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Impacts of vehicle emissions on vegetation

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Abstract

A system has been constructed which provides stable, realistic urban atmospheres with pollutant mixtures at concentrations and proportions relevant to those found at roadsides in urban areas. This system has been used in conjunction with a range of field sites to assess the impacts of urban pollution mixtures on a broad range of plant species of contrasting morphological and functional types. Impacts of pollution treatments have been assessed in terms of visible injury symptoms, growth, rates of stomatal conductance, senescence, and leaf surface characteristics. Our data clearly demonstrate that levels of pollutant mixtures typical of urban areas do have species-specific, direct effects on plant growth and may make plants susceptible to other environmental stresses.

1 Introduction

The main constituents of vehicle emissions are carbon dioxide (CO_2) nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs eg benzene, toluene) and particulates. Urban environments always contain complex mixtures of these pollutants and they are often present at high concentrations. Potentially, these urban pollutant 'soups' may have direct toxic effects on vegetation or increase susceptibility of plants to other environmental stresses. While previous research has examined the effects of individual components of urban pollution on plants, there is a dearth of information impacts of pollutant mixtures. Some field-based studies have shown symptoms of damage to plants growing near to roads (Sauter et al.[1]) and crop growth was reduced along an air pollution transect into London in the 1980s (Ashmore *et al.* [2]). However, field-based studies do not allow the separation of pollutant impacts from those of other environmental factors. In this paper we report on studies conducted in a unique experimental exposure facility which provides stable, realistic urban atmospheres. The system has been used to assess the impacts of urban pollutant mixtures on a broad range of plant species found in urban areas.

2 Exposure system

Exposures were conducted in four 3.1 m diameter hemispherical glasshouses (Solardome®, Southampton, UK). Each dome was ventilated with charcoal-filtered air, at a rate of 0.58 complete air changes per minute, via a ring of tubing around the inner circumference. The basic system design has been successfully used over many years for large-scale exposures of plants to pollutant gases (Rafarel & Ashenden [3]). Exhaust emissions from a 4kw diesel generator (Lombardini, Italy) were bled into the air streams entering two domes. The other two domes were clean air controls.

Stable concentrations of pollutants within the treatment domes were achieved by a special motorised control valve, linked to a chemiluminescent NO_x analyser (API 200A, USA), which continuously adjusted the flow of exhaust fumes to maintain a set point of 100 ±10 ppbv of total NO_x. This control was found to be sufficient to stabilise the proportions of the different components of the pollutant mixture. Table 1 shows the mean concentrations of pollutants within the treatment domes over 6 months' of operation. Concentrations and proportions of pollutants are comparable with those found at roadsides in UK cities (UK National Air Quality Information Archive [4]).

Table 1. Pollutant concentrations in treatment Solardomes compared with *Cromwell Road (roadside) and †Marlebone Road (kerbside), London (May to October, 2001)

	NO ppbv	**NO_2** ppbv	**NO_x** ppbv	**CO** ppmv	**PM_{10}** $\mu g.m^{-3}$	**Toluene** ppb	**Benzene** ppb
Treatment	58	38	96	~1.0	40.4	5.1	0.9
Roadside	54^*	37^*	91^*	0.85^*	$33.3^\dagger$	$5.6^\dagger$	$1.3^\dagger$

3 Impacts on herbaceous plants

3.1 Materials and methods

Plants of *Centaurea nigra* and *Rumex acetosa* were grown from seed of native British origin in an unheated greenhouse. When seedlings were approximately 4-weeks-old they were potted up in John Innes No. 2 compost in 4-litre pots. Osmocote slow release fertiliser was added at a rate of $2.5 gl^{-1}$. 6 plants of each species were placed in each Solardome on 5th June 2001. The plants were monitored over the summer and then left to overwinter in the Solardomes.

Measurements of plant growth, including leaf number and plant height were made at regular intervals during the summer. The numbers of dead and chlorotic leaves were also counted to assess the state of senescence of the plants.

3.2 Results and discussion

Figure 1 shows the leaf count in the pollution treatment, as a percentage of the control, for *C. nigra* and *R. acetosa* at four points during the summer. It can be seen from the graph that the pollution treatment induced a species-specific growth response. Plants of *R. acetosa* showed growth stimulation in response to exhaust gases while those of *C. nigra* were inhibited.

