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Using commercial tree nurseries to monitor visible ozone injury—An evaluation

Suzanne E. Benham[a,*], Mark S.J. Broadmeadow[b], Marcus Schaub[c], Vicent Calatayud[d], Filippo Bussotti[e]

[a] Forest Research, Centre for Forestry and Climate Change, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK
[b] Forestry Commission England, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK
[c] Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland
[d] Fundación C.E.A.M., Charles R. Darwin 14, Parc Tecnològic, 46980 Paterna, Spain
[e] Dept. of Plant Biology, University of Firenze, Italy

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ABSTRACT

Ozone damage on trees leaves no residue that can be detected analytically; therefore visible assessment is the only easily detectable method for collecting evidence. Here we present an evaluation of an assessment method using damaged detected on trees grown in commercial tree nurseries. The extent of visible ozone injury to susceptible species was investigated on a total of 95 species across 13 nurseries, over four European countries during the 2006 season. Commercial nurseries were chosen because nurseries stock a wide range of accessible, susceptible species which are irrigated when necessary and therefore represent the optimum conditions for assessment of potential risk. Ozone climate at each site was characterised using a combination of passive and active samplers to estimate the accumulated ozone exposure over a threshold of 40 ppb (AOT40). Meteorological and ozone monitoring data were used to calculate cumulative ozone flux using the DO$_3$SE model (Emberson et al., 2000). Ozone injury was observed in all countries demonstrating that the impacts of ozone are not restricted to countries with higher ozone concentrations; the longer day-length, higher moisture availability and cooler conditions in northern Europe resulted in a greater potential for ozone uptake. Further use of commercial nurseries as an important, unofficial, bioindicator network is warranted.

1. Introduction

Tropospheric ozone (O_3) is a photo-oxidant formed by complex reactions under UV radiation and high temperatures between its precursors, primarily nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Background levels have risen in recent years and are predicted to continue rising although peak concentrations have fallen with the introduction of NO_x control policies. The harmful effects of ozone to plants are principally associated with the cumulative dose taken up through the stomata. This uptake causes degradation of cell membranes particularly in photosynthetic cells leading to a reduction in photosynthetic capacity. In combination with the metabolic cost required to repair damage this often results in reduced gas exchange (Zhang et al., 2001; Novak et al., 2005) and reduced growth (Novak et al., 2007), including a reduction in root biomass (Pell et al., 1997). There is also evidence that ozone causes degradation of the waxy surfaces of the plant leaf, leading to increased water loss. Ozone exposure is thus likely to exacerbate the effects of drought and result in increased susceptibility and mortality. Stomatal uptake is dependent on a number of environmental variables including relative humidity (vapour pressure deficit), soil moisture, radiation and air temperature and also varies between species and with plant age. Hence the evaluation of ozone flux and potential plant injury relies on the ability to model the uptake of the specific species based on these environmental variables.

Large ozone uptake may cause characteristic visible injury to the leaves of sensitive tree and shrub species. This can vary from reddening and bronzing on the leaves of broadleaved tree species to mottling on conifer needles, leading ultimately to cell death (necrosis) and premature senescence (Skelly et al., 1999; Novak et al., 2008). Ozone across Europe regularly reaches levels at which injury can occur (e.g. Innes et al., 2001; Sanz et al., 2001). There is evidence that ozone can significantly reduce the total biomass of trees by as much as 10% when compared to pre-industrial levels. Both above and below ground productivity are affected with significant reductions in height, diameter and leaf area (Semenov and Koukhta, 1996; Wittig et al., 2008). Visual damage can be

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* Corresponding author. Tel.: +44 1420 526209; fax: +44 1420 520180.
E-mail address: sue.benham@forestry.gsi.gov.uk (S.E. Benham).

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Table 1
Detailed information on the investigated 13 commercial tree nurseries.

