Environmental Pollution 214 (2016) 549–555

Contents lists available at ScienceDirect

Environmental Pollution

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

Citizen science identifies the effects of nitrogen dioxide and other environmental drivers on tar spot of sycamore ☆

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ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form
15 April 2016
Accepted 18 April 2016
Available online 29 April 2016

Keywords:
Citizen science
Nitrogen dioxide
Tar spot
Rhytisma acerinum
Acer pseudoplatanus

ABSTRACT

Elevated sulphur dioxide (SO_2) concentrations were the major cause of the absence of symptoms of tar spot (*Rhytisma acerinum*) of sycamore (*Acer pseudoplatanus*), in urban areas in the 1970s. The subsequent large decline in SO_2 concentrations has not always been accompanied by increased tar spot symptoms, for reasons that have remained unresolved. We used a large citizen science survey, providing over 1000 records across England, to test two competing hypotheses proposed in earlier studies. We were able to demonstrate the validity of both hypotheses; tar spot symptoms were reduced where there were fewer fallen leaves as a source of inoculum, and elevated nitrogen dioxide concentrations reduced tar spot symptoms above a threshold concentration of about 20 $\mu g\ m^{-3}$. Symptom severity was also lower at sites with higher temperature and lower rainfall. Our findings demonstrate the power of citizen science to resolve competing hypotheses about the impacts of air pollution and other environmental drivers.

1. Introduction

Citizen science is a research method that is increasingly being used to capture environmental data (Silvertown, 2009). It can be broadly characterised as a method that uses volunteers in the collection and/or analysis of scientifically useful data, particularly those related to environmental observations and biological monitoring (Roy et al., 2012). Citizen science allows phenomena to be studied at a geographical and temporal range that is normally outside the scope of what is typically achieved by individual researchers (Dickinson et al., 2010). It has proved successful in many instances: for example, Bonney et al. (2009) cite several examples of the role that citizen science has played in a variety of ornithological studies in North America, and citizen science is having an impact on tree health monitoring in the UK (e.g. Pocock and Evans, 2014). Despite the success of these projects, there are concerns regarding the quality of data derived by volunteers, although it is acknowledged that, with careful project design and data handling, these concerns can be overcome (Bonney et al., 2009). Nonetheless, citizen science is recognised as a powerful instrument, not only for advancing research, but also as a tool for engaging the public in science and improving their understanding of scientific methods (Dickinson et al., 2012).

The concept of using the presence or frequency of biological organisms as an indicator of air quality originates in the 19th century, with the work of Nylander (1866) on lichens in Paris. Although there are examples from the past of using simplified bioindicator methods to allow citizen science surveys of air pollution (e.g. Gilbert, 1974), there has been little recent use of this approach. One specific bioindicator of the presence of high levels of air pollution is visual symptoms of fungal infections on leaves, including the presence of leaf yeasts (Dowding and Richardson, 1990). The most well-known of these fungal bioindicators is *Diplocarpon rosae*, for which Saunders (1966) found a relationship between sulphur dioxide (SO_2) concentrations and the intensity of leaf infection, which was subsequently confirmed by fumigation experiments. A related bioindicator of elevated SO_2 concentrations is *Rhytisma acerinum*, which forms black typically circular stromata (tar spots) on the upper surface of leaves of *Acer pseudoplatanus* (Jones, 1925). *Rhytisma acerinum* overwinters in fallen leaves, and re-infection of new leaves occurs through ascospore release from these fallen leaves in the following spring, typically in cool wet

☆ This paper has been recommended for acceptance by Charles Wong.
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http://dx.doi.org/10.1016/j.envpol.2016.04.066

conditions when this infection stage may be particularly sensitive to air pollution. Formation of the typical black spots takes about another two months after infection, and symptoms are most apparent in late summer.

Vick and Bevan (1976) reported a survey in and around Liverpool in which tar spot symptoms were only found at sites with annual mean or early summer SO_2 concentrations below 80–90 $\mu g\ m^{-3}$, a threshold similar to that reported by Saunders (1966) from both field surveys and controlled experimental exposures for *Diplocarpon rosae*. Based on further transplant experiments, Bevan and Greenhaigh (1976) suggested that SO_2 inhibited the germination or penetration stage of leaf infection during the spring. This study also introduced the use of a tar spot index, defined as the number of spots per 100 cm^2 of leaf area, which has been adopted in subsequent studies. In the UK, as in many areas of Europe and North America, SO_2 concentrations have fallen dramatically over recent decades, to levels at which no effects on the presence of tar spot symptoms would be expected. This was partly confirmed by a study in 1999 by Jarraud (2000), who resurveyed a number of sites in South Yorkshire where SO_2 concentrations were high and tar spot was reported to be absent in the early 1970s; at all but one site, tar spot was now present, an effect that could be attributed to the much lower SO_2 concentrations.

