A Scientific Model for Estimating Edinburgh's Urban Air Pollution using Lichen Epiphytes

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> Background

Lichen epiphytes are a well-established bioindicator of air pollution (Nash 2010) and the consequent effects on human health (Cislaghi & Nimis 1997). Several major initiatives have been designed to map lichens as proxies for air pollution at the UK-wide scale, including the Open Air Laboratories project (OPAL) (Seed *et al.* 2013).

At a city-scale, the Edinburgh Living Landscape project (ELL) was launched in 2014, and aims to create a cityscape in which improvements for urban biodiversity yield positive effects on human well-being. In contribution to the ELL, the Royal Botanic Garden Edinburgh partnered with the Conservation Volunteers to deliver a new set of lichen bioindicators, which would form the basis for an air pollution toolkit specifically designed for Edinburgh. Through his project, individuals and communities would be invited to assess the air quality of their neighbourhoods, critique their results within the context of the Edinburgh cityscape, share this information on-line, and explore options for behaviour change to reduce air pollution. It was important that the survey was statistically robust, and the sampling and analyses are presented below.

> Field Sampling

The study sampled thirty sites that were adjacent to the Automatic Urban and Rural Network stations (AURNs) used for direct monitoring of air quality (Fig. 1). In each of these sites epiphytes were sampled from four trees that were closest to the monitoring stations (distance from station measured), and if a choice of trees was available, those with the greatest epiphyte cover were sampled. Tree species was noted and girth measured; all sampled trees were deciduous, and a majority were > 20 cm dbh at 1.3 metres. Epiphytes were sampled from a height zone on each tree from 50 cm to 175 cm above ground-level. The sample categories were as follows:

- Estimated percent cover of algae, bryophytes, lichens (sub-divided into fruticose, foliose and crustose), for each of the four cardinal aspects of the tree trunk;
- A full species list for bryophytes and lichens on the trunk and for accessible branches/twigs;
- Presence-absence for fruticose, foliose and crustose lichen species on branches/twigs.

Figure 1. Example of an Automatic Urban and Rural Network station used to monitor Scotland's air quality. Thirty sampling sites sites were based around AURNs in Edinburgh.

> Statistical Analysis

The recording data for several pollution variables proved too incomplete across the AURNs to consider in the analysis, including for sulphur dioxide, carbon monoxide, ozone and PM 2.5. However, data for the most complete available time-series, mean daily maximum values of NO_2 (µg.m^3) for the period 2010-2014, correlated with other available AURN measurements for NO_x ($r = 0.78$, 24 df), NO_x as NO_2 ($r = 0.83$, 24 df), and PM10 ($r = 0.52$, 23 df).

The analysis of field-sampled data proceeded in four stages, implemented in the R statistical language:

1. Ordinal cover classes for the contrasting epiphyte groups on each of the different tree aspects (none, 1-25%, 26-50%, 51-75%, 76-100% cover, for values averaged per site), compared with values of NO_2 and tested for significance using a Kruskal-Wallis test;

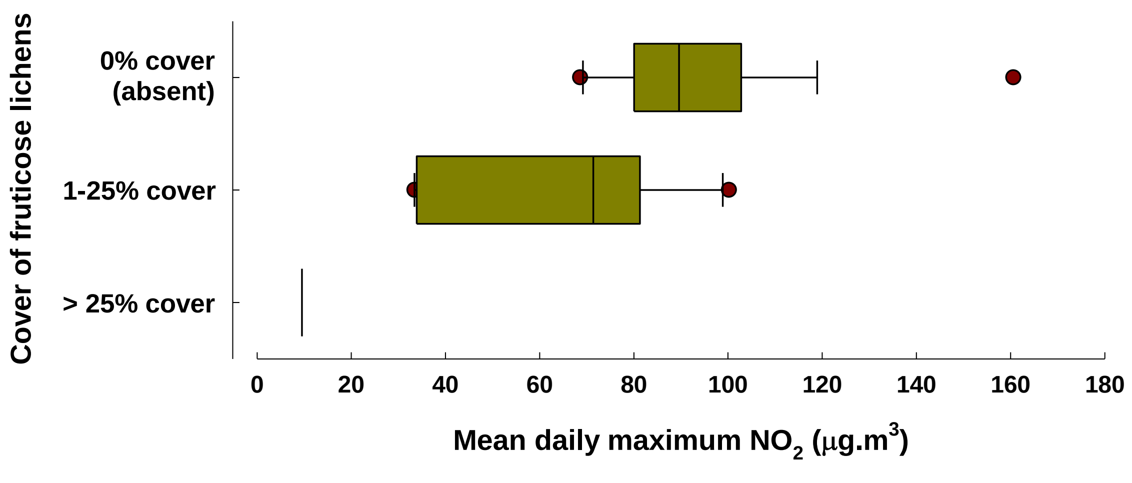
2. Presence-absence of epiphyte groups on branches/twigs (occurrences grouped per site) compared to NO_2 using a generalised linear model with a binomial error structure;
3. Species richness values on the trunk for all species, and lichens and bryophytes separately, and on branches/twigs (values averaged per site), compared to NO_2 using a generalised linear model with a Poisson error structure;
4. The presence-absence of all individual species, and species grouped into recognisable morphological types (e.g. 'grey foliose lichens', 'crustose lichens with apothecia' etc.), compared to NO_2 using a generalised linear mixed model (implemented using the R library '*lme4*') with a binomial error structure and with site-identity as a random effect.

