Geogenic control on soil chemistry in urban areas: a novel method for urban geochemical mapping using parent material classified data

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Abstract

The purpose of the study reported here is to assess whether it may in some circumstances be useful and appropriate to use a parent material (PM) soil chemistry mapping method developed for national soil chemistry data to portray spatial variation in urban soil chemistry data in Great Britain. Analysis of variance (ANOVA) of the urban soil data suggests that spatial interpolation of soil ambient background concentrations (ABCs) using parent material classified soil data may be justified for those elements with strong geogenic control. The PM soil chemistry mapping method for urban soil data is demonstrated using data from the Northampton urban area, in the English Midlands. Geometric mean (GM) and inverse distance weighting (IDW) interpolations based on the nearest 4 topsoil samples were evaluated. Independent validation indicated that for As, Cr, Fe and to a lesser extent K, which all exhibit relatively strong geogenic control in the Northampton urban area, (i) the PM soil chemistry mapping method is more accurate and effective than the conventional IDW grid mapping and (ii) PM soil chemistry mapping based on the average of the nearest four Ln_e element concentrations is more accurate than mapping based on IDW values calculated from the nearest four Ln_e element concentrations. The variation in effectiveness of the methods can be explained by the fact that parent material exerts a significant control on As, Cr, Fe and K in the Northampton area whereas anthropogenic inputs appear to be the dominant control on the spatial variation of Pb, especially at high concentrations. The PM mapping method would be expected to work efficiently in other urban areas and for those elements where a significant proportion of the variation can be explained by PM.

1. Introduction

1.1 Urban geochemistry

Albanese et al. (2008) observed that the main objectives of an urban geochemical survey are to: (i) portray the distribution of elemental concentrations in the environment (i.e. the geochemical baseline); (ii) establish the 'natural' geochemical background to determine the influence of anthropogenic activities on urban soil chemistry; (iii) delineate areas of the urban environment where reference levels established by governments, such as the soil guideline values (SGVs) in England and Wales, are exceeded; and (iv) identify the principal sources of anthropogenic pollution/contamination. Albanese et al. (2008) described a range of methods that had been used to map the spatial variation of geochemical data in urban areas, including kriging and multi-fractal inverse distance weighted methods. Reimann et al. (2005) suggested that methods not strongly based on statistical assumptions (such as IDW) should be the first choice when interpolating the spatial pattern of geochemical data and numerous examples of this are available in the recent literature (Lee et al., 2005; Fordyce et al., 2005; Flight and Scheib, 2011). Kriging and other interpolation methods have also been used (Rawlins et al., 2005; Hooker and Nathanial, 2006; Birke et al., 2011).

Many urban geochemists prefer classified or graduated symbol maps on the basis that interpolated maps can give misleading results. The high degree of small-scale spatial variation in the chemistry of some elements (such as Pb, Sn, Zn) in urban areas results in the spatial extent of high element concentrations being over-emphasised using standard interpolation methods, such as inverse distance weighting (IDW) based on non-transformed data (Johnson and Ander, 2008; Flight and Scheib, 2011). Smith et al., (2011) noted that Pb can vary from 5000 mg kg^{-1} to 200 mg kg^{-1} within 10 m. As a

consequence, interpolation between sample sites, which may be separated by a hundred meters or more, is likely to give a false impression of the variability of elements whose concentrations are mainly determined by anthropogenic contamination. Geogenic control on the spatial distribution of a range of elements is widely discussed in the published literature, but no studies were found in which mapping the spatial variation of soil chemistry within urban areas had been based on parent material classified data.

1.2 Geology and geochemistry of the Northampton urban area

The purpose of the study reported here is to assess what proportion of the variability of lithogenic and potentially harmful elements (PHEs) can be explained by soil parent material and whether it may in some circumstances be useful and appropriate to use the parent material soil chemistry mapping method (Appleton et al., 2008) to portray spatial variation in urban soil chemistry data, rather than the classified symbol and IDW interpolated map data conventionally used (Flight and Scheib, 2011). Topsoil data from the British Geological Survey for the Northampton urban area is used to evaluate the mapping method because of the strong geochemical contrast between the bedrock and superficial geological units and the importance of high As concentrations, which frequently exceed the current SGV of 32 mg kg^{-1}, a threshold used in the preliminary assessments for land contamination (Environment Agency, 2009).

A parent material map (Figure 1) based on the simplified geological classification used for radon mapping (Digital Geological Map of Great Britain 1:50 000 scale data, DiGMapGB-50, Version 3.14, Miles and Appleton, 2005) shows a bedrock sequence going upwards from the Middle Lias (mudstone and sandstone of the Dyrham Formation) through the Upper Lias (Whitby Mudstone Formation), and ironstones of

the Northampton Sand Formation (NSF). The Great Oolite Group at the top of the bedrock sequence comprises the Blisworth Limestone and Blisworth Clay Formations, and the mudstone, siltstone, sandstone and limestone sequence of the Rutland Formation (which itself includes the thin Wellingborough Limestone). Alluvium, and sand and gravel river terrace deposits occur in the valley of the River Nene, which runs E-W through the centre of Northampton, and some of its tributaries. Relatively small patches of glacial till are found in the north and west of the urban area (Figure 1). High As concentrations are associated with the ironstones of the Jurassic Northampton Sand Formation (NSF) within the urban area (Palumbo-Roe et al., 2005). Sedimentary ironstones may be enriched in arsenic due to the abundance of iron oxyhydroxides which have a high affinity for arsenic. In the Northampton area, high arsenic in soil has been attributed to the weathering of the ironstone bedrock (Rawlins et al., 2003). High arsenic in soil is also associated with soils derived from other Jurassic and Cretaceous ironstones in eastern England (Breward, 2007). Arsenic, Cr and Fe were selected, since these elements are enriched in the NSF; K was selected because of the potentially strong contrast between the high concentrations expected to be associated with alluvium, glacial till deposits and Upper Lias clays, and lower concentrations associated with the NSF and limestone units. Finally Pb was also studied, because it was anticipated that the spatial variation of this element at higher concentrations is likely to be associated with point source and diffuse anthropogenic pollution, rather than being controlled by the distribution of the parent material units.

