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Gravestone decay and the determination of deciduous bulk canopy resistance to acid deposition

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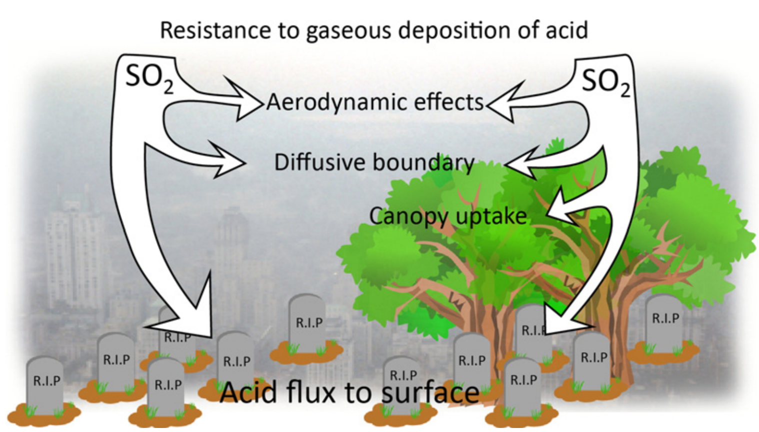
HIGHLIGHTS

- Gravestone decay provides a measure of the flux density (F) of acid.
- Bulk canopy resistance is derived as the difference between deposition velocities.
- Quantitative estimate of tree canopy resistance to gaseous deposition of acid.
- Up to 55% annual reduction in acid deposition under seasonal tree canopy.

GRAPHICAL ABSTRACT



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ABSTRACT

Gravestone decay and atmospheric concentrations of SO_2 are used to determine deposition velocities in two adjacent cemeteries in the Birmingham, UK, Jewellery Quarter. Warstone Lane cemetery is essentially open to the environment with only a limited number of trees. Key Hill Cemetery, located within 100 m, has a continuous canopy of 100+ year-old London plane; gravestone decay at Key Hill is 50% less than at Lane for the period after 1960. This difference is used to calculate canopy resistance as a residual term assuming that aerodynamic and quasilaminar resistances are generally similar at both sites. Calculated resistances range from approximately 300 to 900 $\mathrm{s\,m^{-1}}$ and are consistent with estimated and calculated values from a wide variety of studies.
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1. Introduction

Dramatic contrast in decay of lead-lettered marble gravestones between two adjacent cemeteries in Birmingham, UK, allows estimation of the canopy resistance to gaseous deposition of SO_2. Warstone Lane

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and Key Hill cemeteries are located in Birmingham's Jewellery Quarter and lie 100 m apart (Fig. 1). The cemeteries lie at the same elevation, are nearly identical in topographic relief, and both are surrounded by commercial properties of the Jewellery Quarter. However, Key Hill lays under a continuous canopy of 100+ year-old London plane, a hybrid of *Platanus orientalis* (oriental plane) and *Platanus occidentalis* (American sycamore). Warstone Lane is largely open with approximately 25% tree cover and most of the trees are located adjacent to Pitsford St. (Fig. 1). Tree coverage has remained unchanged since the 1945 post-war aerial photography. The effect of tree canopy on gravestone decay is remarkable with Key Hill recording 50% less gravestone decay for the period prior to 1980 (Fig. 2) (Mooers et al., 2016b). After 1980 the reduction in decay at Key Hill is up to 70% greater than at Warstone Lane.

Vegetation is well known to be an effective trap for both wet and dry deposition of acidifying gases (e.g. Baldocchi, 1988; Schaefer et al., 1992a, 1992b, Draaijers et al., 1997; Neal, 2002; Wesely, 1989; Yang et al., 2005; Nowak et al., 1998, 2006). Schaefer et al. (1992b) report that deciduous canopies in their study at any level of acid deposition result in nearly complete neutralization. Furthermore, they suggest that neutralization of dry acid deposition is far more efficient than neutralization of wet acidity because of the prolonged contact with the canopy surfaces. Plants remove gaseous pollutants by uptake through leafs via stomatal and non-stomatal pathways and by interception of airborne particles (Nowak et al., 2006; Baldocchi, 1988; Baldocchi et al., 1987), and numerical simulation of air pollution has become an important part of urban and regional planning and assessment of air quality (Massman, 1999, 2004; Massman et al., 1994; Chang et al., 1993; Ranzieri and Thuillier, 1993; Nowak et al., 2006). Air pollution models, however, require a number of parameters that are difficult to measure and are therefore determined typically by inferential techniques (Hicks et al., 1987). In general, air pollution removal, or the downward flux (F), is the product of the deposition velocity (v_d) and the atmospheric concentration (C). The deposition velocity is related to a number of factors that can be modeled as resistances to gaseous deposition and include canopy resistance (Nowak et al., 2006; Baldocchi, 1988; Baldocchi et al., 1987).