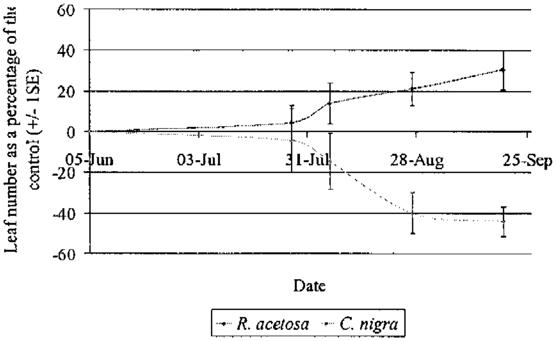

Figure 1: Leaf Count for *R. acetosa* and *C. nigra* in pollution Solardomes as a percentage of the control.

Due to the unique mixture of gases used during fumigation it is impossible to link plant responses to individual pollutants. However, due to their high concentrations and known effects, the oxides of nitrogen are the most likely pollutants to affect plant growth. Gaseous oxides of nitrogen are interesting pollutants because nitrogen is a plant nutrient. Nitrogen oxides taken up by plants are eventually metabolised by the normal pathways of nitrogen metabolism and can potentially contribute to the nitrogen budget of the plant. Thus low levels of both NO and NO_2 have been shown to stimulate plant growth. However, at higher concentrations gases become phytotoxic, leading to a range of adverse plant effects (Adaros *et al* [5], Ashenden *et al* [6], Bender et al [7].

Figure 2 shows the percentage of leaves classed as dead in the pollution and control treatments for *R. acetosa* at 4 points over the summer. Plants exposed to exhaust gases senesced either slightly earlier or at a faster rate than those in the control. This trend was found for a number of other species in the experiment including *Plantago major*, *Leontodon autumnalis* and *Lotus corniculatus*.

These results are in accordance with a number of studies in the literature which have reported increased leaf senescence in response to air pollution (Bleasdale [8], Gratani *et al* [9]). The results from these experiments show that the current levels of vehicle emissions in our urban areas have the potential to affect plant growth and senescence.

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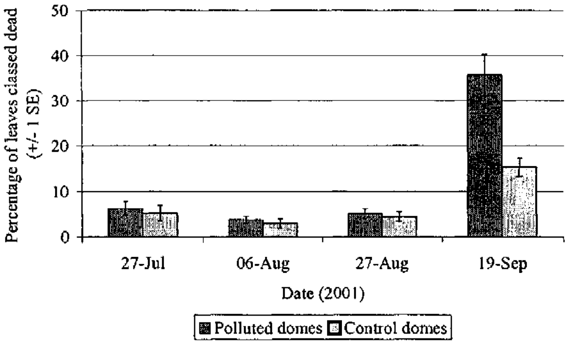

Figure 2: Percentage of leaves classed dead in pollution and control domes for *R. acetosa.*

Plants growing in mixed species swards are constantly competing for resources. The additional stress placed on plants by urban air pollution could potentially lead to changes in the competitive ability of individual species and ultimately to shifts in species composition.

4 Impacts on ornamental trees and shrubs

4.1 Materials and methods

In April 2001, 10 one-year-old *Ligustrum ovalifolium* plants, purchased from a commercial grower, were planted in 10 cm diameter x 100 cm deep pots and placed into each Solardome glasshouse. After two months, a drought was imposed on half the individuals in each glasshouse. For the droughted plants, water was withheld until the onset of wilting. Well-watered plants were given 300ml of water each day.

Changes in water relations of plants were evaluated by measuring leaf water potentials and stomatal conductance. The water potential gives an indication of degree of water stress, with more negative values (measured in MegaPascals) indicating greater stress. Measurements were taken every 2-3 days using a Merrill Thermocouple Psychrometer. Stomatal conductance is a measure of the openness of the stomata, the microscopic pores which control the extent of gas exchange between the leaf and the atmosphere. The stomata are the main site of water loss and are also the major route of entry for pollutant gases. Stomatal conductance was measured with a ΔT Porometer (Delta T Devices, UK)

4.2 Results and discussion

Stomatal conductance was found to be reduced in plants exposed to exhaust gas pollution compared with those exposed to clean air (Figure 3). This could be due to a direct affect of one or more of the pollutant gases on stomatal functioning, or to an effect on the rate of photosynthesis. The overall result would be reduced

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pollutant uptake and reduced water loss. Figure 4 shows that as the drought progressed, the water potentials of all droughted plants declined steadily, while those of the well-watered plants remained relatively constant. There was a clear pollution/drought interaction; the droughted plants in exhaust gas-polluted conditions wilted much less rapidly than the droughted plants in clean air. This inferred that urban pollution mixtures confer some protection to plants against drought stress. The depressed stomatal conductances observed in polluted plants means that less water vapor is lost from the plant during gas exchange. This could have important consequences for plants in urban situations, where small areas of open soil surfaces and soil compaction may often induce water stress.