2. Materials and methods

2.1 Soil chemistry data

Soil geochemical surveys have been carried out by BGS at selected urban centres in Great Britain (Flight and Scheib, 2011). Soil samples were collected from open

ground on a 500 m grid at a density of approximately 4 samples per km^2. At each site, composite samples, based on 5 sub-samples taken at the centre and four corners of a 20 m square, were collected from the topsoil (5–20 cm depth) and profile (35-50 cm depth). At the time of the Northampton urban survey, approximately 40 chemical elements were determined in the <2 mm size fraction of the topsoils using X-ray fluorescence spectrometry (XRFS). Sample preparation, analytical methods, and quality control procedures are described in Allen et al. (2011) and Johnson (2011). Summary statistics for UK urban soils are given in Table 1.

2.2 Analysis of variance

One way analysis of variance (ANOVA) in MINITAB® 15 was used to calculate the proportion of the variation of log-transformed element concentrations explained by soil parent material (bedrock/superficial geology combination) using the sum of squares between group means (Appleton and Miles, 2010). The F-statistic was utilised to measure significance level (p-value) and the fraction of the variation related to parent material was generally significant statistically (p <0.0001). ANOVA statistics assume that population distributions are normal for each group, variances are equal for all groups, and also that observations are randomly and independently representative of the populations (Reimann et al., 2008). All these conditions are unlikely to be met perfectly in soil geochemical data representing a wide variation of parent materials and the influence of a wide range of environmental and anthropogenic factors. Fortunately, ANOVA is little affected by relatively small or moderate departures from homogeneity of variance. The application of a log-transform in general produces more normal distributions with lower skewness coefficients, especially for elements such as Cr and Pb where anthropogenic contamination is a significant factor in the Northampton area. Where PM is the major

control, the proportion of variance explained by PM is broadly similar for untransformed and log-transformed data (Table 2). ANOVA and non-parametric Kruskal-Wallis statistics for the Northampton urban soil data grouped using the simplified PM classification (Figure 1) have comparable p values. Kruskal-Wallis statistics are very high (p <0.0001) for As, Cr, Fe and K when the proportion of the variance is relatively high for the log-transformed data (13-26%) and the ANOVA F values are high (p <0.0001). The significance of the Kruskal-Wallis and ANOVA statistics is much lower when the proportion of variance explained by PM is low (e.g. Pb 3 - 4%). Data for the Middle Lias was not included in the analysis since this group has only 3 samples.

2.3 Soil chemistry mapping using PM classified data

Urban soil geochemical data have in some cases large positive skewness coefficients so are transformed by taking natural logarithms. To overcome the bias associated with log-normal data, the geometric mean (GM) and IDW GM were used for mapping the spatial variation in As, Cr, Fe, K and Pb concentrations. Using PM polygons as soil chemistry mapping units, it is possible to estimate element concentrations based on local averages, without significant errors at PM boundaries (Appleton et al., 2008). This methodology is appropriate in situations and for elements where PM explains a relatively high proportion of the variance, but less so for elements where the proportion of variance explained by PM is low, for example where point source anthropogenic contamination is a major factor, such as Pb.

Parent material classes are based either on the concatenation of separate codes for the underlying bedrock and any superficial deposits present or on surface geology. Made ground is not used as a soil PM class, because spatial information on the distribution of made ground in urban areas in the UK is incomplete. A simplified bedrock and

superficial geology classification developed for radon mapping in England and Wales (Miles and Appleton, 2005) was used in order to have an adequate number of soil samples on each PM class to facilitate mapping of spatial variation in element concentrations within the PM units.

Parent material polygons are subdivided into separate 100 m square polygons of the British National Grid using ESRI® ArcGIS geoprocessing tools to produce the shape files which store non-topological geometry and attribute information for the spatial features that form the basis for the production of the geochemical maps. Parent material codes and codes for the relevant 100 m grid square are attached to the locations of all soil samples. Parent material geochemical mapping was executed using an ArcGIS tool written in Vb.Net. On a map extract from the Northampton urban area (Figure 2), the Northampton Sand Formation (NSF, ironstone) is outlined by a thick black line and individual soil samples derived from the NSF identified by black filled circles labelled with As concentrations (mg kg^{-1}). The estimated geometric mean (GM) As concentration for each individual 100 m square polygon within the boundary of the NSF is the average (i.e. GM) of Ln$_e$As in the nearest 4 topsoil samples. Topsoil samples on other PMs are indicated by grey filled circles (Figure 2). The optimum number of samples for calculating GM element concentrations for 100 m-PM polygons was not studied in the Northampton area, but hold out validation studies in England and Wales (Appleton et al., 2008) and Northern Ireland (unpublished data) indicated that the optimum number is between 4 and 7 for topsoils. The PM interpolation method described in this paper is called 100 m-PM; the standard IDW grid square interpolation method is called 100 m.

2.4 Validation

Independent validation of the 100 m-PM and 100 m urban geochemical mapping was carried out by comparing element concentrations in 36 G-BASE topsoil samples, collected during the East Midlands regional survey (Johnson et al., 2005), with estimated values derived from the 100 m and 100 m-PM interpolation of data for 274 topsoil samples, collected during the Northampton urban survey. Mean Squared Deviation (MSD) between the estimated GM at the site and the measured concentration at each of the G-BASE rural topsoil sites was used to validate the mapping methods:

$$MSD = \frac{1}{n} \sum_{i=}^{n} \left(M_{est} - measured \right)^{2}$$

3. Results and discussion

3.1 ANOVA

Parent material is the primary control on soil geochemistry in recently glaciated landscapes such as the British Isles (Rawlins et al., 2003). Appleton et al. (2008) demonstrated that 30 – 43 % of the variance in topsoils in the Humber-Trent area is accounted for by PM. It might be anticipated that PM would generally exert a much less dominant control in urban areas, due to the impact of diffuse and point-source contamination. However, a relatively high proportion of the variance of As, Cr, Fe, K and Pb is accounted for by PM, especially in those urban areas where there is a particularly strong chemical contrast between geological units (for example, Northampton, Scunthorpe, Corby, Mansfield; Table 3). In the Mansfield urban area, the variance of As (49%), Cr (58%) and Fe (53%) accounted for by PM slightly exceeds the proportion of variance for these elements in rural G-BASE topsoils from the Humber-Trent and East Midlands (42-48%, Table 3) areas. As would be expected,

the variance of Pb accounted for by PM is relatively low in many urban areas (e.g. 2-9 % in Corby, Coventry, Glasgow, Hull, Leicester, London, Northampton and York), since anthropogenic contamination is the major factor in these urban areas. Even so, a relatively high proportion of the variance of Pb is accounted for by PM in some urban areas (e.g. 20 % or more in Cardigan, Derby, Ipswich, Mansfield, Scunthorpe and Telford). The data need to be examined in greater detail to evaluate whether this is caused by geological control or whether the sources of anthropogenic contamination are preferentially located on one or more PMs, for example alluvium, as a result of the location of industrial activities on flood plain areas. In general, the ANOVA results justify the evaluation of mapping soil chemistry of the urban areas quoted here; using PM classified data when the proportion of an elements variance explained by PM is relatively high.

