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Associations between land cover/use categories and soil concentrations of arsenic, lead and barium, and population race/ethnicity and socioeconomic status

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Abstract

The potential of using land cover/use categories as a proxy for soil metal concentrations was examined by measuring associations between percentages of Anderson land cover categories with soil concentrations of As, Pb, and Ba in ten sampling areas. Land cover category and metal associations with ethnicity and socioeconomic status at the United States Census 2000 block and block group levels also were examined. Arsenic and Pb were highest in urban locations; Ba was a function of geology. Consistent associations were observed between urban/built up land cover, and Pb and poverty. Land cover can be used as proxy for metal concentrations, although associations are metal-dependent.

Keywords

Residential soils; GIS; human health; metals; Anderson land cover

Introduction

The potential for exposure to environmental contaminants is an important human health issue due to the influx of pollutants from numerous anthropogenic sources (Carrizales et al., 2006; Hinwood et al., 2004; Thepanondh and Toruksa, 2011; Wang et al., 2010). Metals are

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especially important as they are relatively long-lived in the environment (Aelion et al., 2014) and negative health effects from exposure to a variety of metals including arsenic (As) and lead (Pb) have been documented (Ahamed et al., 2006; Calderón et al., 2001; Wright et al., 2006). Unfortunately, research has shown that populations of children, racial/ethnic minorities, and those of lower socioeconomic status (SES) are often disproportionately exposed to metals in soils (Aelion et al., 2012, 2013; Calderón et al., 2003; Calderon et al., 2004; Campanella and Mielke, et al., 2008; Diawara et al., 2008; Mielke et al., 1999) and, therefore, potentially more susceptible to associated negative health outcomes.

For metals with anthropogenic sources, both the presence of and distance to point source facilities emitting certain metals have been found to be associated with environmental soil metal concentrations (Aelion et al., 2009b; Chrastný et al., 2012; Rovira et al., 2011). However, there are numerous other sources that cannot easily be quantified, such as inputs from historical use of leaded gasoline and exterior home lead-based paints, as well as agricultural practices. We propose the use of Anderson land cover/use (referred to henceforth as land cover) categories as a potential alternative preliminary screening tool to extensive soil sampling to estimate soil metal concentrations. These codes were developed by Anderson et al. (1976) to be applied to different land cover types based on remote sensing data. General categories include urban/built up, agricultural, and forested land (Anderson et al., 1976). The area corresponding to these codes may be indicative of different types of contamination (e.g., pesticide application in agricultural areas), and could potentially serve as a proxy for the numerous non-point or historical sources of metals that cannot be easily measured.

Our objectives were to measure surface soil concentrations of As, Pb, and barium (Ba) across 10 residential urban and rural areas in South Carolina (SC), investigate associations between these metal concentrations and the land cover category corresponding to the soil sample location, and examine associations between both metal concentrations and land cover categories with population demographics at the US Census 2000 block and block group levels. We were interested in these comparisons within individual sampling areas, as well as for combined urban, combined rural, and all ten sampling areas combined. We chose these metals for comparisons purposes, because previous research by our group indicated that Ba is generally naturally occurring, Pb is generally from anthropogenic sources, and As may originate from a combination of the two in our sampling areas (Aelion et al., 2012; Davis et al., 2009).

We hypothesize that urban sampling areas will have higher percentages of sample locations with residential, commercial, and industrial land cover, and rural sampling areas will have more sample locations categorized as crop and forested land cover. We hypothesize that both soil As and Pb concentrations will be significantly associated with urban and built up land cover categories (e.g., residential, commercial, and industrial), regardless of sampling area, as sources of these metals include industry and aspects of the residential environment (e.g., road cover). However, we acknowledge that associations may be stronger or more numerous in urban areas, as these generally have more industries, are more densely populated, and have been shown to have higher concentrations of these metals. Although we expect soil As and Pb concentrations to be highest at locations with more urban and built up

land cover, As concentrations may also be significantly higher at locations with more agricultural land cover if As containing pesticides were historically used. We hypothesize that soil Ba concentrations will not necessarily be associated with land cover and will instead be a function of the underlying geology of our sampling areas. We expect no differences in race/ethnicity by land cover, but do expect poverty to be associated with land cover in rural areas, where poverty will be concentrated.