Name	Altitude (m)	Latitude	Longitude	Mean annual air temp (°C)	Mean annual rainfall (mm)	Location
UK 1	70	51°02′N	0°54′W	9.9	867	Hampshire
UK 2	65	56°38′N	3°10′W	9.5	785	Perthshire
UK 3	50	52°08′N	0°12′W	9.6	793	Bedfordshire
UK 4	30	51°11′N	0°56′E	10	748	Kent
UK 5	60	51°53′N	2°25′W	9.6	854	Gloucestershire
CH 1	600	45°51′N	09°03′E	11.1	1333	Southern Swiss, Italian border
CH 2	553	47°21′N	08°27′E	9.1	1135	Birmensdorf (Zurich)
IT 1	450	43°44′N	11°45′E	12.3	1100	Lombardia
IT 2	60	43°56′N	10°54′E	14.3	1250	Pistoia
IT 3	250	45°41′N	9°37′E	13.6	1100	Arezzo
ES 1	1015	38°40′N	0°32′W	13.8	552	Alicante
ES 2	83	39°29′N	0°31′W	16.5	462	Valencia
ES 3	320	39°24′N	0°47′W	13.6	516	Valencia

related to measurements of cumulative ozone exposure, though high peak concentrations (>100 ppb) can also contribute to visible ozone symptoms (Davis and Orendovici, 2006).

As part of the ongoing work of the ICP-Forests Working Group on Ambient Air Quality, the primary objective of the project reported here was to test the possibility of mapping ozone injury to sensitive tree species under optimal site conditions for ozone uptake. Such an approach may provide a more easily interpreted, cost effective way of determining the extent of ozone damage to trees and forests across Europe. This was based on measurements and observations at commercial nurseries where regular irrigation prevents reduced ozone uptake due to drought conditions. Visible injury was assessed because many plant species respond to ambient levels of ozone pollution with distinct visible foliar symptoms, which have been diagnosed in the field (e.g. Innes and Skelly, 1996; Innes et al., 2001; VanderHeyden et al., 2001; Novak et al., 2003). It is often difficult to assess mature trees given the range of sites occupied across a species range. The symptoms are more readily expressed in young trees, in whose foliage samples are accessible making a comprehensive assessment of injury to a range of tree species a manageable objective. Furthermore, the range of species grown in commercial nurseries cover a broad sample of forest and amenity tree species which are known to be sensitive to ozone. However, the use of saplings to predict the responses of mature trees to ozone requires some care, given the phenological and physiological differences between them (Karlsson et al., 2005). This methodology can only provide an *indication* of the risk of injury to mature forests, providing a means to identify the risk and evaluate differences on a European scale.

2. Methods

2.1. Site selection

Research teams in four countries (United Kingdom, Switzerland, Italy, and Spain) participated in the project. In each country, up to five commercial tree nurseries growing a large range of the chosen tree species were identified and agreement obtained for access to the site for assessment (see Table 1). To fully evaluate the potential risk of ozone damage to vegetation in Europe, a total of 95 different species were assessed across the nurseries. Species chosen were primarily selected from the European list of sensitive species (Schaub et al., 2002), and includes several for which sensitivity to ozone and the type of symptoms produced by this pollutant are well-known as a result of open top chamber studies (e.g. Sanz et al., 2001). In some cases other species common to the region were also assessed. At each nursery, irrigation systems ensured that trees did not suffer water stress.

2.2. Ozone monitoring

At each nursery site, ambient ozone concentrations were monitored from April to September using passive samplers to provide a measure of cumulative ozone exposure. Each country used its own type of passive sampler which conformed to the technical requirements of the ICP Forests Manual for monitoring ambient air quality (ICP Forests, 2000). At each site, two or three sampler tubes were exposed, plus one blank for quality assurance, for each 2-week period during the study period. The passive samplers were cross-calibrated with ozone data available from the closest continuous automatic monitoring station, except in Switzerland where continuous automatic analysers were installed at both nursery sites. Meteorological data for temperature, humidity, sunshine and rainfall were provided by the nurseries or from the closest national monitoring site.

