Available online at www.sciencedirect.com

ScienceDirect

Atmospheric Environment 42 (2008) 364–373

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Spatial variation in vehicle-derived metal pollution identified by magnetic and elemental analysis of roadside tree leaves

B.A. Maher[a,*], C. Moore[b,1], J. Matzka[c]

[a]Centre for Environmental Magnetism and Palaeomagnetism, Lancaster Environment Centre, University of Lancaster, Lancaster LA1 4YQ, UK
[b]School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
[c]Geomagnetism and Space Physics, Danish Meteorological Institute, Lyngbyvej 100, DK 2100 Copenhagen, Denmark

Received 22 June 2007; received in revised form 5 September 2007; accepted 10 September 2007

Abstract

Exposure to metal-rich particulate pollution is associated with adverse health outcomes. In particular, lead has recently been shown to be toxic in young children even at low levels previously considered ‘safe’. Lead poisoning from vehicle pollution has been addressed internationally by removal of leaded petrol but toxic blood lead levels in children continue to be reported in urban areas, the source suggested to be resuspended roadside soil, enriched in lead due to previous leaded fuel usage. Here, we use paired geochemical and magnetic analyses of natural biomonitors—kerbside tree leaves—and of air sample filters to examine contemporary sources of particulate pollution, and show that co-associated, fine ($<1\,\mu$m) lead- and iron-rich particles are emitted as vehicle-derived pollutants. Higher and strongly correlated lead, iron and magnetic remanence values were found closer to roads and on the road-proximal rather than road-distal sides of trees. Critically, highest pollutant values occurred on tree leaves next to uphill rather than downhill road lanes. The lead content of the leaf particulates was associated only with sub-micrometre, combustion-derived spherical particles. These results indicate that vehicle exhaust emissions, rather than resuspended soil dust, or tyre, brake or other vehicle wear are the major source of the lead, iron and magnetic loadings on roadside tree leaves. Analysis of leaves at different heights showed that leaf particulate lead and iron concentrations are highest at ~0.3 m (i.e. small child height) and at 1.5–2 m (adult head height) above ground level; monitoring station collectors placed at 3 m above the surface thus significantly under-estimate kerbside, near-surface lead concentrations. These results indicate that vulnerable groups, especially young children, continue to be exposed to fine, lead- and iron-rich, vehicle-derived particulates.

Keywords: Vehicle pollution; Magnetism; Lead pollution; Biomonitoring

1. Introduction

Particulate air pollutants have been found to be strongly associated with adverse effects on respiratory health (e.g. Knox, 2006; Knutsen et al., 2004; Schwartz, 1996; Pope et al., 2002). The degree of hazard depends principally on the site of particulate

---

*Corresponding author. Tel.: +44 1524 510268; fax: +44 1524 510269.
E-mail address: b.maher@lancaster.ac.uk (B.A. Maher).

[1] Now at British Antarctic Survey, Madingley Road, Cambridge, UK.

1352-2310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2007.09.013

deposition within the lungs, in turn reflecting the size, shape and density of the particulates, and their effects on biological tissue, determined by the composition of the particles. Fine particles ($<2.5\,\mu m$, $PM_{2.5}$) can be deposited deep within the pulmonary region of the human respiratory tract when inhaled, with potential bioavailability maximised by the large number and surface area of such particles. If these particulates reach the alveoli, inflammation and diminished pulmonary function can be incurred (e.g. Knutsen et al., 2004; Seaton et al., 1995). Links with lung cancer (Pope et al., 2002; Beeson et al., 1998) and increased cardiovascular mortality rates (Pope et al., 1995; Schwartz, 1996) have also been established. Large proportions of such fine particles are known to be emitted by vehicles (e.g. Maricq, 1999), with diesel-powered vehicles producing several orders of magnitude more $PM_{2.5}$ particles than petrol-driven ones (Rudell et al., 1999; Maricq, 1999; Wang et al., 2003). In terms of composition, analysis of urban anthropogenic particulates has shown them to be enriched in a range of potentially toxic trace metals, including Fe, Pb, Zn, Ba, Mn, Cd and Cr (Huhn et al., 1995; Harrison and Jones, 1995). Keyser et al. (1978) reported that Pb and Cr from vehicle exhausts are preferentially associated with particle surfaces, possibly as a result of condensation from the vapour phase or adsorption from solution. Urban anthropogenic particulates also contain, almost invariably, magnetic particles (e.g. Hunt et al., 1984; Flanders, 1994; Morris et al., 1995; Matzka and Maher, 1999; Petrovsky and Ellwood, 1999). These are derived from the presence of iron impurities in fuels, which form upon combustion of a non-volatile residue, often a mix of strongly magnetic (magnetite-like) and weakly magnetic (haematite-like) iron oxides. Magnetite has been identified specifically as a combustion-derived component of vehicle exhaust materials (Abdul-Razzaq and Gautam, 2001).

Quantitatively, the health risks of urban metal particulates are poorly understood, due to a combination of confounding factors and the relatively low spatial resolution of the data available for pollutant exposure. However, Pb is a significant neurotoxin, posing some health risk even at levels previously considered safe, particularly with regard to brain and kidney damage, hearing impairment and diminished cognitive development in children (Koller et al., 2004; Lanphear et al., 2000; Needleman and Landrigan, 2004). High levels of many other trace metals are implicated in lung disease and central nervous system disorders (e.g. Colls, 2002), ranging from learning disorders to dementia and possibly even Alzheimer's disease (Calderón-Garcidueñas et al., 2004). Aggressive removal of lead from environmental sources, especially petrol and paints, has resulted in major reductions in lead poisoning of children. However, many urban areas still exhibit damagingly high blood lead levels (i.e. $>5\,\mu g\,dl^{-1}$) in children (e.g. Koller et al., 2004; Lanphear et al., 2000; Mathee et al., 2002; Rabito et al., 2004). In a study in the Indianapolis area, resuspended soil dust, enriched with lead from previous decades of leaded fuel usage, was the suspected major source, in light of higher blood lead levels at the urban roadside and seasonal peaks (summer and winter) in blood lead (Young et al., 2002; Filippelli et al., 2005).

