Atmospheric Environment 127 (2016) 139–154

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

A 120-year record of the spatial and temporal distribution of gravestone decay and acid deposition

Howard D. Mooers [a, *], Avery R. Cota-Guertin [a, b], Ronald R. Regal [c], Anthony R. Sames [d], Amanda J. Dekan [a, e], Linnea M. Henkels [a, f]

[a] Department of Earth and Environmental Sciences, University of Minnesota Duluth, Duluth, MN, 55812, USA
[b] 14093 201st Ave NW, Elk River, MN, 55330, USA
[c] Department of Mathematics and Statistics, University of Minnesota Duluth, Duluth, MN, 55812, USA
[d] 3 Tamarisk Close, Birmingham, B29 4DB, United Kingdom
[e] 2834 Arthur St. NE, Minneapolis, MN, 55418, USA
[f] 131 17th St Heron Lake, MN, 56137, USA

HIGHLIGHTS

- Gravestone decay is used to quantitatively reconstruct historical acid deposition.
- Spatial variability in gravestone decay reflects changing land use patterns.
- Up to 98% decrease in acid deposition after 1975 because of air quality regulation.

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form
2 December 2015
Accepted 8 December 2015
Available online 12 December 2015

Keywords:
Gravestone decay
Acid deposition
Air quality
West Midlands
United Kingdom

ABSTRACT

This investigation examines the spatial and temporal variability of marble gravestone decay throughout West Midlands County and adjacent portions of Warwickshire, Staffordshire, and Worcestershire. Gravestone decay has been used effectively as a quantitative measure of acid deposition. Numerous techniques have been used to assess gravestone decay and each is subject to different sources of error. To minimize error we focus only on marble gravestones that use the flush lead lettering technique. Decay of the marble leaves the lead lettering raised above the surface, and the distance can be measured with the use of a digital micrometer. Gravestone decay can be used to quantify the spatial and temporal distribution of acid deposition. Our gravestone decay database consists of 1417 individual measurements on 591 tombstones in 33 cemeteries and covers the period from 1860 to 2010. Sites range from industrial and residential areas to rural settings. These data allow us to establish the natural background rates of decay, the effects of urban/residential expansion, and the efficacy of environmental regulations. Decay rates vary from a minimum of 0.2 mm/century in remote rural areas to nearly 3.0 mm/century in the Birmingham City Center. The data are corrected for environmental variables, converted to acid deposition rates, and plotted at 10-year intervals from 1890 to 2010.

> *"On every side, and far as the eye could see into the heavy distance, tall chimneys, crowding on each other, and presenting that endless repetition of the same dull, ugly form, which is the horror of oppressive dreams, poured out their plague of smoke, obscured the light, and made foul the melancholy air." (Charles Dickens, The Old Curiosity Shop, 1841).*

1. Introduction

This investigation quantifies acid deposition over the last 120+ years in the West Midlands, UK, using lead-lettered marble gravestone decay as a proxy. Gravestone decay has been shown to be a sensitive indicator of air quality (Inkpen, 2013; Gauri and Holdren, 1981) and can be used to determine quantitatively minimum acid deposition rates (Dragovich, 1991; Inkpen, 2013; Inkpen and Jackson, 2000; Cooke et al., 1995; Inkpen et al., 2008). In the

* Corresponding author.
E-mail address: hmooers@d.umn.edu (H.D. Mooers).

http://dx.doi.org/10.1016/j.atmosenv.2015.12.023
1352-2310/

modern atmospheric environment of urban centers, both sulfur and nitrogen oxides are important contributors to acid precipitation (Marsh, 1978; Bricker and Rice, 1993; Menz and Seip, 2004). However, sulfur associated with coal burning was the primary source of acid deposition in industrial England prior to abundant automobile traffic (Viles, 1996).

Our record of gravestone decay is compiled from 1417 individual decay measurement on 591 lead-lettered marble tombstones in 33 cemeteries recorded between 2005 and 2010 (Putz et al., 2005; Mooers et al., 2006; Cota-Guertin, 2012). Gravestone decay data provides a time series of the damage rate (Livingston and Baer, 1990; Inkpen, 2013) at each location, which can then be integrated spatially. Considerable variability in gravestone decay exists within individual cemeteries. This variability is a function of the intrinsic properties and environmental setting of each gravestone. In addition, it has been suggested that there are many sources of nonlinearity in stone decay that affect weathering rates (Phillips, 2003; Viles, 2005). We assess the impact of physical and environmental factors on gravestone decay using analysis of variance (ANOVA) to correct tree canopy effects, algae/lichen cover, gravestone aspect and exposure, and local elevation differences. The corrected gravestone decay measurements are then analyzed using a non-linear regression and decay rates as a function of time determined.

Results indicate that gravestone decay is a robust measure of acid deposition and may provide insights into the sources of acid (Cooke, 1989; Cooke et al., 1995; Inkpen, 1998). The history of acid deposition is reconstructed with decadal temporal sensitivity and spatial variability over relatively short distances on the order of 2–4 km. Temporal and spatial variability in gravestone decay reflects changing industrial and residential land use patterns with the highest decay rates corresponding to major industrial and/or residential centers. A decrease in gravestone decay rates of as much as 98 percent between about 1975 and 1985 reflects the efficacy of air quality regulation.