Materials and Methods

As part of a larger study, ten sampling areas in SC were identified using Bayesian local likelihood cluster analysis based on the increased prevalence of intellectual disability (ID) and/or developmental delay (DD) in children born from 1996–2001 to mothers enrolled in Medicaid (Liu et al., 2010; McDermott et al., 2011; Zhen et al., 2008, 2009). Five areas were urban and five were rural, and ranged in size from 60 to 130 km².

In each of the ten areas a regular 120-node grid was overlaid, and surface soil grab samples were collected as close to grid nodes as possible. Duplicate samples were collected at 10% of the locations for quality assurance/quality control purposes. The latitude and longitude of soil sample locations were identified using a portable GPS device during sampling. Soils were acid digested and analyzed for total concentrations of nine metals including As, Ba, and Pb, by an independent analytical laboratory using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Aelion et al., 2008, 2009a, 2009b, 2012, 2013; Davis et al., 2009). Concentrations were reported in mg/kg dry weight, and minimum detection limits were approximately <0.5 mg/kg. Concentrations below the minimum detection limit were set to 0 for all subsequent statistical analyses.

Metal concentrations at each soil sample location from the GPS coordinates were imported into ArcMap Version 10 GIS software (ESRI, Redlands, CA, USA). An Anderson land cover shapefile (Anderson et al., 1976) and a US Census 2000 block group shapefile (US Census, 2013b), both for the state of SC, were also imported into ArcMap. Using the identify function in ArcMap, we identified the land cover category corresponding to each soil sample location within our 10 sampling areas. We used the following raw and composite land cover categories: residential, other urban (includes commercial, industrial, transportation, communication/utilities, and mixed urban), cropland (includes orchards), forests (includes evergreen, deciduous, and mixed forests), water (all types including wetlands), and barren land (all types). Some types of land cover (e.g., rangeland) were not present in our sampling areas and were therefore not included in any analyses.

We identified the US Census 2000 block group (Census-defined areas with population range of 600–3,000 individuals) and block (geographical subunit of a block group) corresponding to each soil sample location within our sampling areas, which we linked with US Census 2000-defined variables. Percentages of the block population that self-identified as either non-Hispanic black or non-Hispanic white were calculated based on the total block population. The US Census 2000 questionnaire had choices for the following races: white, black or African-American, American Indian, Asian, Native Hawaiian/Pacific Islander, other, and two or more races, and for the following two ethnicities: Hispanic/Latino or not

Hispanic/Latino (US Census, 2014b). These data were then sorted into subsets of individuals who self-identified as black or African-American and not of Hispanic or Latino origin, and white and not of Hispanic or Latino origin. We also identified the percentage of the black group population with a household income less than 50% of the poverty threshold (henceforth referred to as poverty). This categorization depends on household size and household income; for example, a family of four is at <50% of the poverty threshold if its household income is <\$12,000 (US Census, 2014a).

We first calculated the percentage of soil sample locations (total, by urban and rural sampling areas, and within each of the 10 sampling areas) corresponding to our identified land cover categories. We also calculated the medians of all main variables by sampling area and for combined rural and urban sampling areas. Given the skewness of data, we used the non-parametric Kruskal-Wallis test to determine if there were significant differences in variable medians by sampling area, as well as between combined urban and rural sampling areas, and between different land cover categories. Finally we examined associations between metal concentrations, race/ethnicity, and poverty with land use categories using mixed modeling; maximum likelihood estimation and Satterthwaite's method for computing denominator degrees of freedom (Satterthwaite, 1946) were implemented. Soil concentrations of As, Ba, and Pb and US Census population demographic measures were predicted in models adjusted for other metals and population demographics (if applicable), and soil sample location land use categories. These analyses were completed for individual sampling areas, for combined urban and rural sampling areas, and for all ten sampling areas modeled together. SAS Version 9.4 statistical software (SAS Institute, Cary, NC, USA) was used for all statistical analyses and a p-value of <0.05 was used to establish statistical significance.

