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# Citizen science identifies the effects of nitrogen deposition, climate and tree species on epiphytic lichens across the UK☆

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## ABSTRACT

A national citizen survey quantified the abundance of epiphytic lichens that are known to be either sensitive or tolerant to nitrogen (N) deposition. Records were collected across the UK from over 10,000 individual trees of 22 deciduous species. Mean abundance of tolerant and sensitive lichens was related to mean N deposition rates and climatic variables at a 5 km scale, and the response of lichens was compared on the three most common trees (*Quercus*, *Fraxinus* and *Acer*) and by assigning all 22 tree species to three bark pH groups. The abundance of N-sensitive lichens on trunks decreased with increasing total N deposition, while that of N-tolerant lichens increased. The abundance of N-sensitive lichens on trunks was reduced close to a busy road, while the abundance of N-tolerant lichens increased. The abundance of N-tolerant lichen species on trunks was lower on *Quercus* and other low bark pH species, but the abundance of N-sensitive lichens was similar on different tree species. Lichen abundance relationships with total N deposition did not differ between tree species or bark pH groups. The response of N-sensitive lichens to reduced nitrogen was greater than to oxidised N, and the response of N-tolerant lichens was greater to oxidised N than to reduced N. There were differences in the response of N-sensitive and N-tolerant lichens to rainfall, humidity and temperature. Relationships with N deposition and climatic variables were similar for lichen presence on twigs as for lichen abundance on trunks, but N-sensitive lichens increased, rather than decreased, on twigs of *Quercus*/low bark pH species. The results demonstrate the unique power of citizen science to detect and quantify the air pollution impacts over a wide geographical range, and specifically to contribute to understanding of lichen responses to different chemical forms of N deposition, local pollution sources and bark chemistry.

## 1. Introduction

Lichens are poikilohydric organisms, and their sensitivity to atmospheric moisture and air pollution, in particular $SO_2$, is well established. In the UK, recognition of the value of lichens as bioindicators led to the publication in the 1970s of a scale of lichen sensitivity to $SO_2$ concentrations (Gilbert, 1970, 1974; Hawksworth and Rose, 1970). In the period 1970–2010, emissions of sulphur dioxide ($SO_2$) in the UK fell by 94%, and $SO_2$ concentrations throughout almost all of the UK are now below the critical level set to protect lichen species (RoTAP, 2012). Over this period, there is evidence of re-invasion of areas of the UK with historically high $SO_2$ concentrations by lichen species (Bates et al., 2001; Pescott et al., 2015).

Nitrogen deposition (Ndep) from the atmosphere has increased globally over the last 150 years (Fowler et al., 2015), and is now a worldwide threat to sensitive plant species and communities (Bobbink et al., 2010). The major components of nitrogen emissions to the atmosphere are ammonia ($NH_3$), primarily from agricultural sources, and oxides of nitrogen ($NO_x$), a product of high temperature combustion in vehicles, power stations and industry. In contrast to $SO_2$, critical loads of nitrogen deposition to sensitive ecosystems are still exceeded over the majority of the UK land area (RoTAP, 2012), although $NO_x$ emissions in the UK fell by 58% over the period 1970–2010, and $NH_3$ emissions fell by 23% between 1990 and 2010.

Unlike $SO_2$, Ndep occurs in different chemical forms, and there is

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conflicting evidence concerning whether lichen species respond to total nitrogen (N) input or to a specific form of N. For vascular plants, the differential effects of reduced and oxidised N in soils are critical (Stevens et al., 2011), but for lichen species it is the direct toxic effects that are important. There is evidence that gaseous ammonia is more toxic than wet-deposited N to terricolous lichen species (Sheppard et al., 2011), and that there are toxic effects of atmospheric $NH_3$, but not nitrogen dioxide ($NO_2$), on oligotrophic epiphytic lichens (Munzi et al., 2014). In contrast, nitrogen tolerant species may respond positively to moderate inputs of both forms of N (Munzi et al., 2014).

Most of the evidence linking Ndep to the presence and abundance of lichen species is based on spatial associations found in field surveys, although there is some experimental evidence of cause-effect relationships (e.g. Johansson et al., 2012). Surveys of epiphytic lichens in the UK and the Netherlands in sites adjacent to ammonia monitoring sites have shown a loss of N-sensitive species at relatively low levels of gaseous ammonia ($NH_3$), and an increase in N-tolerant species correlated with increasing concentrations of $NH_3$ (Van Herk, 1999; Wolseley et al., 2006, 2009; Sutton et al., 2009). Investigations of oak and birch across the UK have shown a relationship between N-sensitive and N-tolerant species and $NH_3$ concentrations (Sutton et al., 2009), while a survey of lichens on trunks of ash trees in urban areas of London found that concentrations of $NO_x$, rather than $NH_3$, were correlated with the abundance of N-tolerant species and with a loss of lichen diversity at the highest concentrations (Davies et al., 2007).

