data not shown).

In 2000 and 2001, paediatric ER admissions had a shorter summer lull than paediatric IP admissions by four and six weeks respectively (Figure 2), while adult ER admissions had a longer summer lull by three weeks for both years. For ER and IP admissions, both age groups show similar first fall peak timing at weeks 38–40. The summer lull is less defined in adult ER admissions than it is for paediatric admissions, similar to the trend seen in the IP admissions.

When paediatric admissions are broken down by age group, ER admissions show all paediatric age groups beginning their summer lull on weeks 27 and 26, for 2000 and 2001 respectively (Figure 4a,b), however, the first fall peak for ages 5–14 is four weeks earlier than ages 0–4 and 15–18 in 2000, and two weeks earlier in 2001. Therefore, the summer lull for ages 5–14 is shorter than other paediatric age groups by four weeks and two weeks for 2000 and 2001 respectively (Figure 4a,b).

Urban versus rural

Both paediatric and adult ER admission rates for Maine's larger cities are higher than for the smaller cities, and the rest of the state's admission rates throughout 2000 and 2001 (Figure 5a,b and Figure 6a,b). In 2000 and 2001, the highest asthma rates were in Bangor, Augusta, Portland and Waterville. In 2000 Bangor, Portland, Presque Isle and Augusta had the first, second, third and fourth highest overall yearly paediatric rates, respectively, while in 2001 the four highest were Bangor, Augusta, Waterville and Portland (Figure 7). Trends between smaller cities and rural Maine are more similar to one another than to larger cities for both paediatric and adult admissions. The first fall peak of large cities is less defined than the rest of the state for both paediatric and adult admissions.

ER admissions for Maine's larger cities show the first fall peaks in 2000 and 2001 occurring three and four weeks later, respectively, than the rest of the state's first fall peaks. The first fall peak for paediatric admissions in large cities comes three to four weeks earlier than the rest of the state in 2000

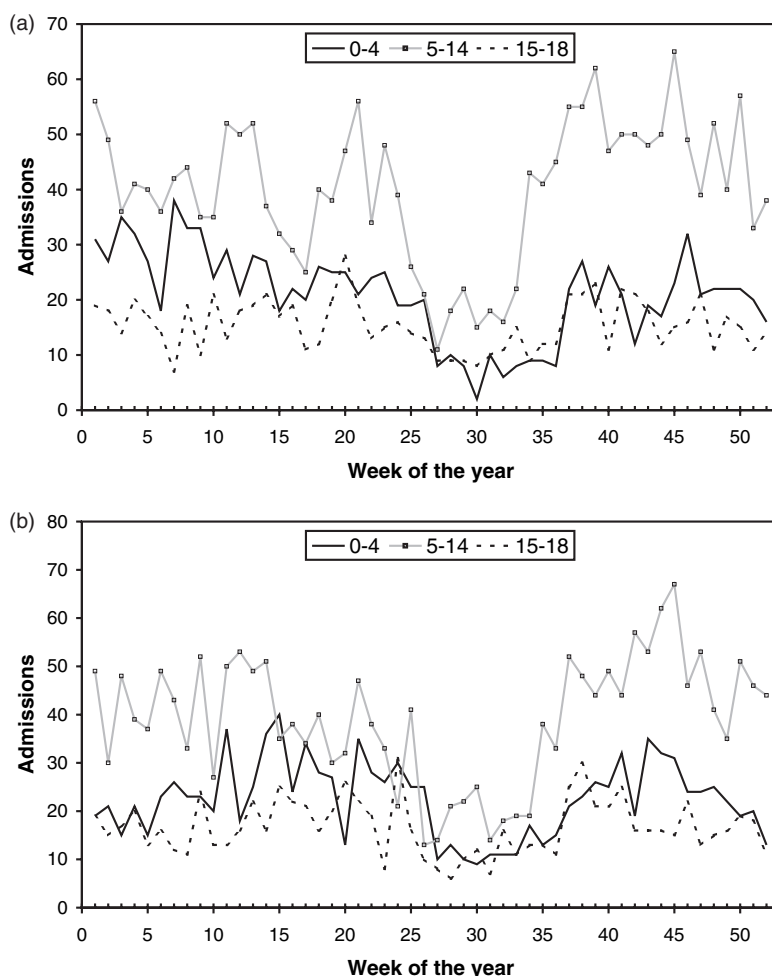


Figure 4. (a) 2000 Maine paediatric ER asthma admissions by age group; (b) 2001 Maine paediatric ER asthma admissions by age group.

and 2001 respectively (Figure 6a,b). Although somewhat noisy, the 22 years of IP admissions show the first fall peak for cities coming after the rest of Maine for 12 years, while occurring on or before only eight times (figure not shown).

PM₁₀

The amount of airborne particulate matter collected on filters was greatest in Portland and least in Presque Isle (Figure 8). Portland filters were heaviest in the winter (January), while Bridgeton filters were heaviest in the spring (May). Presque Isle filter weights varied, but not systematically.

To evaluate the accuracy of the acid extraction method, NIST Standard Reference Material 1648 was analysed. Analysis for the metals in this study, manganese, copper, vanadium, nickel and lead, showed that the method gave amounts that were

at least 75% of the amounts reported by NIST and many were closer. Matrix spikes were also within 25% of the expected values and the ICVS standard was 90% or greater of the expected values (data not shown).