Magnetic biomonitoring (Matzka and Maher, 1999) may provide a robust and cost-effective means both to gain significantly enhanced spatial resolution for pollutant data, and test proposed metal source/health linkages. The deposition of pollution particles on tree leaf surfaces has been shown to result in easily measurable magnetic properties, including magnetic remanence (i.e. the magnetisation remaining after a sample has been placed in and then removed from an applied dc field) and magnetic susceptibility (the magnetisation induced when the sample is placed in a small—~twice the Earth's magnetic field—ac field). Leaves are potentially efficient receptors and biomonitors of particulate pollution, as they provide a large total surface for particle collection, numbers of samples and sample sites can be high (i.e. hundreds), and, in pollution contexts, the leaves themselves are insignificantly magnetic. Tree leaves also preclude sampling problems associated with the use of artificial particle collectors (including power requirements, noise and vulnerability to vandalism). To ensure comparability of results, tree leaves of the same tree species, and similar age, can be used. For a number of industrial sites in N. Germany, Schadlich et al. (1995) found strong correlation between the magnetic susceptibility of pine needles and their Fe content, as a result of deposition of fly ash particles. For a relatively small city with little industry (Norwich, UK; population ~100,000), Matzka and Maher (1999) found minimal values of magnetic remanence for birch leaves in parks within the city centre but increasingly high values for trees located at the roadside, and significantly higher values both for the road-proximal side of the tree and for trees growing on the uphill side of road lanes. These authors estimated the grain size of magnetic particles from vehicle emissions to be of the order of 0.3–3 μm, a size of particular potential hazard to health. Subsequent studies (e.g. Muxworthy et al., 2002; Moreno et al., 2003; Hanesch et al., 2003; Gautam et al., 2005; Sagnotti et al., 2006) have confirmed that, in the absence of heavy industry, traffic pollution is the main source of magnetic particles on leaves.

Here, we report elemental and magnetic data from the ongoing Norwich magnetic biomonitoring study, with the aim of evaluating if magnetic biomonitoring can be used as a robust surrogate for identifying the source and concentrations of toxic trace metals, especially Pb.

2. Methods

Magnetic biomonitoring of traffic pollution in Norwich is being carried out over several sampling and analytical campaigns in order to improve understanding of its links with hazardous pollution and value for high-resolution spatial and temporal identification of pollution exposure. Over a 12-day, predominantly dry summer period (August 1999), hundreds of leaves were sampled from the most abundant species of urban tree in Norwich, the birch (*Betula pendula*). Extending Matzka and Maher's (1999) original study, roadside tree leaves were sampled from Grapes Hill, a dual carriageway with a 12° gradient, part of the city's inner ring road. Around 30,000 vehicles use this road each day. Birch trees are planted in pairs along the central reservation area, providing uphill-adjacent and downhill-adjacent trees. Each sample consisted of six leaves, sampled from the outer canopy at a height of 1.5 m; the oldest leaves from the newest twig growth were sampled (2–13/08/1999), in order to ensure leaves of similar age and exposure time. In addition, leaf samples were taken from one of the Grapes Hill birch trees (11–13/08/1999) at 30 cm intervals, from the ground to a maximum height of 2.1 m. The surface area of the leaves was calculated by digitising their computer-scanned images. For each sample, six leaves were packed into 10 cm^3 plastic sample holders for magnetic measurements, at the Centre for Environmental Magnetism and Palaeomagnetism. A description of environmental magnetic parameters and measuring techniques is given in e.g. Maher et al. (1999) and Walden et al. (1999). Magnetic susceptibility was too low to be measurable for any of the samples. All samples were magnetised (at room temperature) with incremental, pulsed dc fields of 20, 50, 100 and 300 milliTesla (mT) and 1 Tesla (T), using a molspin pulse magnetiser. The resultant isothermal (i.e. room temperature) magnetic remanences (IRMs) were measured using a cryogenic magnetometer (CCL Ltd.; with a noise level of 10^{-10} A m^{-2}—the weakest leaf samples had remanences of the order of 10^{-8} A m^{-2}).

A representative subset of samples was then selected for leaching and elemental analysis. The leaves were leached in 25 ml 1% HNO_3 and left in covered bottles for 72 h. Prior to use, all glass and plastic ware was washed with detergent, soaked in 1% HNO_3 for 24 h and rinsed with high-purity 'MilliQ' water. The leaves were then recovered and their remanence at 1 T remeasured, in order to identify the proportion of the saturation remanence (SIRM) removed by the leaching procedure. Sample leachates were filtered through 0.2 μm filters and then analysed by ICPOES (Thermo Jarel Ash Polyscan 61E) for Fe, Pb, Zn, Mn, Ba, Cd and Cr (elemental limits of detection for this instrument are listed in Table 1). For each sample, the magnetic remanences and elemental concentrations were normalised for leaf area, giving magnetic moment (A m^{-2}) per leaf area (m^2)—hence, in units of Amperes (A), and elemental concentrations in units of μg m^{-2}. Correlations between magnetic parameters and elemental concentrations were investigated using linear regression and *t*-tests. Further selected leaf samples were vacuum-coated in gold and analysed using scanning electron microscopy (SEM) (Hitachi SEM S450) and energy-dispersive X-ray analysis (EDXA). Finally, air filter samples were obtained from the background site (200 m^3 of air sampled) and the closest possible site to the roadside (150 m^3 of air sampled, within 500 m of the roadside), using a high-volume air sampler, and SIRM measurements made of the filters.