3.2 Evaluation of PM soil chemistry mapping in Northampton urban area

Interpolation of the point source topsoil data to a 100 m grid provides a simple impression of the spatial distribution, but without any consideration of the geological controls (Figures 3, 7 and 10).

In the Northampton urban area, interpolation of the topsoil data to 100 m-PM polygons serves to constrain the 'leakage' of high As (Figure 4), Cr and Fe concentrations associated with the NSF into areas underlain by adjacent PMs with lower As, Cr and Fe concentrations. This is particularly important where the distributions of elevated ambient background concentrations (ABCs) are spatially complex, since they relate to the convoluted outcrop pattern associated with the As enriched NSF. Errors at PM boundaries are likely to be reduced when ABC estimates are derived within delineations of the PM mapping units.

There appears to be some down slope dispersion of high concentrations of As (Figures 4-5), Cr and Fe in soil from the NSF onto the adjacent Upper Lias and also onto alluvium in the Nene valley and its tributaries (Table 4).

Similar features are seen on 100 m-PM maps for Fe and Cr, although very high Cr (up to 4251 mg kg^{-1}) occurs in topsoils in the vicinity of historical tanneries and in the alluvial soil located in the Nene valley downstream of the tanneries, presumably as the result of contamination of topsoil with tannery waste (Bini et al., 2008), and redistribution of Cr-enriched soil from the NSF and tannery waste, downstream and down slope (Figure 6).

The 100 m-PM polygon maps illustrate the close association of higher K concentrations with alluvium (clay, silt and subsidiary sand and gravel), glacial till and Upper Lias clays (Figure 8). As would be expected, lower concentrations are associated with the NSF and alluvium, whilst the Great Oolite Group has a wide range of K since the Group includes limestones with low K and mudstones with relatively high K (Figure 9 and Table 4).

Comparison of the distribution of Pb in urban topsoil with the extent of the built-up area of Northampton in 1901-1938 indicates a close associated of Pb contamination with urbanisation of this period. Lead may be related to ash from domestic coal fires, which is often dispersed in urban centres from this period when coal was the main source of heating in domestic and industrial buildings. Much lower Pb concentrations characterise the more recently urbanised area.

3.3 Validation of mapping methods

Validation was based on 36 topsoil samples from the BGS rural survey that are located within the area covered by the urban soil geochemical survey (locations in Figure 7). Mean squared deviations for the 100 m-PM mapping method are lower than

for the 100 m method for As, Cr and Fe, approximately the same for K and much higher for Pb (Table 5), when estimated concentrations at 100 m-PM and 100 m polygon centroids are the average of the nearest four Ln_e element concentrations. When estimated concentrations at 100 m-PM and 100 m polygon centroids are the IDW value, based on the nearest four Ln_e element concentrations, the MSDs for the 100 m-PM mapping method are lower than for the 100 m method for As, Cr, Fe, and K and slightly higher for Pb (Table 5). The MSDs for the 100 m-PM mapping method are lower when estimates for 100 m-PM polygon centroids are the average of the nearest four Ln_e element concentrations, compared with when estimates are the IDW value based on the nearest four Ln_e element concentrations. These results suggest that for As, Cr, Fe, and to a lesser extent K, which all exhibit relatively strong geogenic control in the Northampton urban area, (i) the 100 m-PM method is more accurate and effective than the 100 m method and (ii) mapping based on the average of the nearest four Ln_e element concentrations is more accurate than mapping based on IDW values calculated from the nearest four Ln_e element concentrations.

4. Conclusions

This study has established that the proportion of the variability of some lithogenic and potentially harmful elements (PHEs) explained by soil parent material is relatively high. If the variance accounted for by PM is low (e.g. <10%) then PM mapping is unlikely to be very informative, whereas when the percentage is 20 or higher, PM may well exert a significant control on soil chemistry in urban areas. Where this is the case, (i) the parent material (PM) soil chemistry mapping method can be used to portray spatial variation in urban soil chemistry data more accurately than the IDW interpolated map data conventionally used; (ii) PM mapping allows a better visual

impression to be obtained of the geological control on soil chemistry than graduated symbol maps (compare, for example, Figures 4 and 11). Even so, it is not feasible to establish, on the basis of this study, an exact quantitative threshold (percentage of variance accounted for by PM) which can be used to decide whether PM mapping or conventional grid mapping is the most appropriate method for portraying the spatial variation in soil chemistry in individual urban areas. The PM mapping method is being used to establish 'normal' background concentrations of arsenic in soils in England where there is good evidence these are 'natural' background concentrations controlled mainly by PM. This information may be required in the future by the contaminated land legislative regime under the Environmental Protection Act 1990. The PM maps for As can be used also to delineate areas of the urban environment where reference levels, such as the soil guideline values (SGVs) in England and Wales, are exceeded. Over-plotting of outliers could be used to identify point sources of anthropogenic contamination.