Analysis of the filters showed that aluminium was present in highest concentrations in all filters analysed by acid extraction, regardless of time or location. Copper was the second most abundant element, although V exceeded Cu in the winter in Portland and in Presque Isle in winter 2000 (Figure 9a–d). The third most abundant element varied with time and location – for example, Mn was often the third most abundant element in the spring, summer and fall in all locations. In the winter the third most abundant element was V, Pb, Ni or Mn, depending on location and year. Vanadium, Al and Pb were always higher in Portland than in Bridgeton or Presque Isle.

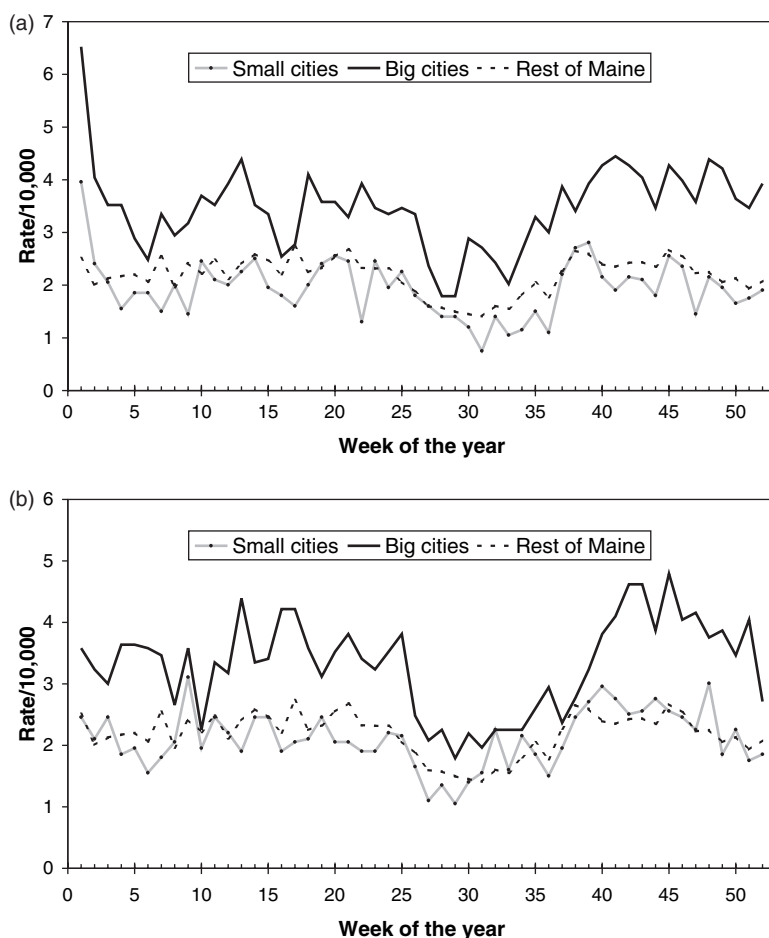


Figure 5. (a) 2000 Maine ER rates by geographic type. (b) 2001 Maine ER rates by geographic type.

Most of the acid extractable elements did not exhibit any temporal trends (with season or year). Cu spiked in the spring in Presque Isle 2001, while in Presque Isle in 2000 Cu concentrations were lowest in the spring. Arsenic spiked in Presque Isle 2000 in the summer and in Bridgeton in the winter of 2000. However, lead and vanadium showed definite trends. Lead was highest in the winter and decreased to fall. The one exception was a spike in Portland in the spring of 2001. Vanadium was highest in the winter, declined through the spring and summer and began to increase again in the fall. In Bridgeton only, nickel appeared to be seasonal, with a winter high and low concentrations the rest of the year.

Soils

Aluminium was always present in highest concentrations in soil extracts, followed by Mn and V

(Figure 10a). All the elements were present in highest concentrations in the Presque Isle soils, with the exception of Pb that was highest in Portland, likely due to past industrial activities. All elements were present in the lowest concentrations in Bridgeton. Soil pH was the most acidic in Bridgeton, and almost neutral in Portland (data not shown).

In general, very little of the acid extractable metals in the soils were biologically available, although 30% of Cu was available (Figure 10b, Table 2). A greater amount of metals in the filters were biologically available. Almost all of the V, As and Cu were biologically available, while >50% of Ni, but <50% of Mn and none of the aluminium and lead was biologically available.

To evaluate the amount of PM₁₀ which came from soils, metal to aluminium ratios were calculated for all PM₁₀ and soils. The PM₁₀ ratios were then compared to soil ratios by location. PM₁₀/soil