3. Results

Fig. 1 shows the spatial variation in birch leaf magnetic values across the urban–rural gradient, with very low SIRMs measured for leaves sampled from the Norfolk coast and increasingly high values obtained for leaves with increasing proximity to the roadside. For the leaves sampled over a 4-day summer period (2–6/08/1999) from Grapes Hill, a

Table 1
Averaged elemental concentrations ($\mu g\,m^{-2}$) of leaf leachates and SIRM (measured in applied dc field of 1 T and normalised for leaf surface area) for sampled birch leaves from Grapes Hill and 'background' values from the campus of the University of East Anglia

Element/SIRM	Roadside ($\mu g\,m^{-2}$)	Background ($\mu g\,m^{-2}$)	Mean enrichment ratio roadside: background	Detection limit ($\mu g\,m^{-2}$)
Pb	29	Below limit		2.5
Fe	427	11	39	0.2
Zn	468	119	4	0.2
Mn	222	81	3	0.05
Ba	82	54	1.5	0.02
2-D SIRM (10^{-6} A)	48	3	16	10^{-10} A

Samples were taken from 40 trees over a 5-day summer period (2–6/08/1999), with wind directions varying mainly within the range of 210–240°; thunderstorms occurred overnight on sample days 4–5/08/1999. Each data point represents a measurement integrating over six leaves from each tree.

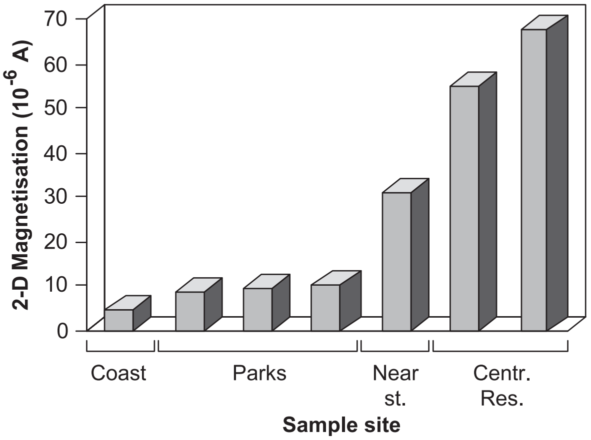

Fig. 1. Variation with location of 2-D magnetic remanence values (SIRMs), measured on sampled birch leaves, from Weybourne on the Norfolk coast to the central reservation of Grapes Hill, a major city centre dual carriageway.

major dual carriageway close to the Norwich city centre, the average, leaf area-normalised (2-D) SIRM value (i.e. the remanence acquired at the maximum applied dc field, 1 T) was 48.5×10^{-6} A (minimum = 27.5×10^{-6} A, maximum = 96.1×10^{-6} A). This compares with a background value (from trees sampled at a parkland site) of 3.6×10^{-6} A (Table 1). Most of the leaf magnetic remanence was acquired at low applied dc fields, indicating the presence of magnetically soft, magnetite-like (Fe_3O_4) material. A small proportion of the remanence (<5% of the SIRM) was acquired at fields beyond 300 mT, indicating the additional (and possibly volumetrically more important) presence of magnetically 'hard' minerals, such as haematite (αFe_2O_3). Coercivity values for the roadside leaves varied over a narrow range, from 42 to 46 mT, slightly higher than that for the background samples, which displayed lower and slightly more variable values, 35–42 mT. For magnetite, these roadside coercivity values are notably high and indicate that the dominant size of the strongly magnetic particles is between ~1 and 0.1 μm (e.g. Maher, 1988; Heider et al., 1996).

Subsequently, to examine the spatial variations in roadside SIRM and metal values, leaves were collected from two birch trees within the central reservation, i.e. between the uphill and downhill lanes of the Grapes Hill dual carriageway (Fig. 2) following the approach described by Matzka and Maher (1999). As reported previously by Matzka and Maher (1999), SIRM values were again always highest for samples from both sides of the uphill-adjacent tree, with slightly lower values for the road-proximal side of the downhill-adjacent tree and lowest values for the distal side of the downhill-adjacent tree (Fig. 2d).

For the leaf leachates (Table 1), Zn and Fe were found to show the highest roadside concentrations, with Mn, Ba and Pb at lower levels, and Cd and Cr below their detection limits at all sampled sites. Background values for Fe and Pb were minimal ($11\,\mu g\,m^{-2}$ and below detection, respectively), in major contrast to the Grapes Hill roadside sites, where Fe values averaged $427\,\mu g\,m^{-2}$ (maximum = $983\,\mu g\,m^{-2}$), with an average enhancement factor of ×39, and Pb values averaged $29\,\mu g\,m^{-2}$ (maximum = $81\,\mu g\,m^{-2}$, indetectable at background). Of the other analysed elements, Zn, Mn and Ba all displayed significant concentrations even at the background sites (~119, 81 and $54\,\mu g\,m^{-2}$, respectively). Their enhancement factors at the roadside were thus correspondingly lower, at ×4,