Results

Soil sample locations in rural areas were dominated by forested land (Areas 2-R and 3-R) and cropland cover (Areas 6-R and 23-R); more than 70% of soil sample locations in these four sampling areas corresponded to one of these two land cover categories (Figure 1). Approximately 50% of soil sample locations in rural Area 27-R corresponded to either forested land or cropland cover. Residential land cover corresponded to the majority of sample locations in urban Areas 4-U, 5-U, and 31-U, while more than 40% of soil sample locations in Area 22-U corresponded to other urban land cover (Figure 1). In contrast to our additional urban sampling areas, both U-31 and U-99 had disproportionately high percentages of cropland + forest land compared to residential + other urban, despite their urban designation; almost half of the soil sample locations in Area 99-U corresponded to forested land cover. Barren land cover percentages are not shown in Figure 1 as they made up only 1% of all soil sampling locations in the ten sampling areas. Recent population growth ranged from -4.1 to 4.3% (Table 1). Four urban areas had the greatest population growth (Areas 4-U, 5-U, 22-U, and 99-U) and two rural areas had the greatest population decline (Areas 23-R and 27-R). Half of the sampling areas were in the Carolina Flatwood ecoregion of SC, and three were located in the Southern (S) Outer Piedmont (Table 1).

Median concentrations of As, Pb, and Ba were significantly greater (all $p < 0.0001$) in urban (approximately 2×; Table 2) as compared to rural sampling areas. No associations were observed for As concentrations less than 2.0 and Pb concentrations less than 20 mg/kg. Median metal concentrations were also significantly greater for urban and built up land cover categories, as compared to cropland and forested land (all $p < 0.004$; Table 2). Median As and Pb concentrations in Areas 4-U, 5-U, and 22-U were significantly greater than in all other sampling areas (all $p < 0.03$). Ba concentrations were significantly greater in both rural and urban areas (Areas 2-R, 4-U and 5-U), as compared to all other sampling areas (all $p < 0.0001$).

Median percentages of non-Hispanic whites and those in poverty were significantly greater (all $p < 0.0001$) in rural compared to urban sampling areas, while median percentages of non-Hispanic blacks were not significantly different for these combined areas (Table 2). Median percentages of non-Hispanic whites were significantly greater in forested land cover ($p < 0.001$), while median percentages of non-Hispanic blacks were significantly greater in both other urban and cropland (all $p < 0.03$; Table 2). Our poverty measure was significantly greater in cropland than other land cover categories (all $p < 0.03$; Table 2). Median percentages of non-Hispanic whites were significantly greater in Areas 2-R, 3-R, and 5-U (all $p < 0.01$), and median percentage of non-Hispanic blacks was significantly greater in Areas 23-R and 31-U ($p < 0.04$; Table 2). The median percentage of poverty was significantly greater in Areas 3-R, 6-R, and 23-R compared to all other sampling areas (all $p < 0.04$; Table 2).

Both positive and negative significant associations between metal concentrations and land cover categories in adjusted models were identified for individual sampling areas, combined urban or rural sampling areas, and for all sampling areas modeled together (Table 3). Most significant associations were with Pb and were in urban sampling locations; however, for combined urban and rural areas, only rural areas exhibited significant associations between Pb and land cover categories (Table 3). Lead concentrations and both residential and other urban land cover categories were also positively associated when all sampling areas were modeled together (Table 3).