All the results were examined for statistical significance and were framed around five questions that had the additional aim of introducing survey participants to lichen biodiversity. The questions were for simplicity stated in a three-part response, from A (poorer quality air) through B (intermediate) to C (higher quality air). These five questions and their associated analyses are presented below:

Q1. Find the tree in your study area that has the most fruticose lichens on its south side; how many futicose lichens are there?

A. None
B. One to a several
C. Covering more than a quarter of the south side of the tree

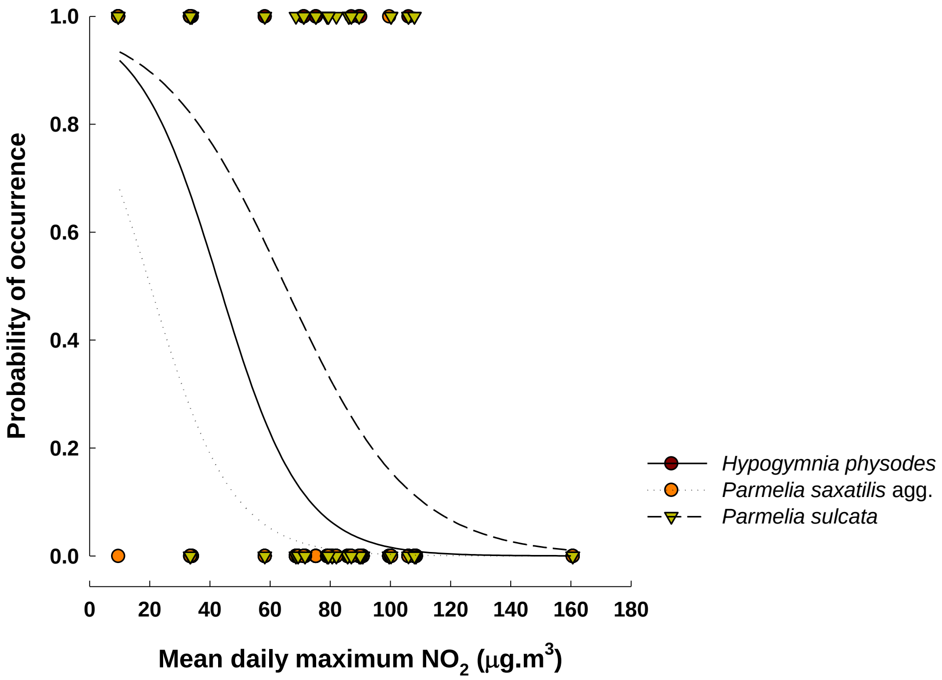
EVIDENCE: Box-plot showing how the cover of fruticose lichens on the south side of a tree is related to the mean daily maximum values of NO_2, tested using a Kruskal-Wallis test: $\chi^2 = 9.77$, $P = 0.00757$, with 2 df.



Q2. Explore between four and ten trees in your study area; how many have grey foliose (leafy) lichens on them?