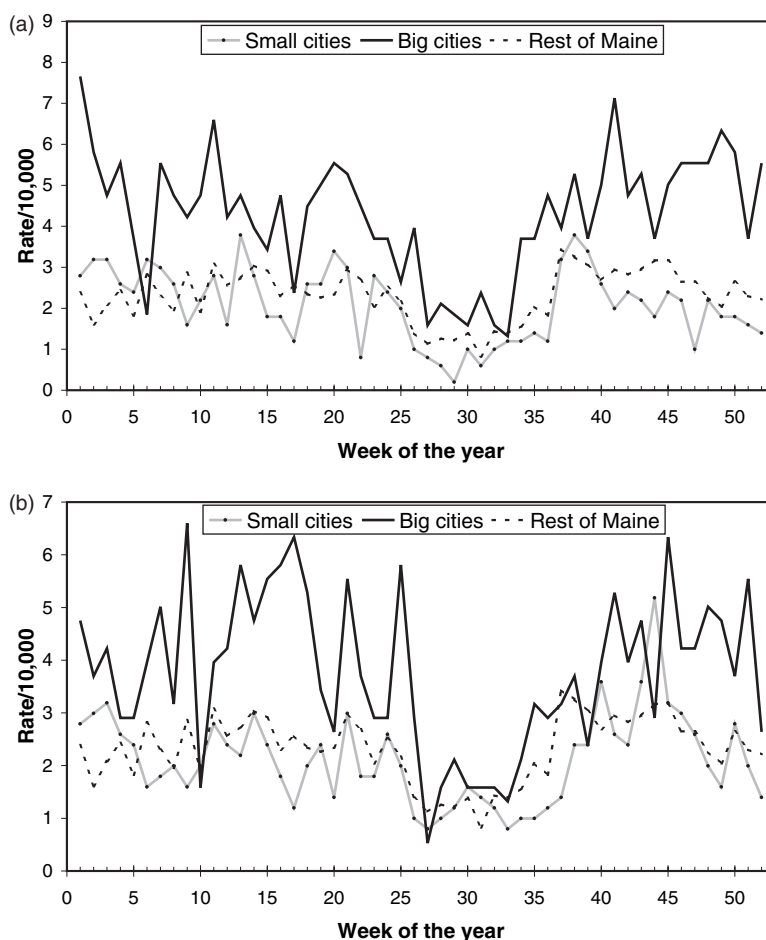


Figure 6. (a) 2000 Maine paediatric ER rates by geographic type. (b) 2001 Maine paediatric ER rates by geographic type.

ratios >5 were taken to indicate a small soil component of that element in the PM_{10} . For most elements for most years the metal source does not appear to be crustal. One exception seems to be Mn and Pb in Portland.

Discussion

In general, Maine records show that there is a summer low in asthma incidences as evidenced by ER visits (2000–2001) and hospital admissions (IP)

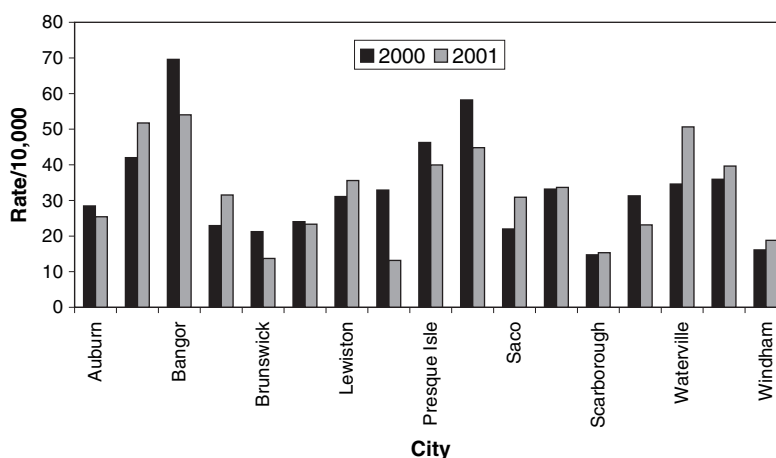


Figure 7. 2000 and 2001 paediatric asthma rates by city.