Acknowledgements

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Table 1 Number (No.) of urban topsoil samples and urban area summary statistics for As, Cr, Fe, K and Pb

Urban area	No.	As^a med.	As^a max.	Cr^a med.	Cr^a max.	Fe^b med.	Fe^b max.	K^b med.	K^b max.	Pb^a med.	Pb^a max.
Cardiff	517	16	150	72	2426	3.6	29.8	na	na	77	7575
Corby	133	19	89	90	232	4.1	16.5	1.6	2.0	37	449
Coventry	395	9	104	64	422	2.8	8.3	1.7	3.5	73	1001
Derby	276	13	63	67	309	3.1	8.9	1.9	3.4	159	2107
Doncaster	279	13	74	64	499	3.8	12.2	na	na	78	1100
Glasgow	1381	9	283	108	4286	4.5	14.1	1.1	2.4	127	5001
Hull	408	20	205	83	1809	4.2	22.1	na	na	117	2900
Ipswich	200	11	47	42	119	na	na	na	na	54	923
Leicester	656	13	84	73	762	3.3	9.5	1.9	4.1	65	2636
Lincoln	215	11	65	44	260	2.0	8.6	1.1	2.0	54	1400
London[c]	7187	15	161	73	2094	2.7	10.8	1.1	2.7	169	6600
Manchester	300	20	1001	76	1238	3.2	14.2	na	na	218	2758
Mansfield	257	11	71	54	250	2.2	10.6	1.5	2.9	76	1319
Northampton	275	30	106	98	4251	5.3	20.5	1.4	2.0	56	672
Nottingham	636	13	87	67	183	2.8	17.7	1.9	4.1	101	1001
Peterborough	275	17	35	78	186	4.2	8.7	1.3	2.7	39	780
Scunthorpe	196	19	190	55	1108	3.2	24.0	1.1	2.5	45	3300
Sheffield	575	22	239	102	1251	4.7	18.4	na	na	164	4300
Stoke	747	14	136	73	441	3.7	22.6	1.3	3.0	93	4208
Swansea	372	53	2047	74	565	4.1	14.8	na	na	221	14714
Telford	295	10	54	67	164	3.0	10.9	na	na	92	1236
Wolverhampton	285	17	157	83	1297	0.3	0.8	na	na	158	2853
York	191	10	93	59	639	2.4	7.1	na	na	106	2400

[a] mg kg-1; [b] %; [c] London includes satellite towns of Brentwood, Basildon, Canvey Island, Southend, Tilbury and Grays; na = not available

Table 2. ANOVA and Kruskal-Wallis statistics for Northampton urban area soil samples grouped by parent material (n = 271, DF = 5).

Element	ANOVA R^2	ANOVA F	ANOVA p	Kruskal-Wallis H	Kruskal-Wallis p
As	24	16.9	<0.0001	75.3	<0.0001
Ln_e As	26	18.6	<0.0001		
Cr	5	3.0	0.013	61.2	<0.0001
Ln_e Cr	13	7.8	<0.0001		
Fe	14	8.9	<0.0001	67.6	<0.0001
Ln_e Fe	18	12.0	<0.0001		
K	17	10.9	<0.0001	52.3	<0.0001
Ln_e K	15	9.1	<0.0001		
Pb	3	1.5	0.196	13.2	0.022
Ln_e Pb	4	2.4	0.036		

Table 3 Proportion of variance accounted for by PM in Log$_e$ transformed topsoil As, Cr, Fe, K and Pb data from urban areas compared with rural soils for the East Midlands and Humber-Trent area.

Urban area	No. samples	Variance (%) accounted for in log$_e$ transformed element concentrations				
		As	Cr	Fe	K	Pb
Cardiff	517	28	20	25	na	37
Corby	133	39	13	20	16	6
Coventry	395	12	17	18	25	5
Derby	276	5	11	13	na	20
Doncaster	279	10	27	19	na	8
Glasgow	1381	10	10	17	19	9
Hull	408	12	16	21	na	2
Ipswich	200	29	35	na	na	21
Leicester	656	18	4	23	20	5
Lincoln	215	40	24	33	20	14
London[1]	7189	11	17	23	28	7
Manchester	300	6	9	14	na	5
Mansfield	257	49	58	53	33	20
Northampton	275	27	10 (16)[a]	22	19	7
Nottingham	636	22	36	38	47	10
Peterborough	275	27	37	31	25	13
Scunthorpe	196	35	35	36	30	22
Sheffield	575	4	14	7	na	10
Stoke	747	13	19	25	23	12
Swansea	372	20	20	15	na	14
Telford	295	28	38	31	na	24
Wolverhampton	284	14	15	15	na	10
York	191	3	15	12	na	5
East Midlands and Humber-Trent rural area	13813	47	42	48	48	46

na = not available

[a] value in brackets determined after removing one highly anomalous sample (4251 mg kg^{-1} Cr)

Table 4. Geometric mean concentrations in topsoil samples from the Northampton urban area (grouped by PM)

PM	No.	As mg kg^{-1}	Cr mg kg^{-1}	Fe %	K %	Pb mg kg^{-1}
Alluvium	35	32	130	6.44	1.46	67
Sand and gravel	19	26	99	5.25	1.36	55
Glacial till	15	24	94	4.68	1.57	56
Gt. Oolite Gp.	56	23	88	4.39	1.31	61
NSF	87	41	104	5.99	1.19	78
U. Lias	59	30	118	6.01	1.40	59
M. Lias	3	25	96	5.19	1.51	33

Table 5 Mean square deviations between measured concentrations in 36 G-BASE rural soil survey samples and estimated concentrations derived from interpolation of urban soil data

Method	LnAs	LnCr	LnFe	LnK	LnPb
100 m (GM)	0.152	0.149	0.180	0.373	0.129
100 m-PM (GM)	0.131	0.133	0.136	0.400	0.159
100 m (IDW)	0.169	0.189	0.147	0.434	0.170
100 m-PM (IDW)	0.154	0.157	0.137	0.420	0.175