2.3. Visible injury assessment

Assessments focussed on field-grown trees and shrubs, although gaps in the chosen species were filled by the use of container grown plants if necessary (see Bussotti et al., 2003, 2006). Each assessor had attended an intercalibration course on visible ozone damage assessment. The extent of ozone injury was determined by the assessment of leaves from the upper fully sun exposed crown of each tree or shrub. Visible injury was assessed on 30 plants per species selected on a random basis, where available. For each species, the number of trees affected was recorded. During the assessments, many tree species presented non-specific ozone-like symptoms. On closer examination, many of these were eliminated due to other causes such as viral attack, mechanical damage or the

Table 2
Visible injury classes for (a) proportion of symptomatic leaves and (b) proportion of leaf area affected.

(a) Percentage of leaves showing ozone symptoms		(b) Percentage of leaf area affected	
A	None of the leaves show symptoms	0	No symptoms present
B	1–5% of the leaves show symptoms	1	1–5% of the surface is affected
C	6–50% of the leaves show symptoms	2	6–50% of the surface is affected
D	51–100% of the leaves show symptoms	3	51–100% of the surface is affected

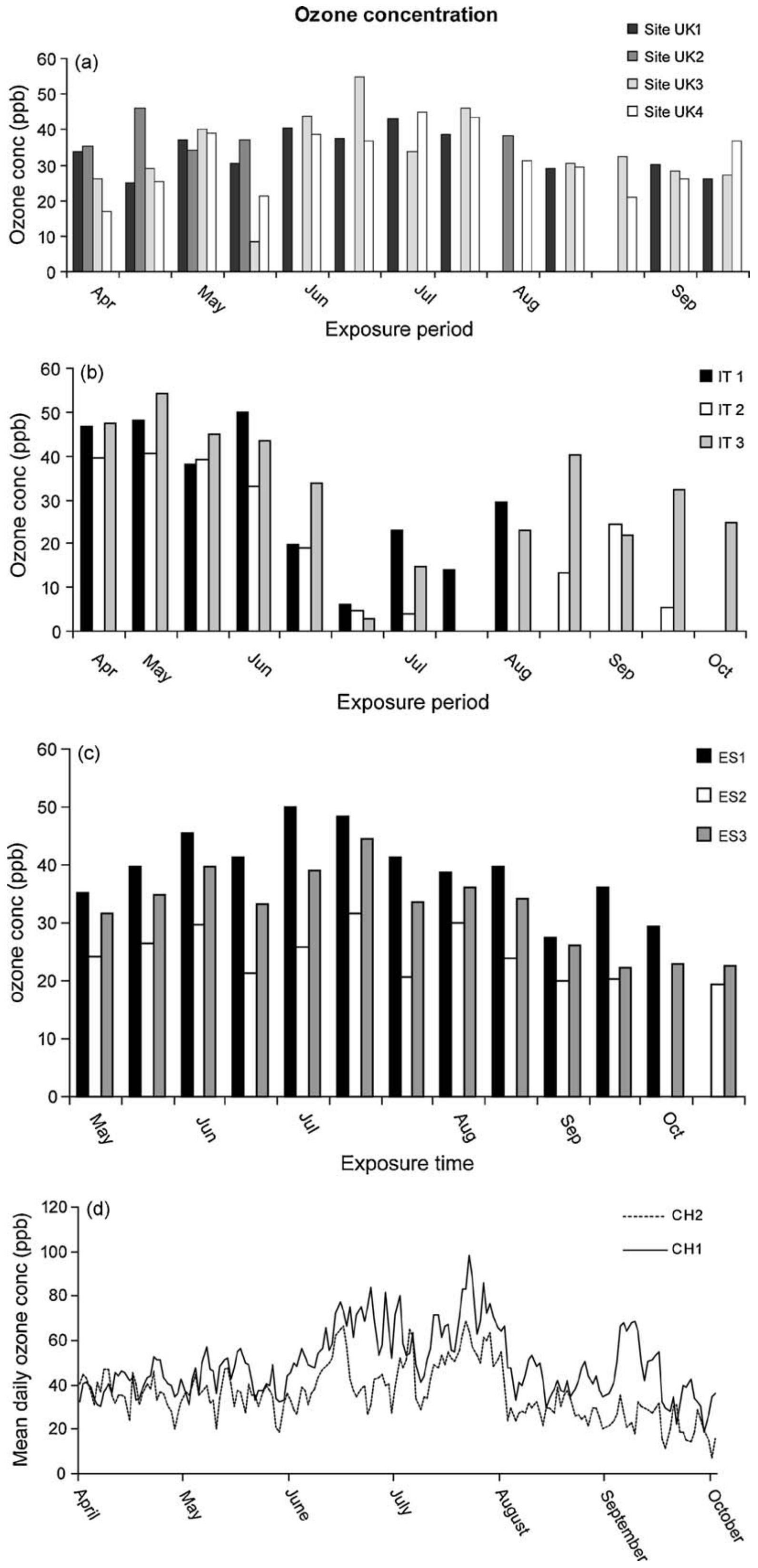

Fig. 1. (a) Mean ozone concentrations measured with passive samplers over approximately 14-day periods in the UK from April to September. Data for each monitoring period are shown for the month during which the main part of the monitoring took place. Missing data are the result of data quality issues with the passive samplers or difficulties with site operatives. Site UK5 