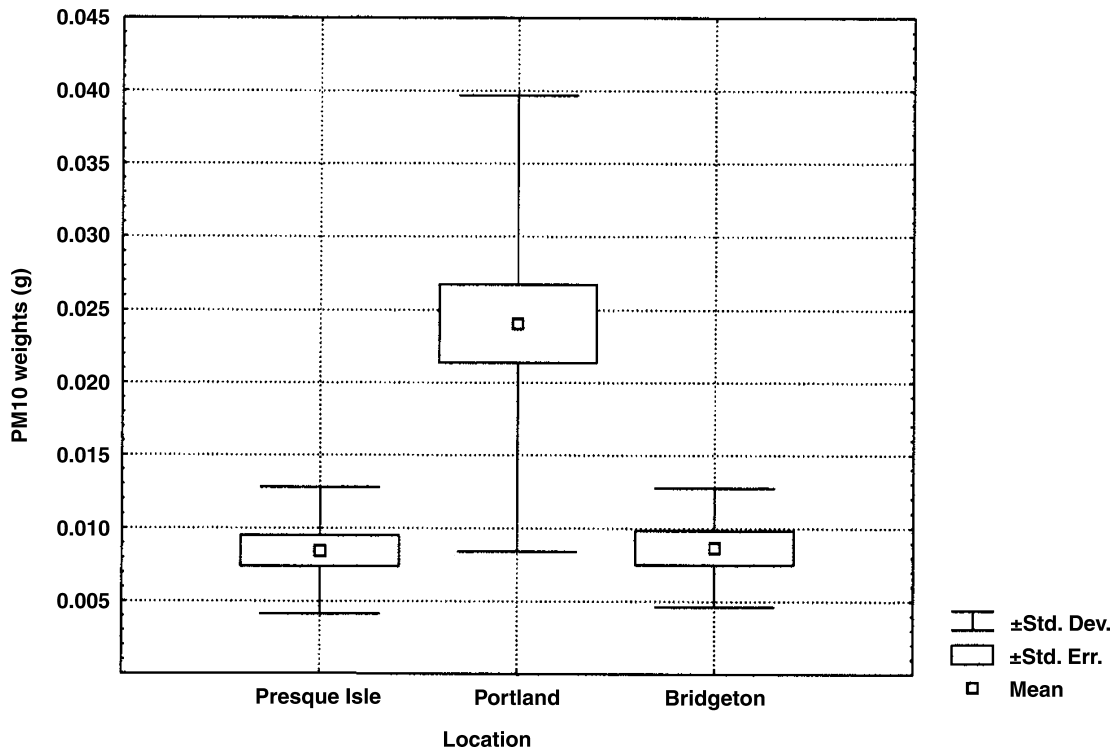


Figure 8. PM₁₀ filter weights versus location.

(1980–2000) for both children and adults. This is followed by an early fall peak, which varies little with time or location, with other peaks occurring in the winter (January) and late spring (May). The consistency of the timing of the fall asthma peak suggests that a similar trigger is operating from year to year. Worldwide, seasonal variation of asthma rates and episodes are reported in a number of locations and populations (Berktaş and Bircan, 2003; Glikson *et al.*, 1995; Linn, 2000; Michaud, 2004; Schwartz, 1993). For example, in Brisbane, Australia, highs were found in May and June (early fall), and the severity of the attacks was not linked to bioaerosols (pollen and fungal spores) alone, but to high levels of air pollution as well (Glikson *et al.*, 1995). In Hilo, Hawaii, there was a strong correlation between number of episodes and month (Michaud *et al.*, 2004). In Ankara, Turkey, high numbers of episodes were found in the winter, April and September, and the severity of episodes was exacerbated by air pollution (Berktaş and Bircan, 2003). In the peak pollen season in Seattle (May and June) similar trends were seen (Schwartz *et al.*, 1993). In Los Angeles peak numbers of hospital admissions (data from 1992–1995) for pulmonary

causes were seen in the winter and correspondingly, the higher the concentration of particulate matter in the air the more admissions. Conversely, the summer months had the lowest number of admissions, but the particulate matter concentrations in the air seemed to have no effect on the number of admissions (Linn, 2000). The general form of northern hemisphere seasonality of asthma admissions involves a moderately elevated rate of admissions through the winter, followed by a small peak in May leading to a summer depression in admissions followed by a strikingly prominent and consistent fall peak occurring in late September to early October (Bates *et al.*, 1990; Garty *et al.*, 1998; Kimes *et al.*, 2004). In Maine the lowest weights of collected PM occurred in the summer in all locations except for Presque Isle in the summer of 2001, corresponding with the summer lull in asthma admissions. The higher PM filter weights in Portland, which also had the highest asthma rates, suggest that PM₁₀ may be acting as an asthma trigger in Maine.

Many hypotheses have been suggested to explain the strong seasonality in respiratory admissions, especially asthma, such as a variety of outdoor and