The effects of $NH_3$ may be partly mediated through an increase in substrate pH on acid-barked trees such as oak and birch (Van Herk, 2001; Larsen et al., 2007). Bark pH varies between tree species and with atmospheric and environmental conditions (Barkmann, 1958) and has been shown to have an effect on lichen communities; increasing bark pH is associated with an increase in N-tolerant species of lichen (Wolseley et al., 2010). However, in an urban area of the Netherlands where all sampled tree species had a pH > 5, Spier et al. (2010) found a significant correlation of N-tolerant lichen species with tree species rather than with bark pH. The age of the substrate may also influence lichen responses; lichens on long-established trees in both rural and urban conditions may respond slowly to changing atmospheric conditions so that lichens on trunks may represent atmospheric conditions of earlier decades while lichens on the younger substrata of twigs and branches may better represent current atmospheric conditions (Wolseley et al., 2009). There is conflicting evidence in the literature about lichen responses to different chemical forms of N deposition. While ammonia has been shown to be a driver of changes on twigs in the canopy (Wolseley et al., 2006; Vilsholm et al., 2009), lichens on the branches of oak trees in a peri-urban area of the UK showed that the strongest correlation was between $NO_2$ concentration and N-tolerant species cover and not with $NH_3$, bark pH or N-sensitive species cover (Gadsdon et al., 2010). In contrast, in a study of epiphytic lichens on acid-barked *Pinus* and *Quercus* across a range of climatic and environmental conditions in California, where bark pH was >4, Jovan et al. (2012) found that N-tolerant species abundance was negatively correlated with bark pH and that it was best correlated with total N in throughfall and not with $NH_3$ or $NO_2$ concentrations.

Citizen science involves the general public, or trained volunteers, in collection and/or analysis of environmental data (Roy et al., 2012). It enables the collection of data over temporal and geographical scales which are often precluded by the limitations of funding, materials or personnel (Silvertown, 2009; Dickinson et al., 2012), with projects such as the British Trust for Ornithology's wildfowl counts running since the 1940's and attracting generations of volunteers from across the UK. It is recognised that sensitively designed and analysed citizen science projects have the potential both to collect robust data and raise awareness of environmental issues (Bone et al., 2012). Since 2007, the major UK citizen science programme, Open Air Laboratories (OPAL), has been producing and delivering citizen science surveys covering a range of environmental issues, including water quality, tree health and biodiversity, as well as N deposition through the OPAL Air Survey. This survey comprised two activities related to bio-indicators of air pollution, and specifically nitrogen oxides and ammonia. Analysis of results for one of these bio-indicators – tar spot on sycamore leaves – showed that the national data generated by the survey could be used to demonstrate that both the degree of urban street cleaning and the concentrations of $NO_2$ significantly affected the severity of tar spot symptoms (Gosling et al., 2016).

The OPAL Air Survey asked participants to record the abundance or presence of lichens on trunks and twigs of deciduous trees. The OPAL method was based on a lichen index developed by Wolseley et al. (2009), and involved recording the abundance of nine lichen generi, classed into three groups - N-tolerant, N-sensitive, and intermediate. Evaluation of the OPAL lichen methods has indicated that, whilst the methodology may not be as in-depth as a traditional study, the spatial scale and number of responses enables the detection of environmental variation (Seed et al., 2013; Tregidgo et al., 2013). Seed et al. (2013) reported an analysis of effects of air pollution and climate from the OPAL lichen survey, using data collected only in England between 2007 and 2011, focussing on the response of individual lichen species. However, they only considered data for lichens recorded on *Quercus* species, they did not directly compare the response of lichens on trunks and twigs, or the response of N-sensitive and N-tolerant lichens, and they did not use the information recorded by participants on local environmental factors.

Here we focus on three indices of lichen response which Seed et al. (2013) found were affected by pollutant deposition – the abundance (for trunks) and presence (for twigs) of N-sensitive lichens, the abundance (for trunks) and presence (for twigs) of N-tolerant lichens, and (for trunks only) a weighted pollution index. We made use of an expanded database, resulting from the spatial extension of the OPAL survey from England to all of the UK, inclusion of all tree species rather than oak only, and additional records between 2011 and 2015. We aimed to test:

(1) If the effects of N deposition on lichens growing on *Quercus* species differs significantly from those on other major tree species, and if this relates to their bark pH
(2) if there are effects of local sources, specifically busy roads, on OPAL indicator lichens
(3) if responses of the lichen groups are more strongly related to total N deposition or different chemical forms of N input;
(4) If the response to N deposition differs between lichens growing on trunks and twigs; and
(5) If N-sensitive and N-tolerant lichens differ in their relationship to climatic factors.

## 2. Methods

### 2.1. Lichen data collection

Lichen data were collected using the OPAL Air Survey methodology, carried out by volunteers between 2009 and 2015. Participants are directed to examine the abundance (on trunks) or presence (on twigs) of nine lichens on up to four individual trees. The six lichens selected for the purposes of this analysis were classified as either nitrogen tolerant (leafy *Xanthoria*, cushion

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