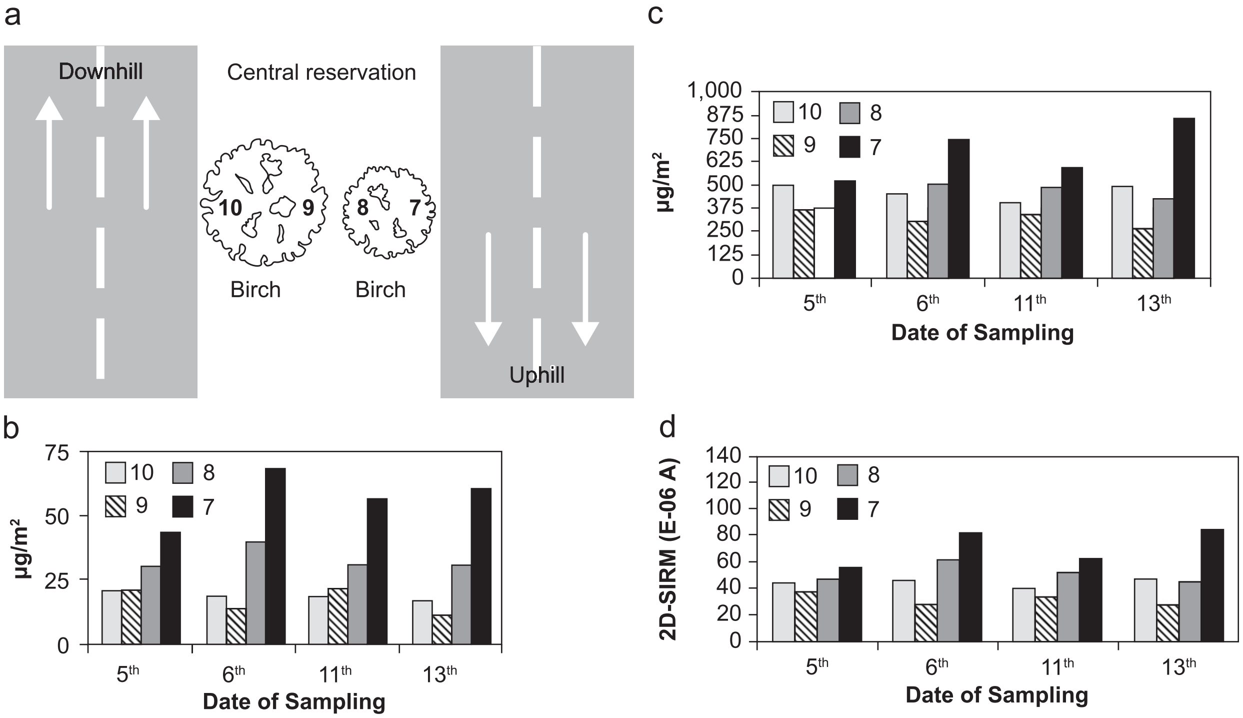

Fig. 2. Pb, Fe and 2-D SIRM values for tree leaves sampled across the central reservation of the uphill and downhill lanes of a major dual carriageway (Grapes Hill) in Norwich, UK: (a) sample locations, (b) Pb concentrations, (c) Fe concentrations, (d) 2-D SIRM. Leaves were sampled over a predominantly dry summer period (5–13/08/1999); heavy rain fell overnight between 06/08/1999 and 11/08/1999.

×3 and ×1.5, respectively (Table 1). Demonstrating the effectiveness of the analytical procedures, remagnetisation of a subset of leaf samples after the leaching process showed that it had removed ~75% of the original magnetic remanence; the acid leach treatment (1% HNO_3) is reported to remove up to 80% of total Pb, Zn and Cd (Little, 1973).

Thus, compared with the 'background', parkland site, the leaf SIRM, Pb and Fe values show the greatest roadside enrichment. Lower roadside enrichment factors are evident for Zn, Mn and Ba, reflecting their significant concentrations even at the 'background' greenfield site. In terms of spatial variations across the Grapes Hill dual carriageway, Fe and Pb concentrations display very similar patterns to the leaf SIRM values, being highest at the uphill-proximal sample site (Fig. 2b and c). Zn, Mn and Ba values display greater spatial variation than Fe and Pb, with some maximal values associated with the downhill-proximal samples. Leaf SIRM and metal values were reduced (by between ~5% and 30%) after a rainstorm event (the night of the second sampling day), before subsequently increasing once more in the following dry weather conditions. Figure 3a shows the correlation coefficients (R^2 values) for the measured leaf SIRM values and the elemental concentrations from the leaf leachates. Very strong correlation is evident between the SIRM and concentrations of Fe ($R^2 = 0.976$, $n = 40$, $p \leqslant 0.0005$) and Pb ($R^2 = 0.871$, $n = 40$, $p \leqslant 0.0005$). Significant albeit weaker correlation ($R^2 = 0.4$–0.5, $n = 40$, $p = 0.05$) exists between the measured Zn, Mn and Ba concentrations. No significant correlation exists between this group and the SIRM, Pb and Fe group (Fig. 3a).

Analysis of roadside leaves sampled at different heights showed that leaf particulate Pb, Fe and SIRM concentrations reached peak values at ~0.3 m and 1.5–2 m above ground level (Fig. 4). In contrast, Zn, Ba and Mn displayed lowest values at 0.3 m height, and steadily increased in concentration with height, indicating (together with their higher background values) a more pervasive distribution of these metals. The results were replicated over several days of sampling.

SEM and EDXA were applied to pollutant particles washed from the sampled birch leaves from Grapes Hill. Two types of particle morphology were most frequently observed: clusters of a

	SIRM	Fe	Pb	Zn	Mn	Ba
SIRM	1					
Fe	0.976	1				
Pb	0.871	0.849	1			
Zn	0.035	0.028	0.101	1		
Mn	0.009	0.014	0.014	0.444	1	
Ba	0.001	0.006	0.003	0.414	0.500	1

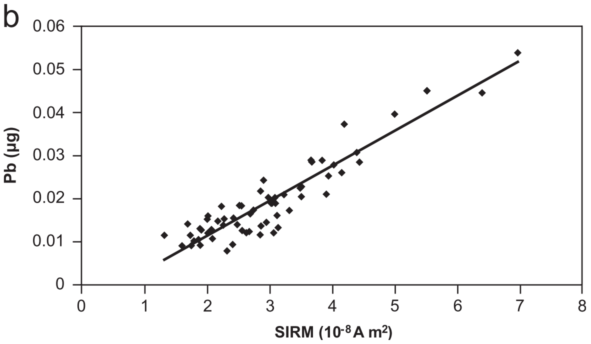

Fig. 3. Correlations between leaf particulate metal concentrations and SIRM, Grapes Hill, Norwich: (a) all analysed metals ($n = 40$, shaded boxes with significance <0.05) and (b) Pb concentration and SIRM ($n = 40$, $p \leqslant 0.0005$).

spheres (cooled droplets), ranging in size from ~20 to <0.5 µm (Fig. 5), and angular particles, between 1 and 10 µm in length. EDXA of the spheres identified their major elements as Fe, Si and Al, with varying concentrations of minor elements, including Mn, K, Ca and Pb. Notably, Pb appeared to be associated only with the smallest spherules, $\lesssim 1$ µm. The angular particles were Fe rich, some particles also containing S, Al, K and Ca. Minor numbers of fine, irregular particles (~1 µm diameter) were also observed, dominantly containing Ba, S and Mn. Finally, large conglomerates of particles (>50 µm diameter) were also observed, dominantly consisting of Al, K, Ca and Si; such particles are most likely of natural origin, probably soil-derived dust. Notably, few of the analysed particles revealed the presence of zinc, even for leaf samples at sites where the measured levels of Fe and Zn were comparable. Zinc oxide particles derived from rubber dust have been shown to occur as ovoid particles <0.5 µm (McCrone and Delly, 1973), below the resolution of SEM. Further sampling and analysis of the ultrafine pollutant particles is ongoing at this site.

