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The relationship between historical development and potentially toxic element concentrations in urban soils☆

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ABSTRACT

Increasing urbanisation has a direct impact on soil quality, resulting in elevated concentrations of potentially toxic elements (PTEs) in soils. This research aims to assess if soil PTE concentrations can be used as an 'urbanisation tracer' by investigating geogenic and anthropogenic source contributions and controls, and considering PTE enrichment across historical urban development zones. The UK cities of Belfast and Sheffield are chosen as study areas, where available shallow and deep concentrations of PTEs in soil are compared to identify geogenic and anthropogenic contributions to PTEs. Cluster analysis and principal component analysis are used to elucidate the main controls over PTE concentrations. Pollution indices indicate that different periods of historical development are linked to enrichment of different PTEs. Urban subdomains are identified and background values calculated using various methodologies and compared to generic site assessment criteria. Exceedances for a number of the PTEs considered suggest a potential human health risk could be posed across subdomains of both Belfast and Sheffield. This research suggests that airborne diffuse contamination from often historical sources such as traffic, domestic combustion and industrial processes contribute greatly to soil contamination within urban environments. The relationship between historical development and differing PTEs is a novel finding, suggesting that PTEs have the potential for use as 'urbanisation tracers'. The investigative methodology employed has potential applications for decision makers, urban planners, regulators and developers of urban areas.

1. Introduction

Globally, more people now live in urban areas than in rural areas; in 2014 54% of the world's population lived in urban areas. This has rapidly increased from just 30% in 1950 and is projected to reach 66% by 2050 (UN, 2014). The demand put on these geographically limited urban environments will intensify as population density increases, with a direct impact on soil quality.

Sources of potentially toxic elements (PTEs) in urban areas are often both geogenic and anthropogenic (Argyraki and Kelepertzis, 2014; Rodrigues et al., 2009), with both point and diffuse anthropogenic sources common (Marchant et al., 2011). Typical anthropogenic sources such as industry, traffic (leaded fuel, brake pads and tire wear (Argyraki and Kelepertzis, 2014; Dao et al., 2014)) and waste disposal are known to contribute to PTE concentrations in soil (Ajmone-Marsan and Biasioli, 2010). Domestic outputs in urban environments, in the form of fuel burning and waste, can also be large contributors to soil PTE concentrations (Biasioli et al., 2006; Glennon et al., 2014).

As urban areas continue to grow, a factor that must be considered is how human health can be affected by PTEs in soil. Can development be appropriately and sustainably managed considering previous land uses and soil PTE concentrations? The economic importance of urban soils must be balanced with ensuring potentially contaminated urban sites are safe for redevelopment.

Numerous urban geochemical investigations have been completed across the world (Argyraki and Kelepertzis, 2014; Biasioli et al., 2006; Glennon et al., 2014; Golden et al., 2015; Johnson et al., 2011; Kelepertzis and Argyraki, 2015; Mielke, 1999; Thorton, 2009) and it is by building upon this library of research that we can fully understand how urban PTE sources vary geographically. The study areas used in this research have diverse bedrock and rich industrial histories, making them the ideal

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locations for investigating combined geogenic and anthropogenic contributions to soil PTE concentrations.

This research aims to understand if PTE concentrations in soil can be used as a tracer for urbanisation by; (1) investigating geogenic and anthropogenic contributions to PTE concentrations in soil, (2) identifying groups of PTEs controlled by similar sources, (3) understanding how historical city development may have influenced soil quality by considering PTE enrichment across city development zones and (4) calculating typical threshold values for the anthropogenic PTEs from similar sources. A novel investigative methodology will be employed utilising depth ratios, a range of multivariate statistical techniques and pollution indices. The objective is to generate a methodology for use in other urban areas, for a range of potential pollutants, to inform on city areas most likely to be contaminated.

Eleven PTEs are considered; arsenic (As), cobalt (Co), chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), tin (Sn), vanadium (V) and zinc (Zn). These elements are expected to be related to different geogenic and anthropogenic sources within the study areas; in particular they are likely to represent contamination from a variety of historical industrial processes. Elements such as As, Cr, Cu, Ni, Pb and Zn commonly feature in urban geochemical studies due to their anticipated anthropogenic sources (Johnson and Ander, 2008) while Carrero et al. (2013) demonstrate a relationship between a variety of the chosen PTEs, including Mo, Sb and Sn, and soils heavily impacted by traffic. Previous research in one of the study areas (Barsby et al., 2012; Cox et al., 2013; McIlwaine et al., 2015, 2014; Palmer et al., 2015) has demonstrated concentrations of various PTEs to be controlled by geogenic sources in the form of bedrock geology.