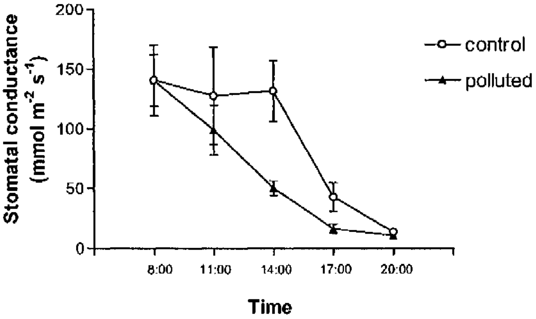

Figure 3: Diurnal pattern of stomatal conductance in *Ligustrum ovalifolium* under clean air and exhaust gas-polluted air.

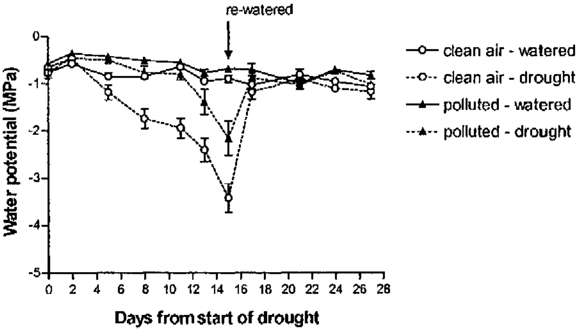

Figure 4: Leaf water potentials for droughted and well-watered *Ligustrum ovalifolium* plants in clean air and exhaust gas-polluted air.

Exposure to exhaust gas pollution did not affect biomass in this species (data not shown). In other species of trees and shrubs, effects on growth have been observed. Some species have shown elevated growth, whilst some have exhibited suppressed growth in polluted compared with clean atmospheres. Where urban pollution mixtures stimulate growth, it is thought to be due to a fertilizing effect of NO_X which is taken up directly into the leaves. While the pollutants did not influence growth in *Ligustrum*, we found evidence of increased nitrogen taken up by leaves in polluted conditions. The activity of an enzyme, nitrate reductase, which controls the first step in assimilation of nitrate into amino acids, was found to be much higher under polluted conditions. This suggests that the leaves could have contained higher levels of nitrogen and amino acids. These higher levels of nitrogen could affect the nutritional quality of leaves and result in increased insect herbivore attacks. Ornamental shrubs in urban environments are often subjected to high levels of insect herbivory.

5 Impacts on water retention in Scots Pine

5.1 Methods

Scots pine (*Pinus sylvestris*) is a common species in shelterbelts along motorways and trunk roads in the UK and is commonly found in urban areas. 2-year old pine saplings were placed in the Solardomes in April 2000, with 15 trees exposed to each pollution treatment. Sampling was of current year needles only, which had expanded in the dome environment, taken from an upper branch of the sapling. Drying curves were constructed from 2 needles from each tree (30 per treatment), and rates of needle drying expressed as Relative Water Content (RWC) according to Cape & Percy [10]. Needle surfaces of 5 needles per tree were examined at 2000x and 10000x magnification, under a Scanning Electron Microscope (JEOL – 20kV, 20mm spot size, 10mm working distance) following standard preparation and gold coating (Grodzinska-Jurczak [11]). The quality and definition of the wax mesh surrounding the stomata were compared visually. Stomatal conductance was determined using a portable IRGA (Ciras I, PP Systems, UK), on plants under ambient conditions in the domes. Ambient CO_2 was approximately 330ppm, and light varied between 208 and 553μmol/m^2/s (average 371 μmol/m^2/s) with no significant differences between domes.