Finally, in order to check how representative the tree leaves are as pollution collectors, samples were also collected using a high-volume air sampler, adjacent to a roundabout at the top of the monitored dual carriageway and at the background site. The sample nearest to the roadside gave rise to

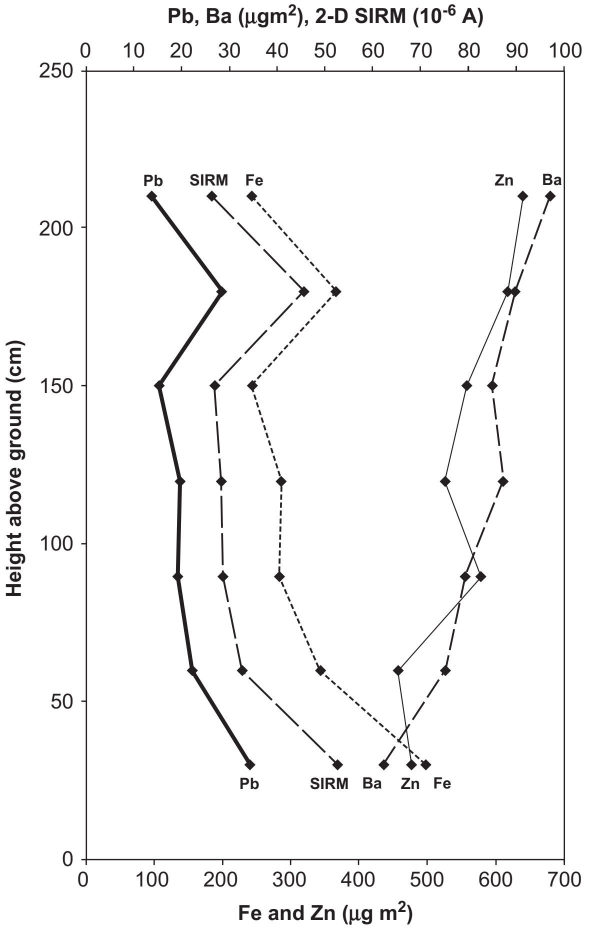

Fig. 4. Variation with height of leaf particulate metal concentrations and SIRM.

3 × higher magnetic values per m^3 sampled air than the background site, and its magnetic properties matched those of the measured tree leaves.

4. Discussion

Roadside tree leaves in this UK city exhibit significant enhancement in their values of SIRM, Fe and Pb, reflecting surface accumulation of particulate pollutants, compared with leaves growing at a background, parkland site. In contrast, much more limited roadside enhancement is shown by the metal group, Zn, Mn and Ba. At high spatial resolution, maximal and strongly correlated Pb, Fe and SIRM values are displayed by roadside tree leaves adjacent to uphill rather than downhill lanes. This association between pollutant loading and road gradient indicates that fuel combustion is the major pollutant

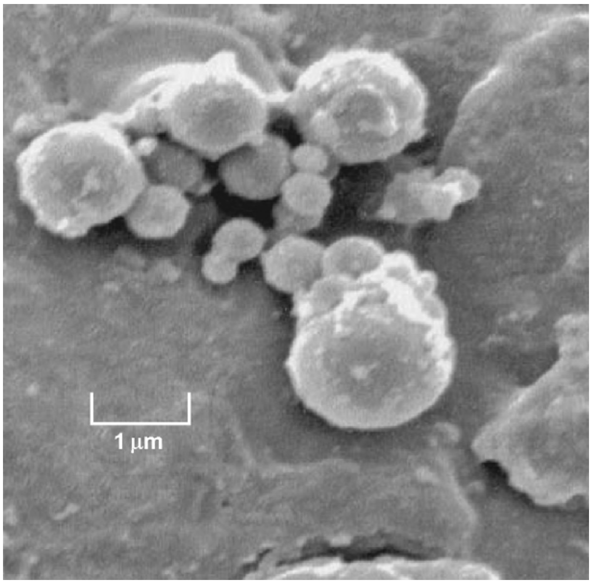

Fig. 5. Scanning electron micrograph of clustered, spherical leaf particulates, Grapes Hill, Norwich. From EDXA analysis, Pb occurs (as a minor element) only within the spherules <1 μm diameter.

source; these patterns would not arise from resuspension of roadside dust (Filippelli et al., 2005) or from tyre, brake or other vehicle wear. The direct correlation between the SIRM values and leaf Pb concentrations is even stronger than that observed between Pb and Fe. This suggests that Pb is strongly source associated with the magnetic Fe particulates, which arise from vehicle combustion/exhaust processes, and less associated with more weakly magnetic phases either of natural origin and/or from vehicle ablation or abrasion. The strong link between SIRM and Pb could reflect coprecipitation of Pb during magnetite genesis (i.e. during combustion) and/or subsequent adsorption of Pb on the surface of the combustion-formed magnetic grains. Olson and Skogerboe (1975) previously reported that lead emitted from vehicle exhausts occurs primarily in particulate form. This present-day co-association of significant levels of automotive Pb and magnetic Fe emissions is evident despite the introduction of unleaded petrol (in the UK, since 1986). Possible, non-fuel, sources of Pb which could give rise to these ongoing, combustion-related emissions include lead plating of fuel tanks and lead in vulcanised fuel hoses, piston coatings, valve seats and spark plugs. Pb is a significant neurotoxin, posing some health risk at any level of exposure, particularly with regard to brain and kidney damage, hearing impairment and cognitive development in children. Given the high correlation coefficients between SIRM and Pb, SIRM values (measurements made easily, rapidly and cheaply) appear valuable as a robust proxy predictor, and capable of providing unprecedentedly high spatial resolution data, for this toxic pollutant.