is not represented as no passive samplers were ever returned for analysis. (b) Mean ozone concentrations (ppb) measured with passive samplers over approximately 14-day exposure period (April–September) on three nurseries in Italy. Data are shown for the main month of monitoring. (c) Mean ozone concentrations (ppb) measured with passive samplers over approximately 14-day periods at the three tree nurseries in Spain between May and October inclusive. Data are shown for the month during which the main monitoring took place. *Note*: Due to technical problems, two data points are missing. (d) Mean hourly ozone concentrations (ppb) measured by continuous automatic analysis at the two tree nurseries in Switzerland, from beginning of April until the end of September.

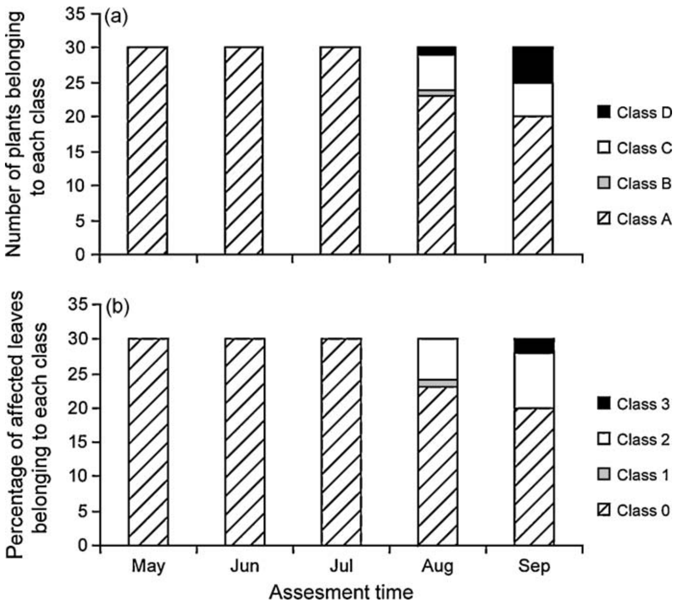

Fig. 2. Evolution of the percentage of symptomatic leaves (a) and affected leaf area (b) by class for *Prunus spinosa* at ES1. *Note*: Assessment was not possible from September due to natural senescence and leaf fall confounding the observations.

natural accumulation of pigments on exposure to sunlight. The latter, however, can be difficult to interpret as ozone is known to increase their development over time and colour changes must therefore be judged in relation to the "normal timing of colour development" at that location. Leaf samples were therefore taken for the validation of any visible symptoms by examination with light microscopy, to confirm collapse in the structure of the palisade parenchyma, characteristic of oxidative stress (Günthardt-Goerg and Vollenweider, 2006). For each individual plant, ozone symptoms were assessed using the classes given in Table 2.