2. Methodology

2.1. Study areas

Two cities within the United Kingdom have been chosen as study areas for this research. Belfast, Northern Ireland's capital and largest city has been compared with Sheffield, a city in South Yorkshire, England. These cities were selected due to their similar industrial heritage in heavy engineering (although Sheffield's is slightly greater and more varied than Belfast) and their similar geology.

The Corine land cover data (European Environment Agency, 2012) was utilised to define both the Belfast and Sheffield study area boundaries (Fig. 1). This data is split into 44 different land uses based on the interpretation of satellite images. The majority of land uses were simplified into either urban or rural; areas of urban fabric and industrial units were obviously urban while areas of pasture and forest were clearly rural. Where any inconclusive land uses were identified, the surrounding land use was utilised as an indicator of land use type on a site by site basis. Within Sheffield, the Corine boundary was slightly reduced due to the spatial extent of the geochemical data available.

2.1.1. Belfast

A simplified representation of the highly diverse bedrock geology in Belfast, from GSNI's 1:250,000 map, is produced in Fig. 1. Silurian greywacke and Silurian shale are the two oldest rock formations, forming part of the Southern Uplands-Down-Longford Terrane, followed by the Permo-triassic sandstones and mudstones. This is covered in the west of the city by Cretaceous sandstone and chalk and finally by the most recent Tertiary basalts which run along the north west boundary of city (Mitchell, 2004). A number of Palaeogene intrusions occur within the study area. Geology has previously been identified as a control over element concentrations in Northern Irish soil (McIlwaine et al., 2014), with areas of basalt and sandstone identified as containing elevated concentrations of different PTEs. This study area is therefore of interest due to the expected geogenic controls within an urban environment.

Superficial geology within Belfast (Supplementary Information 5) has been reproduced from a GSNI map showing the geology of Belfast and District (Bazley et al., 1984). It is found in the form of till, glacial sands and gravels, and alluvium within the vicinity of the River Lagan.

Historical maps of Belfast (Land and Property Services, 1919, 1901, 1858) have been used to produce historical study area boundaries for 1858, 1901 and 1919–1939. Historical development of surrounding towns that are now incorporated in the greater Belfast area (Carrickfergus and Bangor on Fig. 1) has not been included.

Belfast is historically recognised for both linen production and ship-building; the early 18th century saw the introduction of the linen industry involving bleaching, weaving and spinning processes while ship-building was introduced later in the 18th century (Beckett and Glasscock, 1967; Crawford, 1986). The city was an important manufacturing centre during the industrial revolution with other common businesses including rope works, bleachers, glass manufacturers, tobacco factories and distilleries (Royle, 2007). Present-day Belfast is much more reliant on service provision related occupations (82% in Northern Ireland in the 2013 Census of Employment (NISRA, 2014)) than the historical industrial and manufacturing employment.

2.1.2. Sheffield

Sheffield is underlain by Carboniferous deposits of Westphalian and Namurian age (Freestone et al., 2004). The rocks are highly faulted and folded creating many discontinuous outcrops (Fig. 1). The Middle Coal Measures Formation outcrops to the east of the city centre; it is Westphalian in age and composed of sandstone. The Lower Coal Measures Formation, also composed of sandstone and Westphalian in age, underlies most of the city centre. The Rossendale and Marsden Formations are present to the west of the study area comprising of mudstone and siltstones.

Quaternary deposits cover approximately 10% of Sheffield (Supplementary Information 5); silt alluvium is located in the river valleys around and in the city of Sheffield while some river terrace deposits in the form of sand and gravel also infill these valleys (Freestone et al., 2004).

Historical maps (1: 25000 maps of Great Britain, 1953; Bartholomew's "Half Inch Maps" of England and Wales, 1904; Bartholomew's Revised "Half Inch Maps," 1920; OS Six Inch England and Wales, 1851) of Sheffield have also been used to produce historical study area boundaries for 1850–1851, 1904, 1920 and 1938–1951.

Sheffield is located in South Yorkshire in England and is believed to have been originally founded in the 8th century. Coal has played an important role in the city's history, being mined and burnt for "space heating and industrial purposes in Sheffield since Roman times" (Rawlins et al., 2005). By the 1750s, more than 150 firms were dedicated to steel manufacture within the city. High quality cutlery, an export for which Sheffield is recognised, has been produced in the city since that time (Gilbertson et al., 1997). Industrial expansion continued until the late 1960s, when British Steel opened their Tinsley Park Works in the north east of the city. The steel and cutlery industry in Sheffield began to decline in the late 1970s and 1980s when cheaper alternatives were being produced in other areas of the world. This also affected the coal used to fuel industry in Sheffield, with coal use declining dramatically from the mid-1980s (Gilbertson et al., 1997).