Strong correlation also exists between SIRM and Fe content for the Grapes Hill roadside sites, confirming the ferrimagnetic nature of much of the particulate Fe. Based on the strong, direct linear relationship between SIRM and Fe concentration at the roadside, when $\mathrm{SIRM} = 0$, the Fe concentration $= 52 \pm 40\,\mu\mathrm{g\,m^{-2}}$. For the suburban 'background' site, the Fe concentration on sampled leaves was $11\,\mu\mathrm{g\,m^{-2}}$. This suggests that much of the 'non-magnetic' Fe at the Grapes Hill sites is also pollution derived, from surface reception of non-magnetic iron compounds (e.g. abraded rust particles). However, the 'non-magnetic' portion of the roadside Fe content is only 11% of the total.

Background levels of Zn, Mn and Ba are much higher than those for Fe and Pb, resulting in enrichment ratios at the roadside of only 1.6–4 (compared with ×43 and ∞ for Fe and Pb, respectively). The height distribution of the Zn, Mn and Ba group, displaying increased elemental concentrations with height (up to the maximum sampled height, 2.1 m), is again in contrast with the SIRM, Pb and Fe distributions, which peak at ~0.3 m, with a subsidiary peak ~1.5–2 m height. These data suggest that more pervasive, broader-scale atmospheric deposition processes are of importance for ambient Zn, Mn and Ba levels. However, they do display some limited degree of roadside enrichment and significant (albeit weaker) correlation between them suggests some source association. The absence of correlation between the SIRM, Fe and Pb data and the Zn, Mn and Ba group indicates different, non-exhaust-related sources for the latter at the Grapes Hill site. Across the dual carriageway, their spatial variations are less systematic than those of Fe and Pb, but there is some evidence of enhancement at the downhill-proximal sample site, suggesting braking and tyre wear as significant sources. Huhn et al. (1995) have identified vehicle brake and tyre wear as possible sources of Zn. Additionally, Ba is added to diesel fuel as a smoke suppressant and Mn is used as an anti-knock agent (Huhn et al., 1995).

The peak SIRM, Pb and Fe values at ~0.3 m height are likely to reflect exhaust-derived particulate emissions but it is possible that leaf drip from higher parts of the canopy may make a contribution. Local weather conditions, rainsplash and the aerodynamic properties of the tree and its canopy may also play a role in the height distribution of particulate deposition. As raindrops contain particles collected from the atmosphere, they may contribute either to the accumulation of dust on leaf surfaces or, by detaching previously collected particles, to its reduction. Here, rainfall events led to reductions in the measured leaf SIRM and metal concentrations, whilst dry conditions were associated with cumulative increases in leaf pollutant loadings. This suggests that the main physical process responsible for particulate deposition is impaction. Due to their inertia and/or density, particles cannot follow the air flow around the leaves and consequently impact or sediment upon them (QUARG, 1996). Deposited particles must also resist possible resuspension by turbulence; smaller particles may penetrate more deeply into less exposed areas of the leaf surface (Kinnersley et al., 1996).

For the metals analysed here, the highest roadside concentrations were found for Fe (mean-427 $\mu g\,m^{-2}$, maximum $= 742\,\mu g\,m^{-2}$) and Zn (mean-468 $\mu g\,m^{-2}$, maximum $= 968\,\mu g\,m^{-2}$), both metal pollutants thought to be implicated in generating pulmonary inflammation (e.g. Aust et al., 2002; Samet et al., 1998). Notably, even with Zn loadings as high as here, the sampled leaves themselves showed no visible signs of damage (a finding similar to that reported previously by Little, 1973).

We can use the strong, direct correlation between Pb and SIRM to estimate Pb loadings per m^3 of air at this roadside. At the mean SIRM kerbside enhancement ratio of 16 × background, roadside Pb levels equate to 13 $ng\,m^{-3}$; at the maximum SIRM enhancement, the Pb concentration is 25 $ng\,m^{-3}$. These estimated Pb concentrations are comparable with levels recorded by the UK's Air Quality Network for locations including Manchester and Swansea. Critically, however, from SEM here, the vehicle-derived Pb appears to be associated only with fine ($<1\,\mu m$) magnetic particulates. Such fine grains, comprising very large particle numbers ($\sim10^6$–$10^9\,\mu g^{-1}$), pose a great health hazard. Their deposition in the lung may overwhelm the capacity of macrophages to engulf and remove them, leading to prolonged tissue contact times and resultant inflammation, whilst their high surface area also enhances their potential for bioavailability (Donaldson, 2003). That roadside lead emissions are bioavailable is indicated by reports of increased ^{210}Pb-supported ^{210}Po on the outer enamel of permanent teeth in children living in proximity to (<10 km) and downwind from major UK motorways (Henshaw et al., 1995; James et al., 2004). Further, interactions between Fe-rich particles and epithelial tissues are suggested to generate free radicals, leading to oxidative cell damage (Aust et al., 2002). Fine particulates are likely to pose a particular hazard to small children, doubly vulnerable because of developmental health impacts and the measured peak in particulates at low heights, ~0.3 m above ground (the secondary peak in Pb, Fe and SIRM values is close to head height for most adults). Exposure may occur both at the roadside and/or within the passenger cab of vehicles using the road.