2.4. Calculation of ozone exposure

Ozone exposure was calculated on the basis of AOT40 (accumulated ozone exposure over a threshold of 40 ppb), mean ozone concentration, peak ozone concentrations $N > 100$ (number of hourly means >100 ppb) and accumulated stomatal ozone flux over a threshold of 1.6 nmol m^{-2} s^{-1} (AF_{st}) during daylight hours (global radiation >50 W m^{-2}) for the assessment period. AF_{st} was calculated using the DO_3SE multiplicative model parameterised for beech (Emberson et al., 2000; Karlsson et al., 2007). Evaluation of AOT40, AF_{st} and calculations using the DO_3SE model require continuous hourly data sets of ozone and meteorological data, but for some sites, meteorological data were only available as daily records. Sunshine hours were converted to daily radiation using the standard "Angström" method (Angström, 1924), and to hourly values by time curves with positive values between dawn and dusk, such that the total integral equals the daily radiation, with a peak at midday. Daily temperatures were manipulated by fitting a sinusoidal curve between the recorded maximum and minimum temperature, such that the positive amplitude occurs with a maximum at 14:00 h and the negative a minimum of 1 h before dawn. The assumption for predicting hourly relative humidity from daily observed meteorological data is that the vapour pressure stays unchanged though the day, so that vapour pressure deficit changes with the changing temperature. For temperatures above freezing, the saturated vapour pressure (Svp) is given by:

$$Svp = 6.1708\exp^{(17.269T_k)/(237.3+T_k)}$$

where T_k is the temperature in kelvin, and the vapour pressure (Vp) is:

$$Vp = Svp_{wet} - 0.66(T_{dry} - T_{wet})$$

with T_{dry} and T_{wet}, the dry-bulb and wet-bulb temperatures.

Relative humidity, Rh, was calculated from the vapour pressure and the saturated vapour pressure (at T_{dry}; Vp_{dry}) at the relevant time:

$$Rh = \frac{Vp}{Vp_{dry}}100$$

Although there are inevitable assumptions in using these modelled data, this approach proved to be appropriate for describing gross differences in stomatal uptake between the regions exemplified by the nursery sites. Full details of the study methodology are contained in Benham et al. (2007).

3. Results

3.1. Ozone exposure

In the UK, the highest cumulative ozone concentrations were recorded at the highest elevation sites, as expected from previous studies (Fowler et al., 1995). UK sites reported lower ozone concentrations than the countries in Central Europe. UK ozone concentrations were similar across four of the sites, but at a fifth site (UK2, located in Central Scotland) the concentrations were much higher (Fig. 1a). This is likely to be because of less polluted air at the site maintaining high night-time concentrations. At the other sites, higher NO_x concentrations and therefore an enhanced ozone creation/destruction cycle are likely to have resulted in much lower night-time concentrations, as confirmed by the active monitoring