2. Study area

The study lies within the West Midlands (Region) and includes West Midlands County and adjacent areas of Warwickshire, Staffordshire, and Worcestershire and includes the Black Country (Allen, 1929; Cherry, 1994) (Fig. 1). The late 19th and early 20th century industrial and residential expansion within West Midlands County makes this region particularly well suited for evaluating the effects of urbanization on air quality during industrial expansion.

During the latter half of the 18th century, localized manufacture and small industrial centers sprang up throughout the region (Allen, 1929; Cherry, 1994). The location of these centers was dependent upon resource and labor availability and influenced by rapidly evolving needs and historical events such as the wars of the that period (Allen, 1929). Although numerous written accounts describe the deteriorating air and environmental quality in the English Midlands (*e.g.* Burritt, 1868), there are few quantitative assessments of the ambient conditions (Harrison, 2006; Harrison and Aplin, 2002; Mosley, 2009). It was recognized early on, however, that coal combustion was the principle cause of acid rain that was plaguing cities (Smith, 1876). Although sulfur dioxide (SO_2) and nitrogen oxides (NO_x) also occur naturally and contribute to background acidity, industrial and residential burning of fossil fuels are the major contributors to anthropogenic emissions (Gauri and Holdren, 1981; Metcalfe and Whyatt, 1995).

By 1860, the early part of our record of gravestone decay, Birmingham and surrounding communities had become a center for highly finished products such as brass goods, guns, buttons, toys, and jewelry, which included not only precious metals but tableware and other electroplated goods (Allen, 1929). However, by about 1910 industry was changing over to bicycles, motorcycles, tires, electrical equipment and chocolate (Allen, 1929); and the industrialization of agriculture led to net movement of population toward the cities in search of greater opportunity and higher wages (Allen, 1994; Clark, 2001). With the onset of WWI in 1914, the emphasis quickly changed to the manufacture of cars, tanks, shells, bombs, airplanes, and rifles.

Following WWI there was a rapid expansion of the manufacture of electrical appliances, wire, and telephone equipment and also in the production of cars, motorcycles, and commercial vehicles. Between 1923 and 1927 employment increased by roughly 30% (Allen, 1929). Accompanying this boom in industrial output was the rapid residential expansion within Birmingham and surrounding parts of the West Midlands. The jewelry industry, which peaked about 1920, was by this time in decline (Allen, 1929) and was later hit hard by the Great Depression. However, the West Midlands in general fared well during the Great Depression of the 1930s as the demand for vehicles remained high (Constantine, 1980, 2006).

During World War II industrial activity switched again to the manufacture materiel in support of the war. The post war reconstruction saw little change in the Birmingham economy (Cherry, 1994) as the city remained an engineering and metal-working center during the rebuilding of Britain (Cherry, 1994; Hogan, 1989).

Following the London Smog of 1952 the need for air quality regulation became a priority. The Clean Air Act of 1956 (Auliciems and Burton, 1973) set criteria for the emission of dark smoke, grit, dust, and fumes; established regulations for the height of chimneys; and set the stage for conversion from coal to coke and then to natural gas for domestic heating. This act and subsequent legislation led to a dramatic reduction in air pollution during the 1970s (Cole et al., 2005; Inkpen et al., 2012), a trend that continued with the United Kingdom decreasing SO_2 emissions by 79 percent and NO_x emissions by 39 percent during the period 1980 to 2002 (Klein et al., 2004).

3. Gravestone decay as an indicator of acid deposition

The use of stone decay as an indicator of environmental conditions goes back at least to 1870s (Goodchild, 1890; Geikie, 1880), and there is a significant body of research on the impact of acid deposition on gravestones in general (*e.g.* Livingston and Baer, 1990; Meierding, 1981, 1993a, 1993b) and particularly in the UK (Cooke et al., 1995; Inkpen, 1998, 2013; Inkpen and Jackson, 2000; Inkpen et al., 2000, 2001; Thornbush and Thornbush, 2013). These studies use a variety of techniques for analyzing the decay of gravestone lettering and surfaces. Qualitative assessment or quantitative measure of lettering depth, width, and sharpness are widely used (Roberts, 2005). Rahn (1971) and Meierding (1993a) describe a lettering alteration index, which qualitatively categorizes inscription lettering legibility as a result of acid deposition. Others studies have used close-range photogrammetric analysis for quantitative measurement of decay on stone surfaces (Inkpen et al., 2000; Thornbush, 2012) or measurement of stone slab thickness (Meierding, 1993b).

The use of lead-lettered Carrera marble stones has been described in detail by Cooke et al. (1995). This method provides a robust and repeatable method for determining gravestone decay (Cooke et al., 1995; Dragovich, 1986, 1991; Inkpen and Jackson, 2000). Flush lead-lettering is accomplished by first carving recessed lettering into the gravestone. Several holes are then drilled into the base of each carved letter, and preformed lead letters are set. The stone is polished with the lead letters in place making them flush with the stone surface (Cooke et al., 1995) and setting the decay clock to zero. Marble is particularly susceptible to dissolution