Significant associations (10) were also observed between our population demographic measures and land cover categories, but only when sampling areas were modeled individually (data not shown). Additionally, most significant associations (7) were between non-Hispanic whites or blacks and land cover categories, and were in the opposite direction for these two racial/ethnic groups within the same sampling area. Metal concentrations were also significantly associated with all three of our population demographic measures, but the only consistent significant association was between Pb concentrations and poverty for combined urban areas ($p = 0.0002$), and all sampling areas modeled together ($p = 0.0001$).

Discussion

Arsenic concentrations were greatest in our urban sampling areas, and were generally higher at soil sampling locations corresponding to residential and other urban land cover categories. Other analyses by our group in these same areas suggest that there are few As-emitting

facilities reporting to the Environmental Protection Agency (EPA) Toxic Release Inventory (TRI; Aelion et al., 2012); however, this inventory does not include historical sources or small waste generators that may have been potential sources of As in these locations. We also did not note any associations between agricultural land cover and As concentrations, suggesting minimal input of As from pesticide application in our rural sampling areas. This is most likely due to the fact that historical agricultural practices in our areas did not include large fruit production, which were known to have utilized As-containing pesticides.

Similarly to As, Pb concentrations were also higher in urban sampling areas, and at sampling locations corresponding to urban land cover categories. This was what we hypothesized, and may be explained by the fact that Pb in soils is largely associated with traffic density and road coverage, regardless of location, due to historical leaded gasoline use. Since urban areas generally have both higher traffic density and more roads, there is the potential for more Pb in urban soils (Aelion et al., 2012; Rosenfellner et al., 2009).

However, associations for both As and Pb concentrations with urban land cover categories were not uniformly found within individual urban sampling areas. Both Areas 31-U and 99-U had no significant associations with As and Pb concentrations, which may be explained by the land cover category distributions in these sampling areas. Despite their urban designation, 31-U and 99-U both had larger forested + cropland cover percentages and smaller residential + other urban land cover percentages as compared to our other urban sampling areas. Thus land cover categories were a better predictor for As and Pb concentrations than urban or rural designation in these sampling areas.

An additional consideration is concentration threshold. No associations between metal concentrations and sampling areas were found below 2.0 mg/kg As and approximately 20 mg/kg Pb. Both Areas 31-U and 99-U As and Pb concentrations were below these thresholds. As areas undergo high population growth rates such as what has occurred in Area 99-U, both metal concentrations and percentages of residential land cover would be expected to increase, while percentages of cropland and forest land should decrease. This may then result in significant associations between anthropogenic metals and urban and built up land cover categories, as was observed in our older, more established urban areas.

Naturally-occurring Ba concentrations also were greater in urban areas combined, but in both one rural and two individual urban areas. In an examination of soil metal concentrations across the US, Shacklette and Boerngen (1984) found that in SC, Ba concentrations were higher in the vicinity of Areas 2-R, 4-U, and 5-U compared to other areas in the state that were sampled; we found similar results. Associations with Ba concentrations are potentially due to geological characteristics. Areas 2-R, 4-U, and 5-U are all located in the S Outer Piedmont ecoregion of SC (Davis et al., 2009; Griffith et al., 2002), which consists mainly of gneiss, schist, and granite. Barium has been observed in these rock types in other locations (Hetherington et al., 2003, 2008; Rossiter and Gray, 2008) and, therefore, surface soil Ba concentrations may be expected to be significantly higher in this SC ecoregion.

Overall, this study showed that land use cover categories were able to proxy some metal concentrations in our sampling areas. Most significant associations were for the anthropogenic metal Pb, were observed in urban sampling areas, and, more specifically, were with residential and other urban land cover categories. Associations with Pb were significant at all levels of analysis. Given Pb is primarily associated with anthropogenic activities, this proposed method of proxying metal concentrations with land cover categories may be most useful for those metals related to human activities. Fewer associations were found for As than for Pb within urban sampling areas, and for urban land cover categories. Since As is from both anthropogenic and natural sources, additional information on background concentrations, potential point sources, and land use practices (including historical agricultural practices) may be needed. For naturally occurring metals, geology, rather than urban/rural designation or land cover categories, may be most important.