A. None
B. Some, but fewer than half
C. More than half

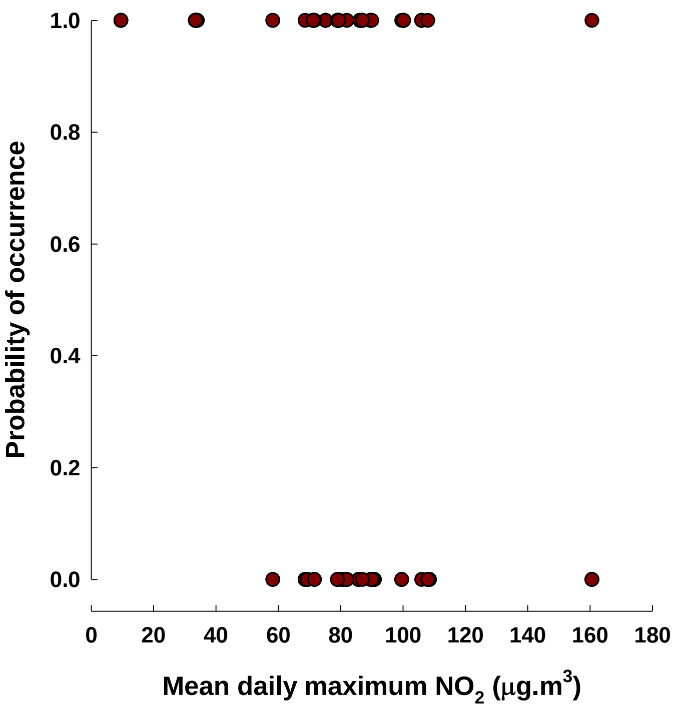
EVIDENCE: Plot comparing species presence-absence to mean daily maximum values of NO_2, and showing the fitted relationship (line) for a significant generalised linear mixed-effects model (binomial error structure, with 'site identity' as a random effect), for *Hypogymnia physodes* (z = -2.673, P = 0.00753 with 83 df), for *Parmelia saxatilis* agg. (z = -3.34, P = 0.00084 with 83 df), and for *Parmelia sulcata* (z = -2.19, P = 0.0285 with 83 df).



Q3. Explore between four and ten trees in your study area; how many have camouflaged green-brown foliose (leafy) lichens on them?

A. None
B. Some, but fewer than half
C. More than half

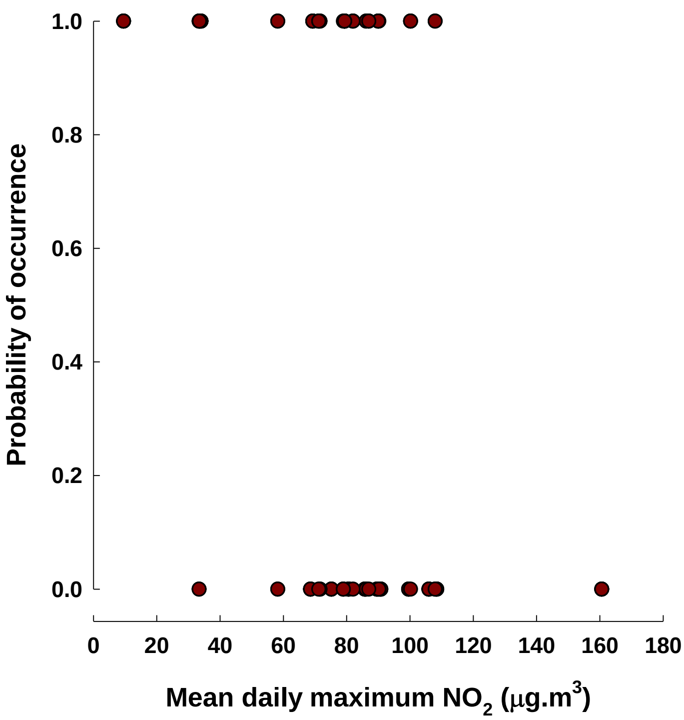
EVIDENCE: Plot comparing species presence-absence to mean daily maximum values of NO_2, and showing the fitted relationship (line) for a significant generalised linear mixed-effects model (binomial error structure, with 'site identity' as a random effect), for combined records of *Melanelixia glabratula* and *M. subaurifera* (z = -2.49, P = 0.0128 with 83 df).



Q4. Explore between four and ten trees in your study area; how many have tiny 'jam-tart' lichens on them?