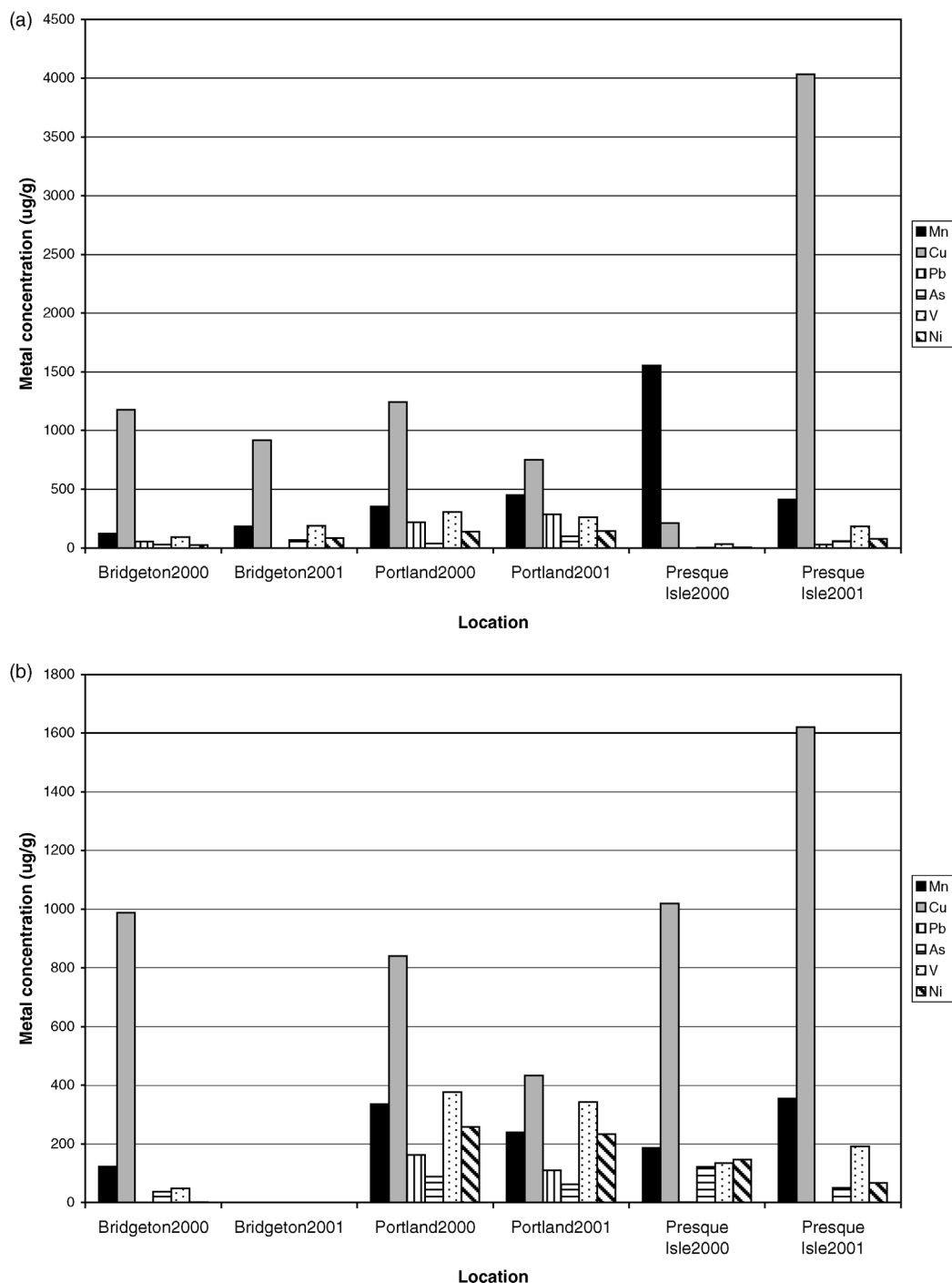


Figure 9. (a) Acid extraction of spring PM₁₀ filters. (b) Acid extraction of summer PM₁₀ filters. (c) Acid extraction of fall PM₁₀ filters. (d) Acid extraction of winter PM₁₀ filters.

indoor environmental factors, as well as psychosocial factors (Kimes *et al.*, 2004). However, relationships between asthma admissions and known and unknown trigger(s) may be complex, with various triggers operating during different times of the year, and some simultaneously. Temporal patterns in

potential indoor and outdoor triggers need to be explored in more detail.

Asthma admissions in Maine were higher in the urban areas. This may be related to the larger amounts of PM₁₀ found on the urban filters, or other potential triggers such as the amount of