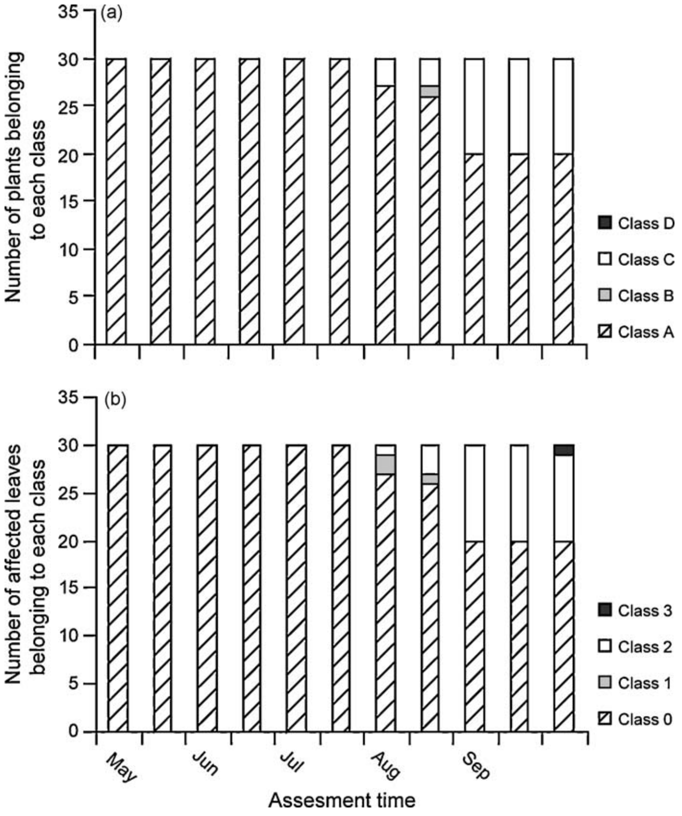

Fig. 3. Evolution of the percentage of symptomatic leaves (a) and affected leaf area (b) in each class for *Viburnum lantana* at ES2. *Note*: Assessment was not possible in October due to natural senescence confounding the observations.