5.2 Results and discussion

Water loss from needles was greater from polluted than from unpolluted Solardomes. Polluted needles had a lower initial RWC. The rate of drying in both treatments was greatest over the first hour, but continued over the 2 days of the experiment (Figure 5). The initial rapid decline in RWC in the polluted needles may have been due to a failure of stomata to close as quickly or fully as in the control plants, and the slower decline over the next 2 days due to a combination of water loss through the partially closed stomata and over the degraded cuticle (Cape & Percy [10]). The slightly lower initial RWC of polluted needles may indicate that even *in vivo*, the polluted environment affected the capacity of needles to retain water.

These potential routes of water loss were examined. Needles taken from polluted Solardomes often carried a heavier particulate burden, and the wax mesh surrounding stomata was degraded and the fine tubes present in pristine needles fused together, giving the wax a “clumped” appearance (Figure 6). These features often appear as needles age (Grodzinska-Jurczak [11]), but were apparent even on current year needles from the polluted Solardomes. This “accelerated ageing” has also been observed on needles exposed to other pollutants [11]. Viskari [12], for example, found that VOCs in exhaust gas

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degraded spruce (*Picea abies*) epicuticular waxes, and attributed this mainly to lipophilic aromatic hydrocarbons, such as benzene and xylene. Particles present in the urban Solardome environment may also physically degrade waxes, as well as being potentially phytotoxic, and reduce light penetrating to the needle. Reduction and abrasion of the wax layer may inhibit its effectiveness as a barrier to cuticular water loss, and have implications for drought tolerance of the trees.

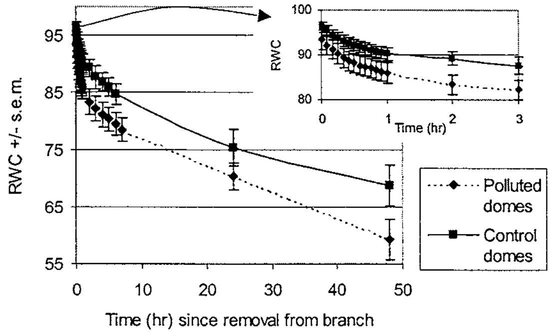

Figure 5: Drying curves of current year needles, dried under laboratory conditions (n=30)

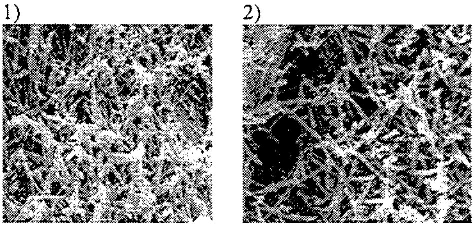

Figure 6: Sample SEM micrographs of current year needles from Solardomes x 10,000 (1-polluted, 2=control)

Stomatal conductance in control domes was 214 millimole/m^2/s (n=15. SE=18.89) and 302 millimole/m^2/s in the polluted domes (n=15, SE=42.06) – an increase of almost 50% in the polluted domes. As stomata are a route of water loss from the plant under normal conditions, they will close when photosynthesis is light limited or inhibited, or under drought conditions. If they are damaged, however, they may not close fully, increasing the rate of water loss from the needle. Pollutants have been shown to perturb stomatal operation in several ways, both increasing and decreasing conductance (Robinson *et al.*[13]). Viskari *et al.* [14] found vehicle exhaust increased stomatal conductance of Norway spruce, which was attributed to direct deposition of toxins onto stomatal guard cells, damaging turgor regulation. This failure to close efficiently was most evident at night (Viskari *et al.* [14]).

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Therefore, the observed increase in water loss from needles exposed in the polluted Solardomes, may be partly attributed to a combination of increased evaporation over an exposed cuticle, and ineffectively closed stomata. In an urban environment this may reduce drought tolerance, and render the trees more sensitive to other stresses such as frost damage and insect attack.

6 Impacts on bryophytes

6.1 Materials and methods

Ten moss species were selected to represent a range of growth forms and habitats. Generally 10 to 30 shoots of each species were cut to a standard size and placed in transparent pots on sand. Shoots of acrocarpous species were orientated vertically and pleurocarps horizontally to reflect the growth form of the species. Pots contained strips of capillary matting that extended into a reservoir of artificial rainwater solution (Meade [15]) to keep the sand moist, and were covered in shading material to minimise desiccation. For *Polytrichum commune*, shoots were stood in beakers of the rainwater solution.