GM = polygon estimate based on average of Ln_e data; IDW = polygon estimate based on IDW average of Ln_e transformed data.
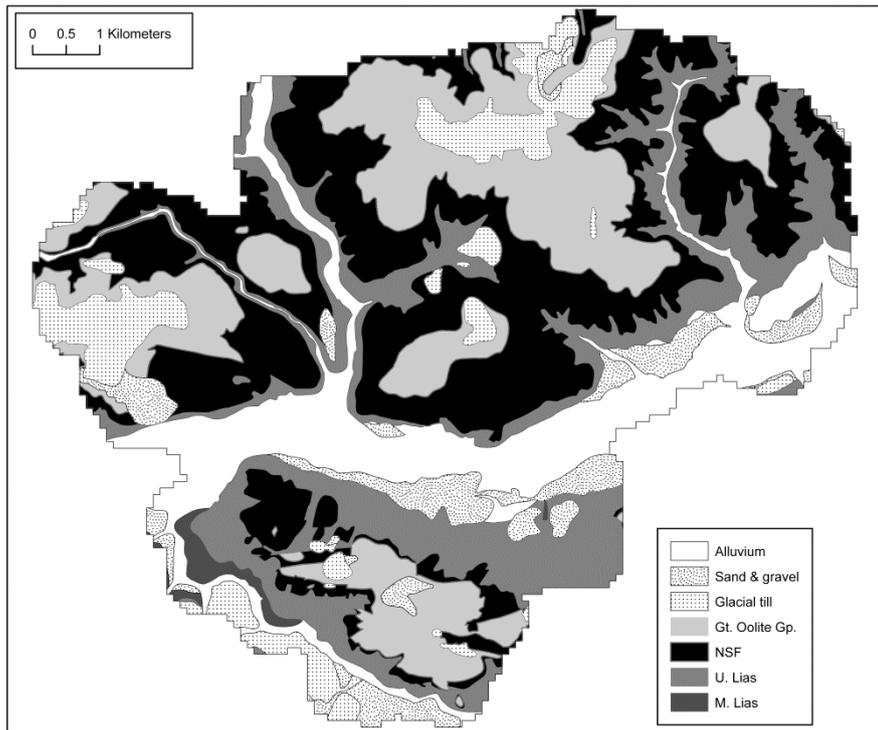
Figure 1 Simplified Soil Parent Material map of the Northampton urban area
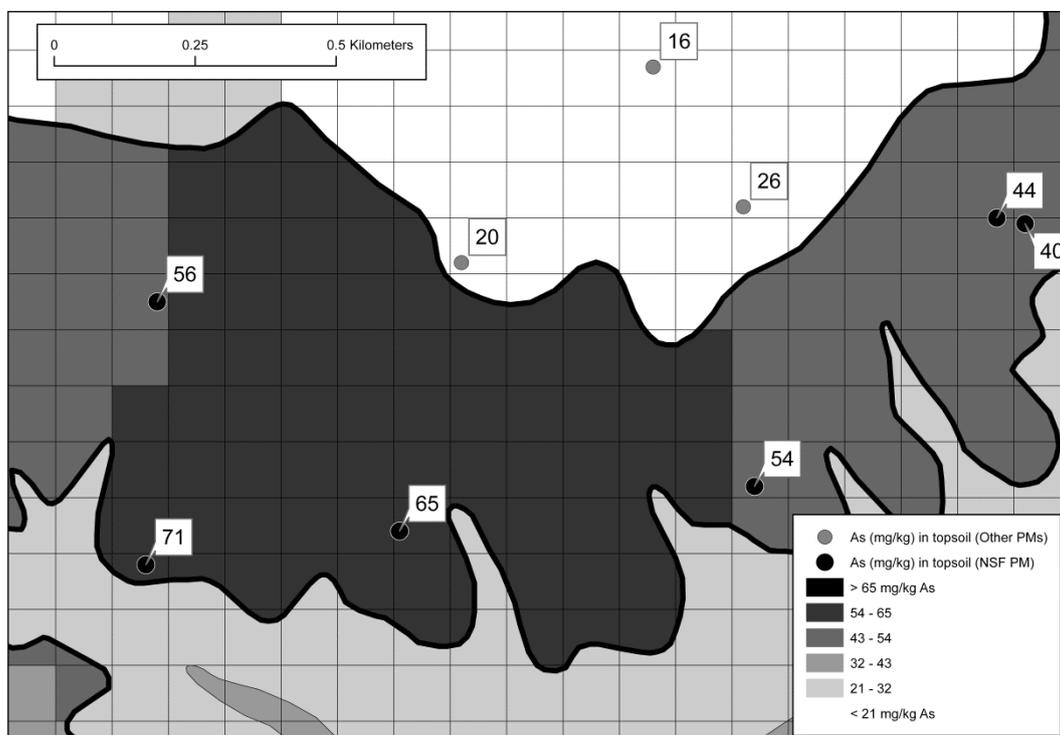
Figure 2 Geochemical mapping using PM-grouped data (see text for explanation)
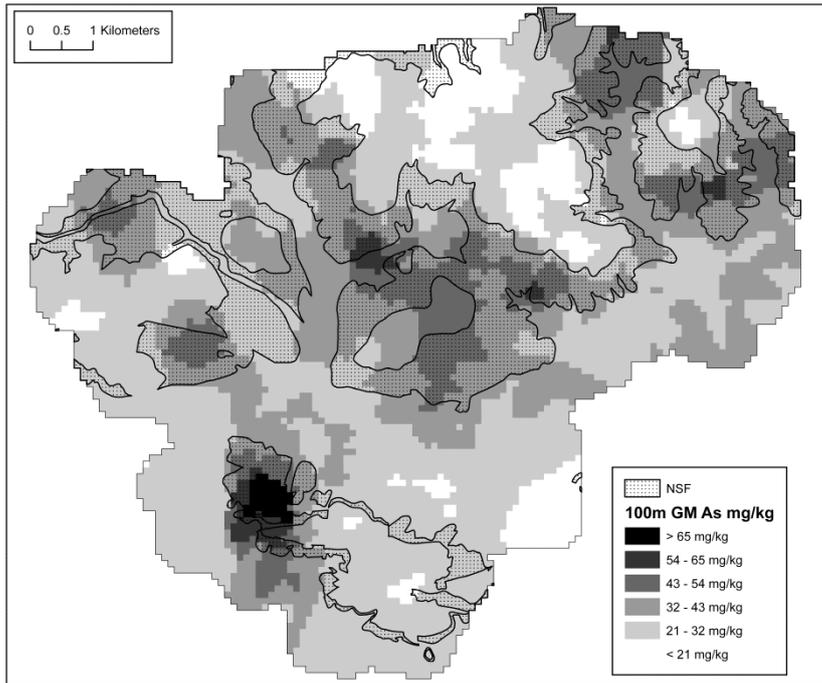
Figure 3 Urban topsoil As interpolated to 100 m grid (GM As derived from nearest 4 topsoil samples)
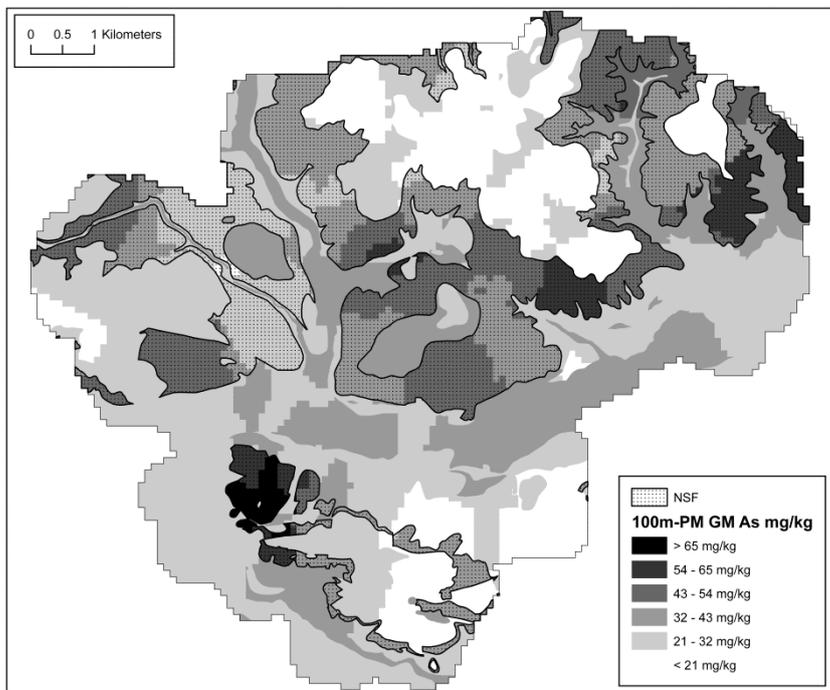