5. Conclusions

- Urban roadside tree leaves exhibit significant enhancement in their values of SIRM, Fe and Pb, reflecting surface accumulation of particulate pollutants, compared with leaves growing at a background, parkland site. Much more limited roadside enhancement is shown by the metal group, Zn, Mn and Ba.
- Maximal (and strongly correlated) Pb, Fe and SIRM values are displayed by roadside tree leaves adjacent to uphill rather than downhill lanes. This association between pollutant loading and road gradient indicates vehicle fuel combustion as the major source for these pollutants, rather than resuspension of roadside dust or from tyre, brake or other vehicle wear.
- The vehicle-derived Pb appears strongly associated with fine ($<1\,\mu m$) magnetic particulates. Such fine grains, contributing very large particle numbers ($\sim10^6$–$10^9\,\mu g^{-1}$) and enhanced bioavailability, pose significant hazard to human health.
- Fine particulates pose a particular hazard to small children, doubly vulnerable because of developmental health impacts and the identification here of a peak in magnetic, Pb- and Fe-rich particulates at child height (~0.3 m above ground).
- Given the high correlation coefficients between Pb and leaf magnetic values, easy, rapid and cheap magnetic measurements of roadside leaves appear valuable as a robust proxy predictor of this toxic pollutant, offering the possibility of greatly enhanced spatial resolution of pollutant data sets, a prerequisite for detailed analysis

of possible pollution/health linkages (Schwarze et al., 2006).

- On an immediately practical level, this study suggests first that pedestrians can reduce their vehicle-derived pollution intake by walking on the downhill side of the road, where possible with intervening trees to act as an exhaust pollution 'filter', and, second, that the pollutant-filtering effects of roadside trees would be significantly enhanced if tree planting were increased and lower-level leaf growth maintained, not removed.

Acknowledgements

This work was supported by a Royal Society-Wolfson Research Merit Award to BAM and a DAAD Award to JM.

References

Abdul-Razzaq, W., Gautam, M., 2001. Discovery of magnetite in the exhausted material from a diesel engine. Applied Physics Letters 78, 2018–2019.

Aust, A., Ball, J.C., Hu, A.A., Lighty, J.S., Smith, K.R., Straccia, A.M., Veranth, J.M., Young, W.C., 2002. Particle characteristics responsible for effects on human lung epithelial cells. Research Report 110, Health Effects Institute, Boston, MA.

Beeson, W.L., Abbey, D.E., Knutsen, S.F., 1998. Long term concentrations of ambient air pollutants and incident lung cancer in Californian adults: results from the AHSMOG study. Environmental Health Perspectives 106, 813–822.

Calderón-Garcidueñas, L., Reed, W., Maronpot, R.R., Henríquez-Roldán, C., Delgado-Chavez, R., Calderón-Garcidueñas, A., Dragustinovis, I., Franco-Lira, M., Aragón-Flores, M., Solt, A.C., Altenburg, M., Torres-Jardón, R., Swenberg, J.A., 2004. Brain inflammation and Alzheimer's-like pathology in individuals exposed to severe air pollution. Toxicologic Pathology 32 (6), 650–658.

Colls, J., 2002. Air Pollution, second ed. Spon Press, London.

Donaldson, K., 2003. The biological effects of coarse and fine particulate matter. Occupational and Environmental Medicine 60, 313.

Filippelli, G.M., Laidlaw, M.A.S., Latimer, J.C., Raftis, R., 2005. Urban lead poisoning and medical geology: an unfinished story. GSA Today 15, 4–11.

Flanders, P.J., 1994. Collection, measurement, and analysis of airborne magnetic particulates from pollution in the environment. Journal of Applied Physics 75, 5931–5936.

Gautam, P., Blaha, U., Appel, E., 2005. Magnetic susceptibility of dust-loaded leaves as a proxy for traffic-related heavy metal pollution in Kathmandu city, Nepal. Atmospheric Environment 39, 2201–2211.

Hanesch, M., Scholger, R., Rey, D., 2003. Mapping dust distribution around an industrial site by measuring magnetic parameters of tree leaves. Atmospheric Environment 37, 5125–5133.

Harrison, R.M., Jones, M., 1995. The chemical composition of airborne particles in the UK atmosphere. Science of the Total Environment 168, 195–214.

Heider, F., Zitzelsberger, A., Fabian, K., 1996. Magnetic susceptibility and remanent coercive force in grown magnetic crystals from 0.1 to 6 μm. Physics of the Earth and Planetary Interiors 93, 239–256.

Henshaw, D.L., Keitch, P.A., James, P.R., 1995. Lead-210, polonium-210, and vehicle exhaust pollution. Lancet 345, 324–325.

Huhn, G., Schulz, H., Staerk, H.J., Toelle, R., Scheuermann, G., 1995. Evaluation of regional heavy metal deposition by multivariate analysis of element contents in pine tree barks. Water, Air, and Soil Pollution 84, 367–383.

Hunt, A., Jones, J., Oldfield, F., 1984. Magnetic measurements and heavy metals in atmospheric particulates of anthropogenic origin. Science of the Total Environment 33, 129–139.

James, P.R., Close, J.J., Keitch, P.A., Allen, J.E., Fews, A.P., Henshaw, D.L., 2004. Aspects of the geographical variations of naturally occurring ^{210}Pb/^{210}Po in permanent teeth of juveniles in the UK. International Journal of Radiation Biology 80, 199–208.

Keyser, T.R., Natusch, D.F.S., Evans, C.A., Linton, R.W., 1978. Characterizing the surfaces of environmental particles. Environmental Science and Technology 12 (7), 768–773.

Kinnersley, R.P., Shaw, G., Bell, J.N.B., Minski, M.J., Goddard, A.J.H., 1996. Loss of particulate contaminants from plant canopies under wet and dry conditions. Environmental Pollution 91, 227–235.

Knox, E.G., 2006. Roads, railways and childhood cancers. Journal of Epidemiology and Community Health 60, 136–141.

Knutsen, S., Shavlik, D., Chen, L.H., Beeson, W.L., Ghamsary, M., Petersen, F., 2004. The association between ambient particulate air pollution levels and risk of cardiopulmonary and all-cause mortality during 22 years follow-up of a non-smoking cohort. Results from the AHSMOG study. Epidemiology 15, S45.