Other studies have examined if land cover categories can predict metal concentrations in both the US and abroad. Pouyat et al. (2007) investigated whether land use and land cover explained differences in physical and chemical properties of surface soils in Baltimore, Maryland, USA, a smaller geographic area (comparable to one of our sampling areas) with more industrial/commercial areas and highways as compared to our areas. Mean Pb concentrations (~230 mg/kg) were greater in Baltimore than those found for this study. Pouyat et al. (2007) concluded that heavy metal concentrations including Cu, Cr, and Pb were not explained by land cover and attributed this lack of association to the inability to detect sources of metals at the scale of observation and sampling intensity used. They analyzed 122 samples compared to approximately 10 times that number used in our study. Lark and Scheib (2013) examined Pb concentrations and associations with land use in London, England and concluded that Pb concentrations were highest in industrial areas and that land cover accounted for some of the variation in Pb concentrations. This was similar to what we found, even though the median Pb concentration observed by Lark and Scheib (2013) was 184.14 mg/kg, or almost five times higher than what we observed in our residential, uncontaminated sampling areas. We found no reports in the literature of studies examining associations with land use and metal concentrations in generally uncontaminated areas.

In our study, we did identify significant associations between our population demographic measures and land cover categories, but these were limited to within individual sampling areas. Associations with metals were also observed, but only Pb and poverty were consistently associated at our different analysis levels. The limited uniformity in associations may be because our sampling areas were diverse ethnically and with respect to poverty. For example, Area 3-R was predominately non-Hispanic white with high poverty and Area 23-R was predominately non-Hispanic black with the same median poverty percentage. Both areas are in the same region of the state, which is known to have high concentrations of individuals in poverty and historically were populated by different racial/ethnic groups. This suggests that associations between population demographics and land cover are highly site-specific, and land cover categories may not be useful for proxying these measures.

We acknowledge that there were limitations to this study. Our Anderson land use/cover shapefile was dated 1980. A more current land cover data set may provide better estimates as it would be more representative of the current land cover of our sampling areas, particularly in high population growth areas. Population growth of these sampling areas may be important with respect to how well land cover categories can proxy metal concentrations. However, availability of a more recent data set at a similar spatial scale is a limiting factor. We also acknowledge that more local population demographic measures may be more representative of the local population on our relatively small spatial scale. While information is available on race/ethnicity at a more local level, income and poverty data are difficult to obtain at a spatial scale lower than the US Census block group, which was what we used in this study. Finally, the race/ethnicity and poverty distributions may be specific to our region, and not necessarily generalizable to other locations.

Conclusions

This study demonstrated that there is the potential for land cover categories to proxy metal concentrations, particularly for anthropogenic metals. For metals of combined anthropogenic and natural sources, both land cover categories and additional information may be useful including additional historical information. For naturally-occurring metals, geologic considerations are of greater importance than land cover categories. Racial/ethnic distributions were not a function of land cover categories, though poverty was consistently associated with Pb concentrations. We acknowledge that there are limitations associated with this method, and it is not intended to estimate exposure. However it may be useful as a preliminary screening tool and alternative to extensive soil sampling in large geographic areas.

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Highlights

- We examined if land cover categories could proxy As, Ba, and Pb in soils
- Urban land cover categories were associated with Pb, mainly in urban areas
- Land cover did not predict As well, and Ba in soils was geology dependent

Figure 1.
Percentages of soil sampling locations for rural (R) and urban (U) sampling area corresponding to land use categories.

Table 1

Sampling area characteristics.