Figure 4 Urban topsoil As interpolated to 100 m-PM grid (GM As derived from nearest 4 topsoil samples on same PM)
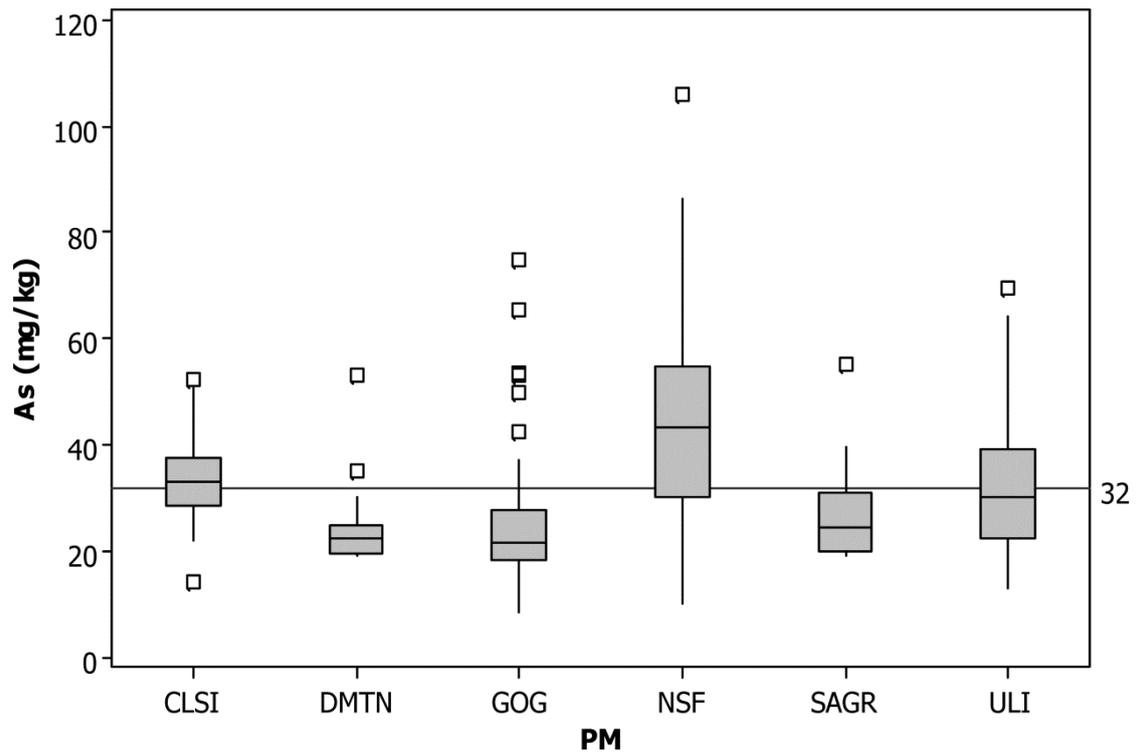
Figure 5. Arsenic in Northampton urban soil samples grouped by PM (CLSI = alluvium (clay-silt), DMTN = glacial till (diamicton); GOG = Great Oolite Group; NSF = Northampton Sand Formation); SAGR = sand and gravel; ULI = Upper Lias)
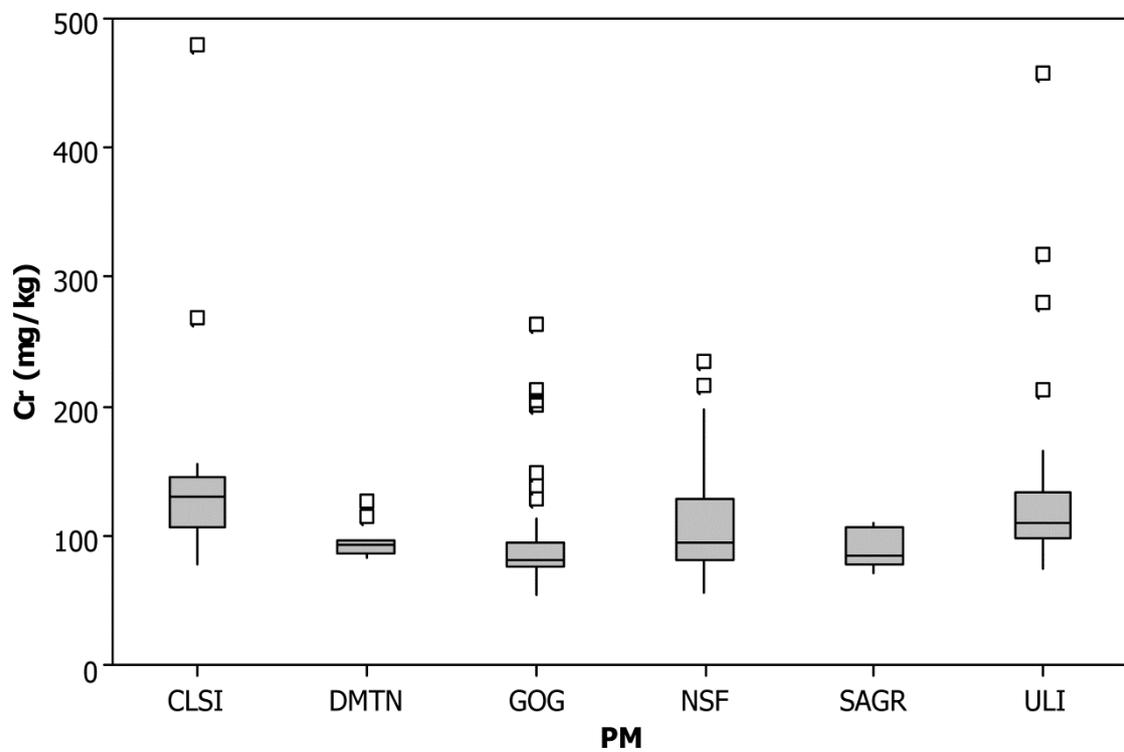