Koller, K., Brown, T., Spurgeon, A., Levy, L., 2004. Recent developments in low-level lead exposure and intellectual impairment in children. Environmental Health Perspectives 112, 987–994.

Lanphear, B.P., Dietrich, K., Auinger, P., Cox, C., 2000. Deficits in cognitive and academic skills associated with lead exposure occur at blood lead concentrations lower than 5 microg/dL. Public Health Report 115, 530–531.

Little, P., 1973. A study of heavy metal contamination of leaf surfaces. Environmental Pollution 5, 159–172.

Maher, B.A., 1988. Magnetic properties of some synthetic submicron magnetites. Geophysical Journal Royal Astronomical Society 94, 83–96.

Maher, B.A., Thompson, R., Hounslow, M.W., 1999. Introduction to Quaternary climates, environments and magnetism. In: Maher, B.A., Thompson, R. (Eds.), Quaternary Climates, Environments and Magnetism. Cambridge University Press, Cambridge, pp. 1–48.

Maricq, M., 1999. Examination of the size-resolved and transient nature of motor vehicle particle emissions. Environmental Science and Technology 33, 1618–1626.

Mathee, A., Schirnding, Y.E.R., Levin, J., Ismail, A., Huntley, R., Cantrell, A.A., 2002. A survey of blood lead levels among young Johannesburg school children. Environmental Research 90, 181–184.

Matzka, J., Maher, B.A., 1999. Magnetic biomonitoring of roadside tree leaves: identification of spatial and temporal variations in vehicle-derived particulates. Atmospheric Environment 33, 4565–4569.

McCrone, W.C., Delly, J.G., 1973. The Particle Atlas: Volume 2, the Light Microscopy Atlas. Ann Arbor, MI, USA.

Moreno, E., Sagnotti, L., Dinares-Turell, J.D., Winkler, A., Cascella, A., 2003. Atmospheric Environment 37, 2967–2977.

Morris, W.A., Morris, J.K., Versteeg, D.W., Bryant, A.E., Legzdins, B.E., McCarry, S., Marvin, C.H., 1995. Preliminary comparison between mutagenicity and magnetic susceptibility of respirable airborne particulates. Atmospheric Environment 29, 3441–3450.

Muxworthy, A.R., Schmidbauer, E., Petersen, N., 2002. Magnetic properties and Mossbauer spectra of urban atmospheric particulate matter: a case study from Munich, Germany. Geophysical Journal International 150, 558–570.

Needleman, H.L., Landrigan, P., 2004. What level of lead in blood is toxic for a child? (Letter). American Journal of Public Health 94, 8.

Olson, K.W., Skogerboe, R.K., 1975. Identification of soil lead compounds from automotive sources. Environmental Science and Technology 9, 227–230.

Petrovsky, E., Ellwood, B.B., 1999. Magnetic monitoring of pollution of air, land and waters. In: Maher, B.A., Thompson, R. (Eds.), Quaternary Climates, Environments and Magnetism. Cambridge University Press, Cambridge, pp. 279–322.

Pope III, C.A., Thun, M.J., Namboodiri, M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath, C.W., 1995. Particulate air pollution as a predictor of mortality in a prospective study of US adults. American Journal of Respiratory and Critical Care Medicine 151, 669–674.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Kazuhiko, I., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Journal of American Medical Association 287, 1132–1141.

Quality of Urban Air Review Group, 1996. Airborne particle matter in the United Kingdom. QUARG third report, UK.

Rabito, F.A., Shorter, C., White, L.E., 2004. Lead levels among children who live in public housing. Epidemiology 216, 263–268.

Rudell, B., Blomberg, A., Helleday, R., Ledin, M.C., Lundback, B., Stjernberg, N., Horstedt, P., Sandstrom, T., 1999. Bronchoalveolar inflammation after exposure to diesel exhaust: comparison between unfiltered and particle trap filtered exhaust. Occupational and Environmental Medicine 56, 527–534.

Sagnotti, L., Macrì, P., Egli, R., Mondino, M., 2006. Magnetic properties of atmospheric particulate matter from automatic air sampler stations in Latium (Italy): toward a definition of magnetic fingerprints for natural and anthropogenic PM sources. Journal of Geophysical Research 111 (b12), B12S22.

Samet, J.M., Graves, L.M., Quay, J., Dailey, L.A., Devlin, R.B., Ghio, A.J., Weidong, W., Bromberg, P.A., Reed, W., 1998. Activation of MAP kinases in human bronchial epithelial cells exposed to metals. American Journal of Physiology Lung Cellular and Molecular Physiology 275, 551–558.

Schadlich, G., Weissflog, L., Schuurmann, G., 1995. Magnetic susceptibility in conifer needles as indicator of fly ash deposition. Fresenius Environmental Bulletin 4, 7–12.

Schwartz, J., 1996. Air pollution and hospital admissions for respiratory disease. Epidemiology 7, 20–28.

Schwarze, P.E., Øvrevik, J., Låg, M., Refsnes, M., Nafstad, P., Hetland, R.B., Dybing, E., 2006. Particulate matter properties and health effects: consistency of epidemiological and toxicological studies. Human and Experimental Toxicology 25, 559–579.

Seaton, A., MacNee, W., Donaldson, K., 1995. Particulate air pollution and acute health effects. Lancet 345, 176–178.

Walden, J., Oldfield, F., Smith, J. (Eds.), 1999. Environmental Magnetism A Practical Guide. Quaternary Research Association Technical Guide No. 6.

Wang, Y.F., Huang, K.L., Li, C.T., Mi, H.H., Luo, J.H., Tsai, P.J., 2003. Emissions of fuel metals content from a diesel vehicle engine. Atmospheric Environment 37, 4637–4643.

Young, T.M., Heerman, D.A., Sirin, G., Ashbaugh, L.L., 2002. Resuspension of soil as a source of airborne lead near industrial facilities and highways. Environmental Science and Technology 36, 2484–2490.