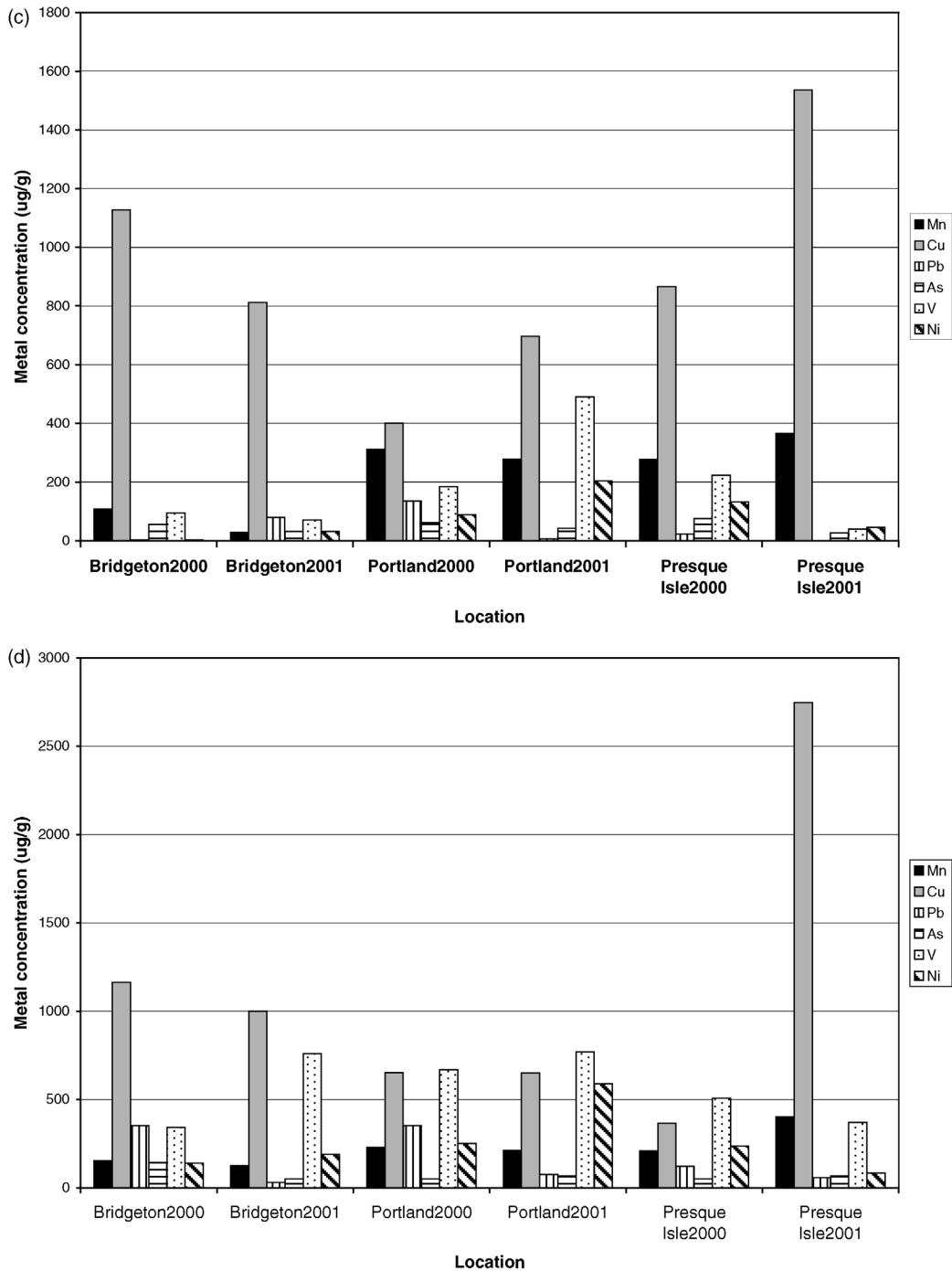


Figure 9. (Continued)

traffic and related air pollutants. Kimes, Ullah *et al.* (2004) also found that urban areas in Baltimore had the highest asthma hospitalization rates, and related this to characteristics such as the higher portion of built areas, lower vegetation cover and higher thermal infrared radiant temperatures. Others have hypothesized that the higher rates are

due to a combination of environmental factors. For example, D'Amato (2000) suggested an interaction between urban air pollution and plant-derived respiratory allergens contributed to increased respiratory disease in urban areas. The higher amount of ER visits for asthma in urban areas may also be partially explained by the fact that patients in urban

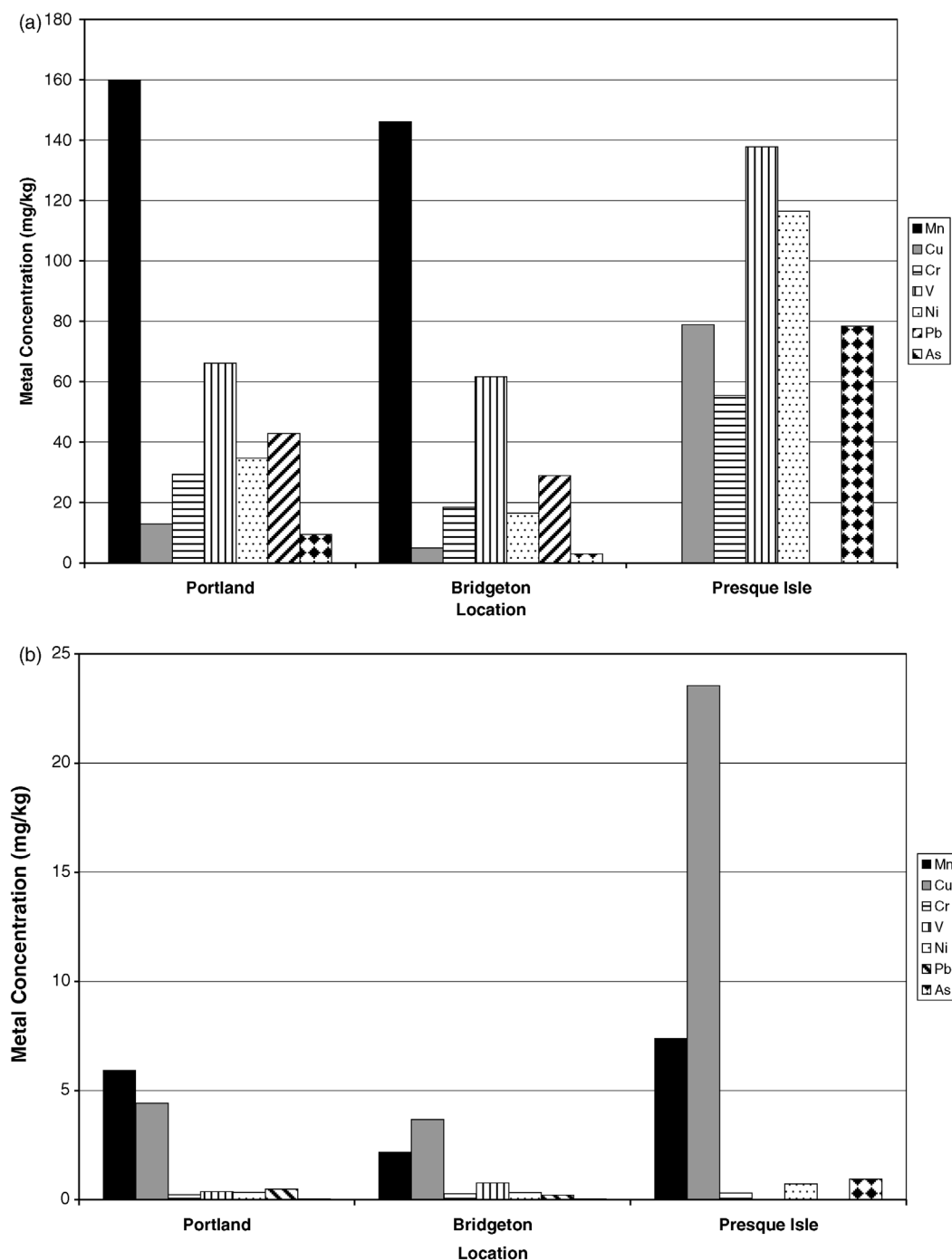


Figure 10. (a) Acid extractions of soil samples. (b) Biological extractions of soil samples.

areas are more likely not to have the resources or ability to manage their disease and consequently rely to a larger extension episodic emergency care (Kattan *et al.*, 1997; Rand *et al.*, 2000).