However, two studies have reported a continued low tar spot index in urban areas of the UK, despite the much lower SO_2 concentrations. Leith and Fowler (1988) described an absence of tar spot symptoms on *Acer pseudoplatanus* from the city centre of Edinburgh, which they attributed to a lack of inoculum caused by active clearing of leaves from urban parks and city streets, rather than air pollution. They confirmed this by demonstrating that, when *Acer pseudoplatanus* seedlings and inoculum on fallen leaves were transplanted together to two urban and one rural sites, there was no significant difference in the tar spot index that developed at the three sites, implying that SO_2 levels did not affect the degree of tar spot development when inoculum was present.

Jarraud (2000) reported a large decrease in tar spot index along a gradient into London, but attributed this to elevated concentrations of nitrogen dioxide (NO_2), which, in contrast to SO_2, remained high in the city centre. He also carried out transplant experiments in which inoculum and *Acer pseudoplatanus* saplings from a single rural site were exposed together at sites along the pollution gradient. In contrast to Leith and Fowler (1988), a strong effect of decreasing tar spot index with increasing proximity to the city centre was found, confirming that an environmental factor (most likely air pollution) was responsible for the observed gradient in tar spot index, rather than the availability of inoculum.

Subsequently, there has been little further research to test these two competing hypotheses. A field survey in southern Poland (Kosiba, 2007) showed that the density of tar spots on maple leaves was lower at more polluted sites with high leaf contents of sulphur, nitrogen and heavy metals, while Kosiba (2009) showed that the occurrence of *Rhytisma acerinum* on *Acer platanoides* was a good discriminator of sites of high and low environmental status across Poland. Almost all previous studies of *Rhytisma acerinum* on *Acer pseudoplatanus* have focussed on individual cities, or polluted regions such as south Yorkshire and southern Poland, and have involved a limited number of sites. There has been no larger-scale survey which might allow the effect of different environmental drivers on the distribution of tar spot symptoms to be distinguished.

The major citizen science programme, Open Air Laboratories (OPAL), which began in December 2007, aims to get more people outdoors to explore the world around them while contributing environmental data for research. Through OPAL, the public were invited to participate in England-wide surveys on different environmental themes, including soil and earthworms (Bone et al., 2012), urban invertebrates (Bates et al., 2015), and climate (Fowler et al., 2013). The OPAL air survey comprised two activities related to bio-indicators of air pollution, and specifically nitrogen oxides and ammonia. The first activity asked participants to record the abundance of lichens on tree trunks and twigs; the results of the national data were reported by Seed et al. (2013), while Tregidgo et al. (2013) showed that the method could identify impacts on lichen communities close to major roads.

The second activity in the OPAL air survey, which is the focus of this paper, asked participants to record the symptoms of tar spot on *Acer pseudoplatanus* trees. Leaf symptoms on *Acer pseudoplatanus* are well suited to such a national survey as the species is widespread across the UK, and is a common tree species in cities, where air pollution levels are generally higher. Inclusion of *Rhytisma acerinum* in this major national citizen science survey allowed us to test two key hypotheses:-

1. The tar spot index on *Acer pseudoplatanus* is lower at sites with fewer fallen leaves to provide an overwintered source of infection for the next spring
2. The tar spot index on *Acer pseudoplatanus* is lower at sites with a high concentration of NO_2

In addition, we tested whether climatic factors were associated with the tar spot index.

2. Methods

2.1. Survey design

The OPAL Air Survey was disseminated throughout England from September 2009. Participants requested survey packs, which included instructions and a recording booklet, via the OPAL website or by directly contacting OPAL staff who were distributed across England. In the tar spot element of the survey, participants selected 2–4 *Acer pseudoplatanus* trees, with the aid of a tree identification guide, and recorded the trunk girth at 1 m above the ground. They estimated the number of fallen leaves beneath the tree using a scale of 0 (no leaves), 1 (a small amount of leaves) and 2 (lots of fallen leaves), aided by appropriate photographs. Participants then selected up to 10 leaves that they could reach, or which had fallen, recorded the number of tar spots present (including partial spots), and measured the width of each leaf at its widest point; this was used as a surrogate measurement of leaf area. They also recorded the type of location of the recorded trees (e.g. in a street, at the edge of a wood). Participants submitted their results using the OPAL website, where they could select their location using a Google Map application and the date on which they carried out the survey. A small number submitted their results by post.

2.2. Data collation and screening

A total of 859 surveys, containing data on 2501 trees and submitted between September 2009 and June 2014, were downloaded from the database for analysis. We removed data on 297 trees surveyed outside England, where the overall survey density was much lower, and a further 217 that did not have complete information on all the relevant parameters. A further 269 trees surveyed between February and July were then removed, since tar spots are unlikely to be fully developed and visible during this time period. Inspection of the remaining 1718 records suggested that there were a number of outliers which most likely were due to observer error. Based on our own observations of a range of *Acer pseudoplatanus* leaves, we removed 73 records with leaf widths outside the range of