Figure 6. Chromium in Northampton urban soil samples grouped by PM
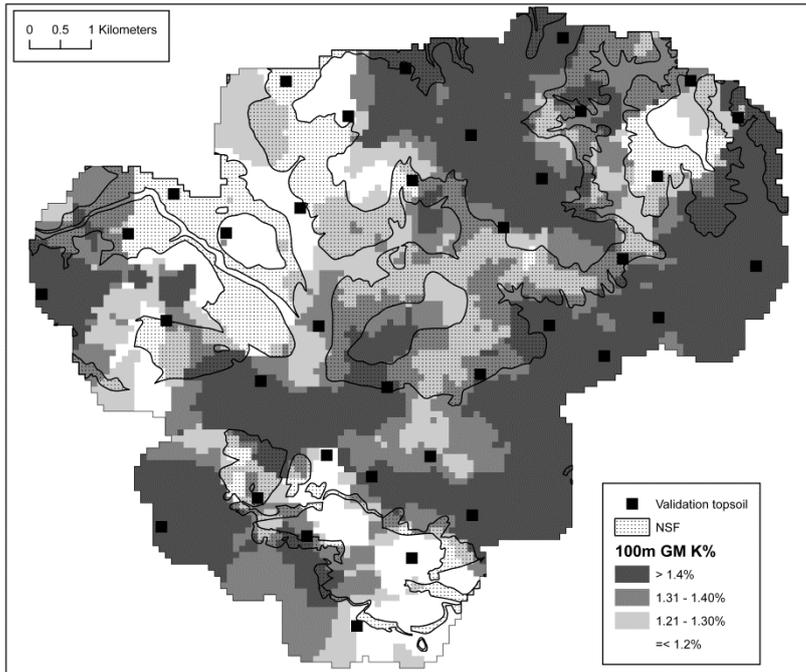
Figure 7 Urban topsoil K (%) interpolated to 100 m grid (GM K derived from nearest 4 topsoil samples)
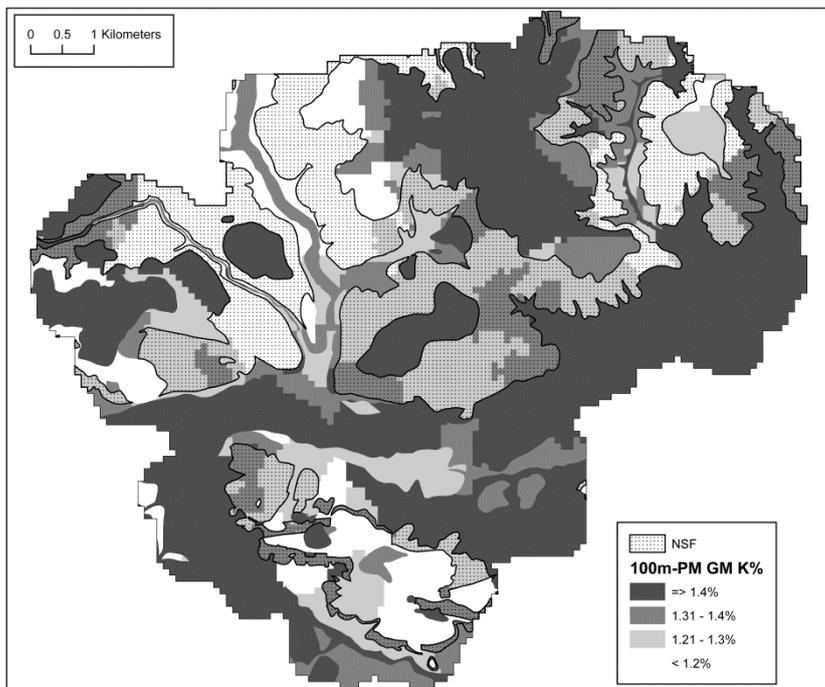
Figure 8 Urban topsoil K (%) interpolated to 100 m-PM grid (GM K derived from nearest 4 topsoil samples)
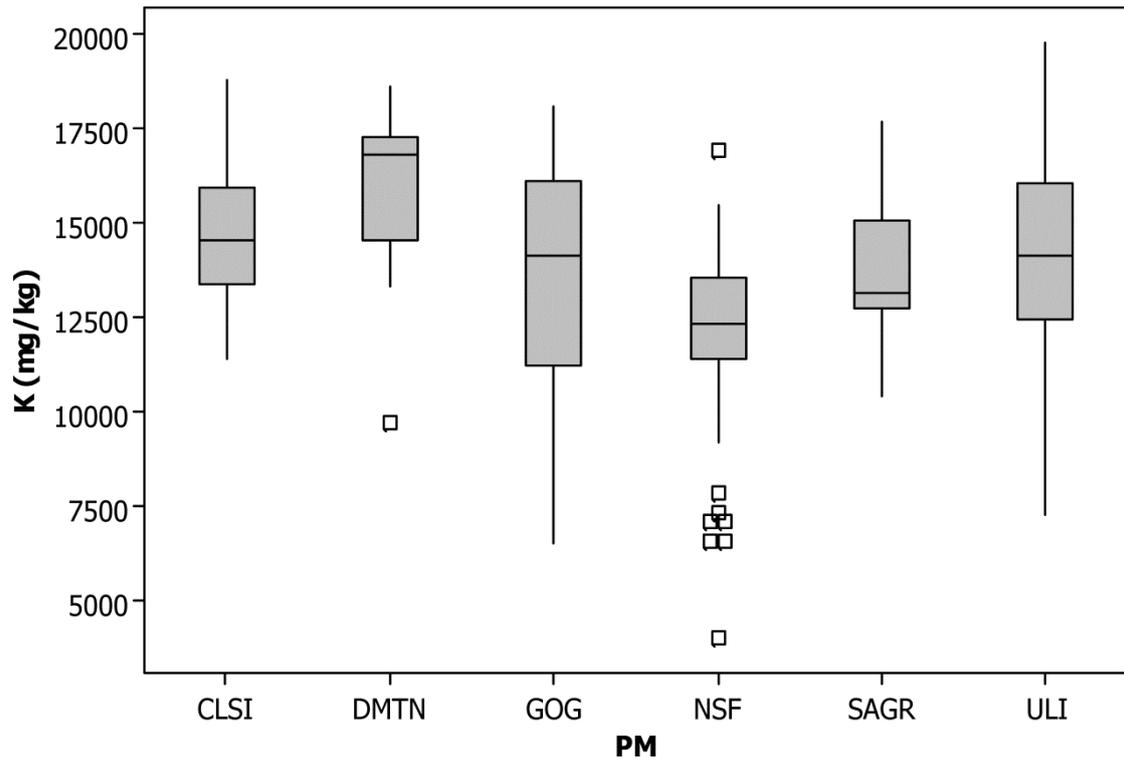