After an 11-day acclimatisation period in the control domes, 8 pots per species were allocated randomly to each treatment. Material was fumigated with diesel exhaust fumes for 4 months during winter (Dec 00 - Apr 01) and was sprayed 3 times per week with artificial rainwater solution. Growth in terms of shoot extension was measured at the end of the exposure period and visible damage (colour changes) was determined after 2 and 4 months. In acrocarps, visible damage was observed at shoot tips, and the length of shoot affected could be measured. In pleurocarps, it occurred in patches along the shoots and so it was recorded as a percentage.

6.2 Results and discussion

Exposure to diesel exhaust fumes caused significant reductions in growth (Figure 7) and increases in visible damage (Table 2) in all 6 pleurocarpous species. There are no clear patterns for the acrocarpous species with respect to growth, but significant increases in visible damage are seen in 2 of the species after 2 months and in just 1 species at the end of the experiment.

Very little growth was recorded in the pollution treatment in pleurocarpous species. There is up to 50% visible damage in the controls suggesting that the conditions in the domes were placing stress on the mosses. This is most likely to be desiccation, which results in photobleaching in intolerant bryophyte species (Seel [16]). The acrocarps exhibit some damage in the controls, but it is far less than the pleurocarps and the plants looked much healthier. It is possible that the increased damage seen in the pollution treatment could be a consequence of the pollution affecting the ability of the plants to control water loss making them more susceptible to photobleaching. Visible pigment loss has decreased slightly in some species over time, particularly in the acrocarps. This was due to development of new green shoots in the spring; however, the recovery, if any, was small.

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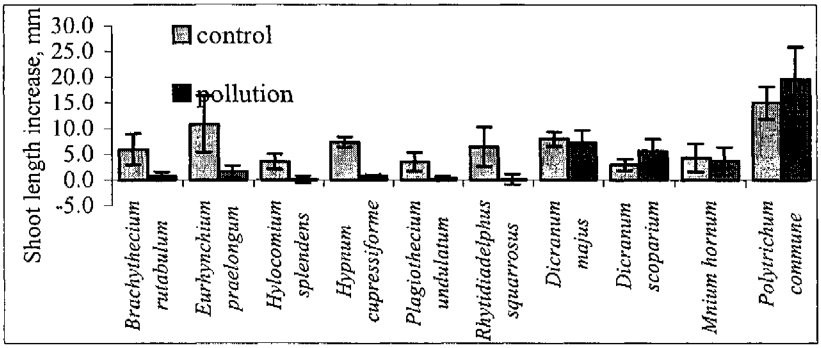

Figure 7: Increase in shoot length after 4 months fumigation with diesel fumes in the solar domes. Whiskers are standard error bars.

Table 2: Visible damage after 2 and 4 months fumigation with diesel exhaust fumes. Values are means ± 95% confidence interval, and are percentages for pleurocarps, and in mm for acrocarps.

		2 months		4 months	
	Species	**Control**	**Pollution**	**Control**	**Pollution**
Pleurocarps	*Brachythecium rutabulum*	26±12	100±0	50±19	99±2
	Eurhynchium praelongum	21±11	96±5	19±15	95±6
	Hylocomium splendens	7±6	21±5	81±7	100±0
	Hypnum cupressiforme	15±12	99±2	15±5	95±5
	Plagiothecium undulatum	36±15	99±1	43±10	90±11
	Rhytidiadelphus squarrosus	29±15	99±2	23±13	89±5
Acrocarps	*Dicranum majus*	9.8±1.1	9.5±1.9	4.7±1.4	5.7±0.6
	Dicranum scoparium	6.6±0.6	6.0±1.0	3.5±0.9	2.9±0.4
	Mnium hornum	2.3±1.2	7.5±2.3	2.6±0.8	4.6±1.1
	Polytrichum commune	2.0±0	5.3±0.7	2.6±0.7	2.9±0.9

The data suggests that the acrocarps tested are less sensitive to exposure to diesel fumes than the pleurocarps. However, differences in culture methodology may have favoured the acrocarps by creating a more favourable microclimate: shoots were in contact, which would increase humidity and reduce desiccation. In contrast the shoots of pleurocarps were not in contact. This would have the added effect of having a greater surface area exposed directly to the pollution.

The damage and reductions in growth observed in response to diesel exhaust fumes could have important implications for the survival of these bryophytes species in urban areas and in the vicinity of busy roads and motorways.

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