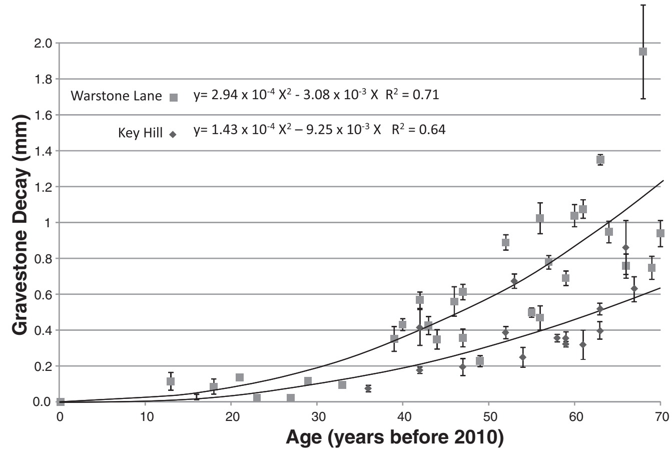

Fig. 2. Gravestone decay as a function of age for Key Hill and Warstone Lane Cemeteries. 2nd order least squares regressions and correlation coefficients are shown. Error bars are the standard deviation of the trimmed mean decay for each inscription.

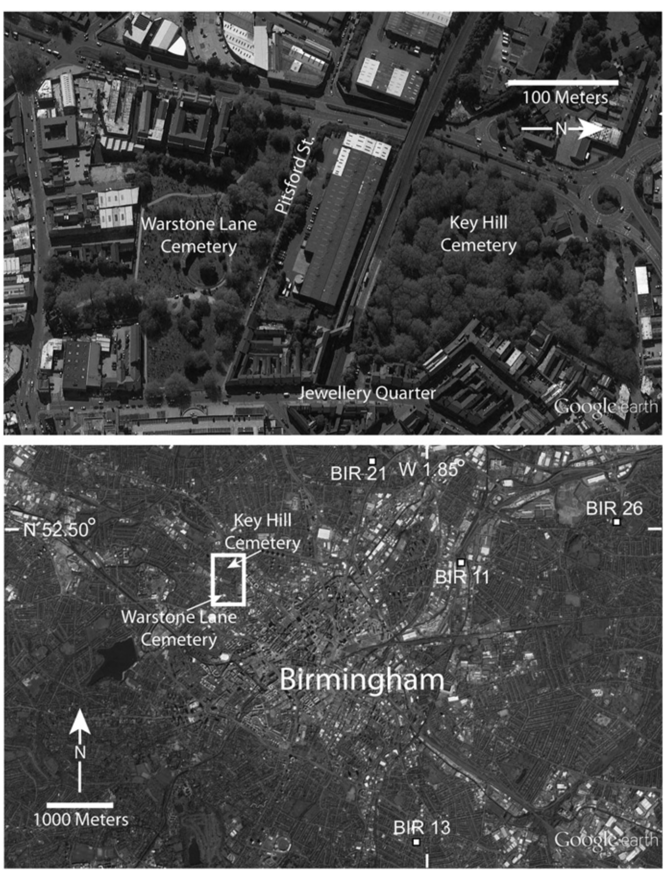

Fig. 1. Warstone Lane (52° 29.31′N; 1° 54.88′W) and Key Hill (52° 29.45′N; 1° 54.87′W) Cemeteries in the Birmingham, UK, Jewellery Quarter. Location of the four nearest air-quality monitoring stations are indicated by their BIR numbers. Period of record and concentrations of SO_2 are tabulated in Tables 1 and 2 respectively. Images modified from Google Earth.

This investigation seeks to determine the magnitude of the uptake of acidifying gases by vegetation by calculating the difference in canopy resistance between Key Hill and Warstone Lane cemeteries. The downward flux (F) of acid is determined by the decay of Carrera marble gravestones. Atmospheric concentrations (C) of SO_2 are available from the National Survey (Mosley, 2009), and the deposition velocity is then calculated (Wesely and Hicks, 2000; Nowak et al., 2006). These two cemeteries are in close proximity and nearly identical in physical setting; therefore the difference in canopy resistance can be calculated as a residual term. Calculated values agree closely with previous studies (Sheih et al., 1979; Baldocchi, 1988; Wesely, 1989; Massman et al., 1994). The overall goal of this investigation is therefore to demonstrate the utility of gravestone decay as a measure of acid deposition and its utility in calculating resistances to the deposition of acidifying gases and in particular the canopy resistance.

2. Background

2.1. Gravestone decay

Mooers et al. (2016b) evaluate the spatial and temporal deposition of acid in West Midlands, UK, over the period 1890 to 2010 using lead-lettered marble gravestones. The lead-lettering provides a stable reference for measurement of surface recession of the marble, which has been used extensively as a proxy for air quality and measurement of acid deposition (Cooke, 1989; Cooke et al., 1995; Dragovich, 1991; Inkpen, 1998, 2013; Inkpen and Jackson, 2000; Inkpen et al., 2000, 2001, 2008; Meierding, 1981; Mooers et al., 2016b; Inkpen et al., in press; Thornbush and Thornbush, 2013; Viles, 1996).

Gravestone decay from Key Hill and Warstone Lane (Mooers et al., 2016b) are plotted for period 1940 to 2010 (Fig. 2). Stones were selected for measurement according to the general requirements of Cooke et al. (1995). Measured stones were standing vertically, had planar surfaces, used lead lettering, and contained two or more inscriptions per stone. All stones meeting these requirements were measured in both cemeteries. Ten measurements were made along the date line of each

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