Figure 9. Potassium in Northampton urban soil samples grouped by PM
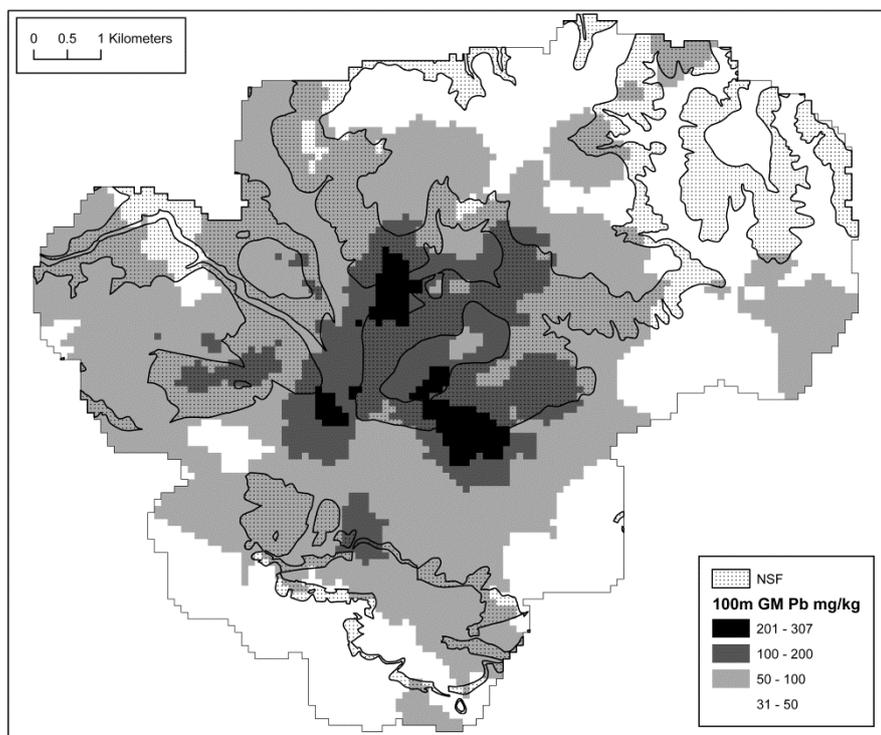
Figure 10   Urban topsoil Pb interpolated to 100 m grid (GM Pb derived from nearest
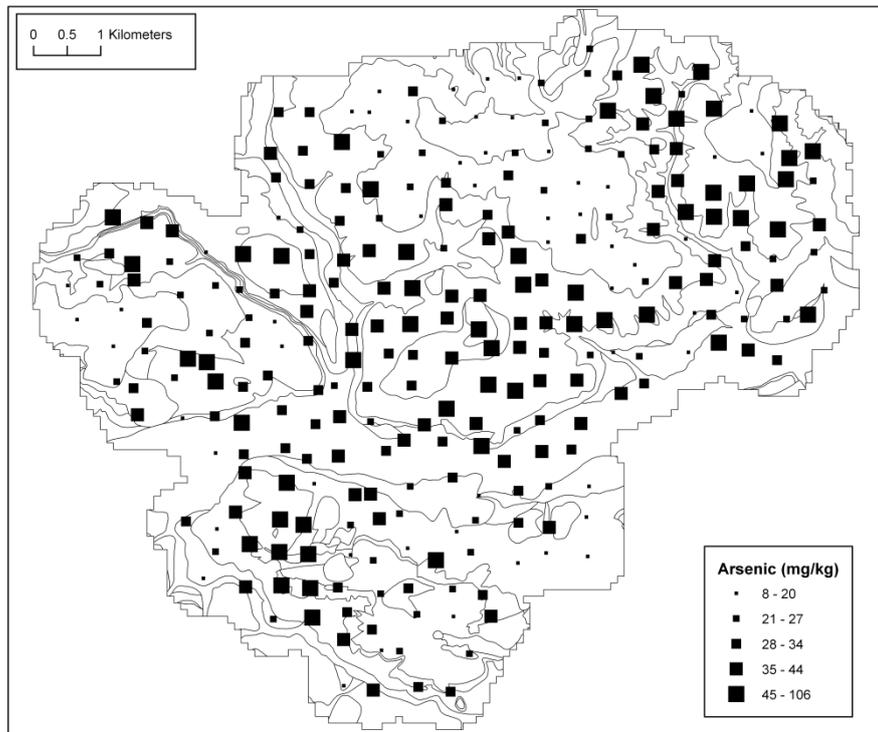
4 topsoil samples)

Figure 11. Quantile classified symbol map of arsenic in Northampton urban soil
samples (solid lines = parent material boundaries; see Figure 1 for more detail)