Many epidemiological studies have been done which examine correlations between ER and IP data for asthma and other pulmonary conditions,

and some environmental factors. Many have shown a positive correlation with particulate matter (PM_{10} , $PM_{10-2.5}$ and/or $PM_{2.5}$). As mentioned previously, these positive correlations have been shown to exist worldwide (e.g., Brunekreef *et al.*, 1995; Buckeridge *et al.*, 2002; Peden 2002; Schwartz *et al.*, 1993; Tolbert *et al.*, 2000; Yu

Table 2. Per cent of biologically available metals in PM and soils.

Filters	Mn	Cu	Pb	As	V	Ni	Al	
Winter								
Portland 2000	30	121	0	—	84	94	0	
Portland 2001	33	125	0	68	112	16	0	
Spring								
Portland 2001	23	88	0	82	209	4	0	
Presque Isle 2001	55	270	—	—	206	181	0	
Summer								
Portland 2000	70	204	0	262	131	58	0	
Portland 2001	24	141	114	155	125	117	0	
Presque Isle 2001	16	614	0	202	175	—	0	
Fall								
Portland 2000	25	180	0	133	89	62	0	
Portland 2001	57	232	728	384	190	147	0	
Average of seasons	37	219.4	105.3	183.7	146.8	84.9	0	
Soils	Mn	Cu	Pb	As	V	Ni	Al	Cr
Portland	4.0	34.3		8.2	0.6	1.0	0.3	0.8
Bridgeton	1.4	73.5			1.3	2.0	0.7	1.5
Presque Isle	0.0	60.4	0.0	2.4	0.0	1.2	0.9	1.1

et al., 2000). Further evidence for a positive correlation with particulate matter PM₁₀ comes from experimental studies using animal models and actual particulate matter. These studies showed that particulate matter causes lung irritation by acting as either a direct irritant or as a sensitizing agent which increases the severity of response when a known irritant is then applied (Costa and Dreher, 1997; Dreher *et al.*, 1997; Kodavanti *et al.*, 1998; Lambert *et al.*, 2000; Saldiva *et al.*, 2002; Samet *et al.*, 1997; Walters *et al.*, 2001). Another possibility is that the particulate matter in the air may act as a carrier for bioirritants (Glikson *et al.*, 1995). In addition, model studies have shown that the PM may not have just an immediate effect (in the first 24 hours) but its effect can have a lag time as long as five days (Campen *et al.*, 2002; Gordian and Choudhury, 2003; Lin *et al.*, 2002; Saldiva *et al.*, 2002; Vedal *et al.*, 1998).

Not only is it possible to correlate the asthma episodes with PM, which is a complex mixture of materials, the composition of which varies from location to location, but some models and experiments have been able to determine which components have positive correlations with episodes. The major components that are suspected are metals, organics and endotoxins, and results exist which implicate each of these components (Leikauf, 2002; Peden, 2002; Soukup and Becker, 2001; Walters *et al.*, 2001). There have been limited studies which

consider synergistic effects between these three classes, although there have been studies that show combinations of metals exacerbate an injurious effect while other combinations of metals decrease that effect (Campen *et al.*, 2002). For example, it has been shown by three different groups that vanadium in concentrations found in Residual Oil Fly Ash (ROFA) gives a positive correlation with lung irritation in animal studies (Dreher *et al.*, 1997; Kodavanti *et al.*, 1998; Lambert *et al.*, 2000; Samet *et al.*, 1997). ROFA has nickel and vanadium concentrations at least 10 times higher than those found in urban PM. Other animal studies using metal concentrations found in urban PM₁₀ have implicated iron, copper, nickel, vanadium and zinc (Costa and Dreher, 1997). Consequently, in order to relate asthma episodes in Maine to components in the particulate matter in Maine, it was important to determine the composition of the particulate matter at the times when asthma episodes are at their peak and for comparison, during the period of low rates in the summer. The metals and concentrations found in Maine were of similar concentration and magnitude, with the exception of lead, to particulate matter in St Louis, Baltimore, NYC and Underhill, VT (Costa and Dreher, 1997; Gao *et al.*, 2002; Polissar *et al.*, 2001; Walters *et al.*, 2001). Although the acid extractable metals showed no striking differences by season, there tended to be more lead, nickel and

vanadium in winter samples. The lack of difference between seasons was also found in PM monitored around NYC (Gao *et al.*, 2002). It is interesting to note that temporal trends in vanadium were similar to trends in asthma admissions, with a distinct summer lull, and increase in the fall.