Sampling Area	Month/Year Sampled	Approximate Area (km ²)	No. of soil sample locations	Population growth 2010–2012 (%) ^a	South Carolina Ecoregion ^b
Area 2-R ^c	12/2006	120	119	0.2	S ^e Outer Piedmont
Area 3-R	07/2007	100	114	0.6	Carolina Flatwoods
Area 4-U ^d	11/2007	130	119	1.1	S Outer Piedmont
Area 5-U	04/2008	60	120	2.7	S Outer Piedmont
Area 6-R	07/2008	90	114	1.0	Atlantic Loam
Area 22-U	01/2011	110	110	4.3	Sea Island
Area 23-R	12/2010	80	115	-4.1	Carolina Flatwoods
Area 27-R	07/2010	100	113	-1.6	Carolina Flatwoods
Area 31-U	06/2011	80	108	-0.7	Carolina Flatwoods
Area 99-U	10/2011	100	110	3.9	Carolina Flatwoods

^a Population growth of the major city/town located within each sampling area (US Census, 2013)

^b From Griffith et al. (2002)

^c R: Rural (based on US Census designation)

^d U: Urban (based on US Census designation)

^e S: Southern

Table 2

Median arsenic (As), lead (Pb), and barium (Ba) soil concentrations and population demographic percentages by urban and rural sampling areas combined, by land use category for all sampling areas combined, and within individual sampling areas.

Sampling Area	As (mg/kg)	Pb (mg/kg)	Ba (mg/kg)	Non-Hispanic white (%) ^a	Non-Hispanic black (%) ^a	Income <50% of poverty threshold (%) ^b
All Urban (U)	2.0*	23*	28*	58	24	6.1
All Rural (R)	0.98	13	16	69*	25	10*
Residential	2.0	30*	33*	63	22	6.7%
Other Urban ^c	2.4*	36*	31*	50	33*	9.7%
Cropland	1.0	12	16	57	33*	11%*
Forested	1.2	12	17	72*	19	6.0%
Area 2-R	1.5	19	52*	80*	13	3.7
Area 3-R	0.95	11	12	82*	10	13*
Area 4-U	2.9*	29*	57*	58	26	4.2
Area 5-U	3.3*	38*	67*	78*	6.6	6.1
Area 6-R	1.5	15	20	60	38	11.3*
Area 22-U	2.0*	29*	22	46	37	8.9
Area 23-R	0.58	8.6	13	25	70*	13*
Area 27-R	0.63	7.6	8.2	74	22	7.2
Area 31-U	1.1	13	15	12	86*	8.0
Area 99-U	1.1	8.2	13	72	20	3.2

^a Calculated from US Census 2000 block level data

^b Calculated from US Census 2000 block group level data

^c Includes commercial, industrial, transportation, communication/utilities, and mixed urban

* Denotes metal concentrations or population demographic percentages that were significantly higher ($p < 0.05$) for combined urban or rural sampling areas, for at least one other land use category, or for the majority (> 5) of individual sampling areas

Table 3

Parameter estimates (p-values) for significant association in adjusted models for metals with land cover categories by individual sampling area, combined urban (U) or rural (R) sampling areas, and for combined sampling areas.

Associations	Individual sampling areas	Combined urban or rural	All sampling areas
As-other urban	4-U: 7.99 (<0.0001)	Not applicable (NA)	NA
Pb-residential	27-R: 31.8 (0.01) 99-U: 41.9 (0.03)	R: 26.8 (0.0004)	20.8 (0.01)
Pb-other urban	4-U: -50.4 (0.001) 27-R: 55.7 (0.0001)	R: 32.9 (0.0008)	28.7 (0.002)
Pb-cropland	22-U: -208 (0.02)	NA	NA
Pb-forested	4-U: -21.3 (0.04)	NA	NA
Ba-cropland	4-U: -32.4 (0.046)	NA	NA
Ba-forested	4-U: 28.0 (0.03) 99-U: -8.86 (0.04)	NA	NA