A. None
B. Some, but fewer than half
C. More than half

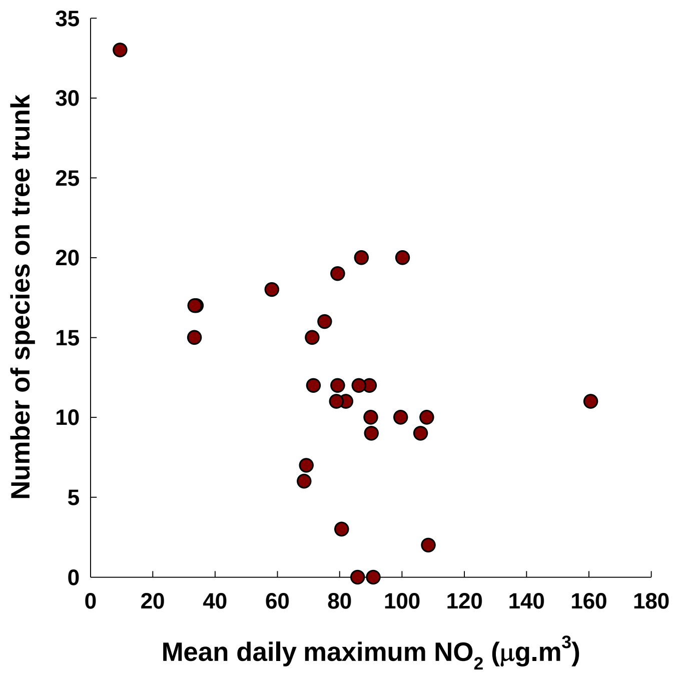
EVIDENCE: Plot comparing species presence-absence to mean daily maximum values of NO_2, and showing the fitted relationship (line) for a significant generalised linear mixed-effects model (binomial error structure, with 'site identity' as a random effect), for crustose lichens with lecanorine fruits (z = -2.513, *P* = 0.012 with 83 df).



Q5. Find the tree in your study area that has the most lichens on it (north, east, south and west); how many different types there are?

A. None
B. One to ten
C. Over ten

EVIDENCE: Plot comparing species richness on the tree trunk to mean daily maximum values of NO_x, and showing the fitted relationship (line) for a significant generalised linear model (Poisson error structure), z = -5.27, *P* < 0.00001, with 26 df.



> Cross-Validation

To ensure the robustness of the five survey questions, which represented a very simplified version of the statistical results, the original data was reframed as a response to the survey questions, and cross-referenced through regression against the NO_2 values. To emphasise the decreasing air quality from answer C, to answer B, to answer A, a metric (Ap) was tested as:

$$\text{Ap} = \text{\# of C responses} - \text{\# of B responses} - (\text{\# of A responses} \times 2) \qquad \text{Eq. 1}$$

The survey values could therefore range from a score of plus five (clean air) to minus ten (polluted air), and on this basis the survey results provide reasonable evidence from which to infer local air quality (Fig. 2). However, the high degree of residual variance supports an emphasis placed in the survey on the need to carefully explore results within the context of a local environment by considering any confounding effects to lichen occurrence, and assimilating further evidence to confirm or refute the estimated good/poor air quality.

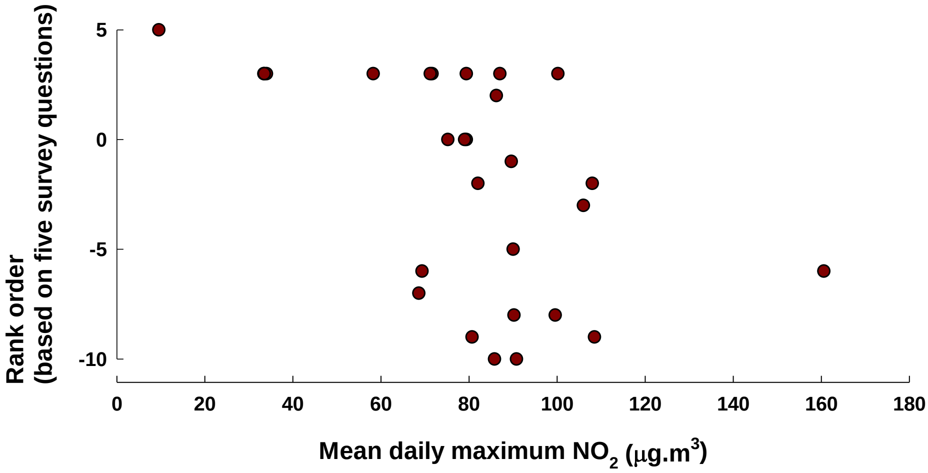


Figure 2. Comparison of air pollution (NO_2) with a ranking of field-sampled results based on the five survey questions designed for public engagement: $r = -0.52$, $P < 0.005$ with 26 df).

> References

Cislaghi, C. & Nimis, P.L. (1997) Lichens, air pollution and lung cancer. *Nature*, 387: 463-464.

Nash, T.H. (2010) Lichen sensitivity to air pollution. In: *Lichen biology* (Nash, T.H., ed.), pp. 301-316. Cambridge University Press, Cambridge.

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