Not only was it important to determine concentrations of the metal present from the acid extraction procedure so that total amounts of metals in the PM during the different seasons were known, it was important to know which of these metals would be available to biological systems. Our results showed that biologically most of the copper, nickel, vanadium and arsenic were extractable, approximately half of the manganese and none of the aluminium or lead. This is in direct contrast to the soils where none of the metals were nearly as extractable. Similar results were found for transition metals in St Louis PM (Costa and Dreher, 1997). The similarities between temporal vanadium variability and asthma admissions, along with the high biological availability of vanadium, suggest that this metal deserves further study as a potential asthma trigger in Maine.

Although the PM weights were lowest in the summer, corresponding to the summer lull in asthma incidence, and highest in the winter, when local soils are frozen, it is possible that more of the particulate matter in summer is crustal material as there is no snow cover and farming and construction activities may disturb the soil. However, the ratios of metal to Al for PM₁₀ and soils were mostly higher for the particulate matter than the soil (Table 3). Studies around NYC have examined the

crustal contribution to PM, and determined when the ratio of the M/Al ratio for the PM to M/Al ratio for the soil is greater than 5, the PM has other major components besides the crustal material (Gao *et al.*, 2002). This study and another in Underhill, VT, both showed that the crustal component to PM in the respective areas was less than 4% (Polissar *et al.*, 2001). Most of the ratios of M/Al for PM to M/Al for soil for Maine particulate matter are >5. Based on these results and the lower solubility of the metals in soils, the crustal component in Maine PM is probably not an important contributor to its bioavailable metals.

From the composition of the PM it has been possible to identify the sources and fraction of contribution to the PM from each source using models. This determination has been made for organic deposition in Freeport, Maine and for particulate matter by month from extensive analyses done in Underhill, VT (Golomb *et al.*, 2001; Polissar *et al.*, 2001). The Vermont study showed one important component in the winter was East Coast Oil, which contributed high concentrations of Ni and V to the particulate matter. The results of this study suggest that this source could be a contributor in Maine as well.

Solubilities and M/Al ratios tend to rule out soil metals as a contributing factor to asthma episodes in Maine. However, the soils in Bridgeton were also more acidic and acid has been shown to be another factor which causes exacerbation of asthma (Gauderman *et al.*, 2002). But, the pH of the resulting particulate matter is basic so the acid in soils is probably not a contributing factor.

Table 3. PM₁₀ metal/aluminium ratios compared to soil metal/Al ratios^a.

		Mn	Cu	V	Ni	Pb	As
Bridgeton	Winter 2000	6	1750	40	75	65	350
	Summer 2000	13	2000	8	0	0	350
	Winter 2001	8	4000	186	250	75	100
	Summer 2001	5	500	10	17	0	100
Presque Isle ^b	Winter 2000	5	38	20	9	>500	12
	Summer 2000	5	12	16	14	>500	12
	Winter 2001	11	260	20	3	>500	8
	Summer 2001	3	80	7	21	>500	12
Portland	Winter 2000	2	75	22	16	10	14
	Summer 2000	1	14	0	2	0	3
	Winter 2001	2	90	17	38	2	15
	Summer 2001	1	35	5	8	2	8

^aValue of 0 used when PM₁₀ value was below detection limits.

^bMn soil value was not measured; used average of Portland and Bridgeton. Pb soil value was reported as 0, used <0.0000001 for M/Al soil value. Values >5 indicate a very small soil component in the PM₁₀.

The metal composition results show that the composition of Maine PM₁₀ is similar to PM₁₀ found in other locations with approximately the same amounts of biologically available metals present in the Maine PM during peak periods of asthma episodes (Costa and Dreher, 1997; Gao *et al.*, 2002; Polissar *et al.*, 2001; Walters *et al.*, 2001). Furthermore, work from other locations has shown the particulate matter and the biologically available metals in it correlate positively with asthma episodes or with evidence of lung irritation in experimental animals (Costa and Dreher, 1997). Consequently, particulate matter and its components are potential factors which contribute to the peak periods of ER and IP for asthma in Maine as well.

Conclusions

Maine Health Data, both IP and ER, show that asthma episode occurrence is lowest during the summer, then rises to a peak in the fall, usually in late September or early October, with other substantial peaks in the winter (January) and spring (late May) for all of the populations (both adult and paediatric) examined and for all of the years studied. These results correlate well with trends found in other geographic locations. Furthermore, overall urban asthma rates in Maine were higher than less urban and rural sites. PM₁₀ filter weights were also highest in the urban area, which suggests a link between PM₁₀ and asthma episodes in Maine. Analysis of PM₁₀ collected at times corresponding to the peaks and low asthma periods in 2000 and 2001 showed that the PM₁₀ contains >50 ppm Al (highest), Cu, Mn, V, Ni, Pb and As. Only lead and vanadium, and nickel in Bridgeton, showed any seasonal variation. Of the metals found in the PM₁₀, Cu, Mn, V, Ni and As were soluble under biological conditions. These results for PM₁₀ in Maine were similar to results reported for PM₁₀ in other locations. For the soil samples, the metals present were at least an order of magnitude less concentrated and much less soluble under biological conditions. The crustal component of the PM₁₀ is small with the exception of Mn and Pb in Portland. However, the insolubility of these metals under biological conditions implies that they would not be important asthma triggers. Finally, based on

our results and similarities of our results to those in the literature, we feel that PM₁₀ and its metal components are possible contributing factors for IP and ER asthma episodes in Maine.

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