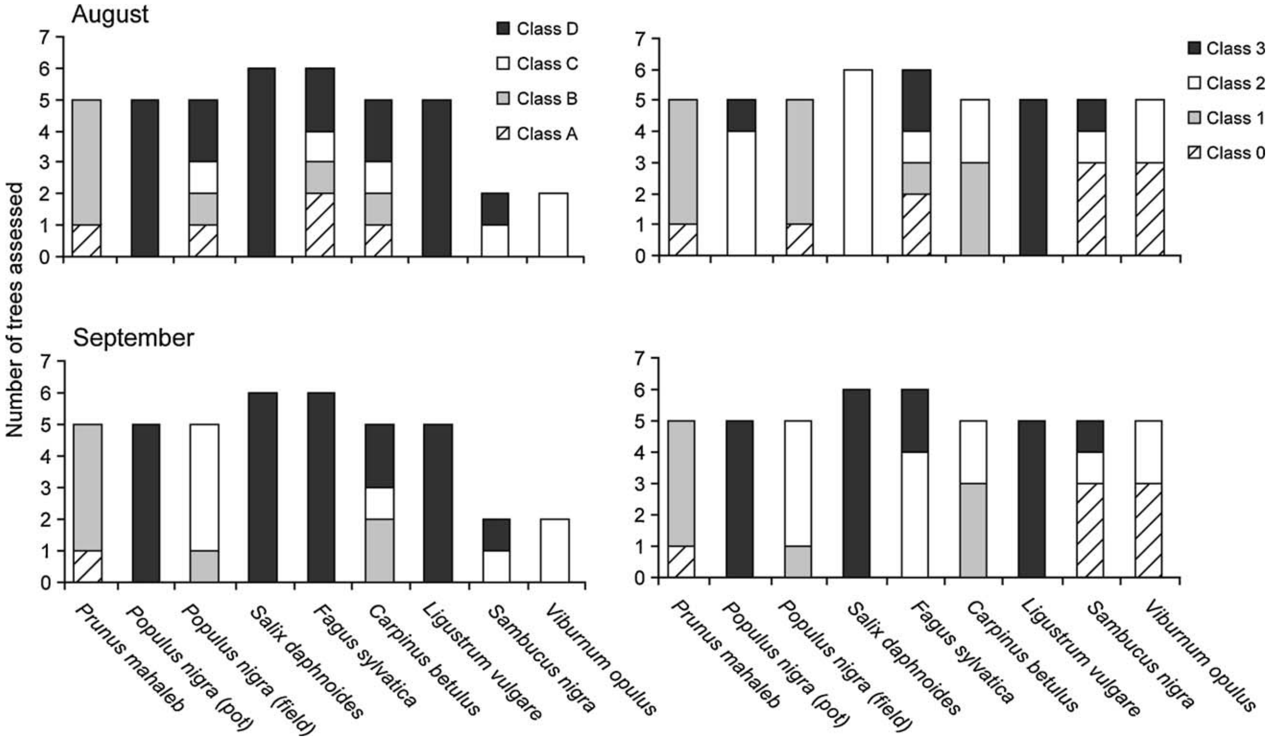

Fig. 4. Evolution of ozone-induced damage at site CH1, expressed as the number of trees (left) and leaves (right) affected in August (top) and September (bottom) and broken down by damage classes.

data. This highlights the benefit of using stomatal flux estimates of ozone exposure instead of AOT40 or mean concentration.

Only the sites in the south of the country experienced mean hourly peak values of greater than 100 ppb. The highest number (255 h) was recorded for site UK2, with UK1 having the least (23 h).

In Italy, the highest ozone concentrations were recorded during the early part of the growing season from April to June (Fig. 1b), in contrast to the other countries where they were recorded during July and August. The two higher altitude sites showed the highest concentrations with a maximum of 50 ppb at IT1 and 55 ppb at IT3 for a fortnightly period. IT2 at a much lower altitude recorded a

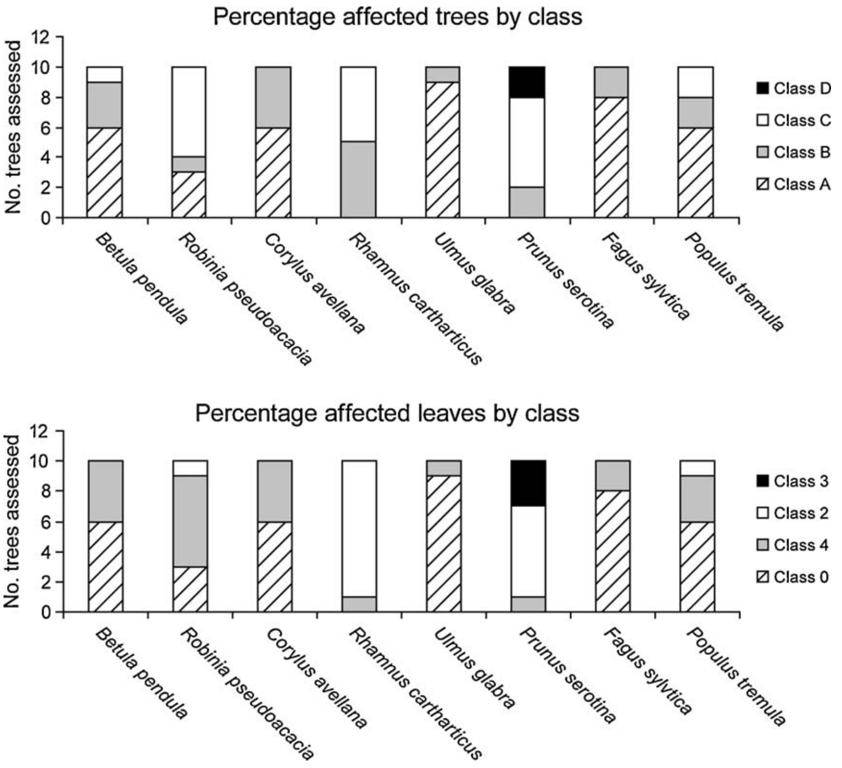

Fig. 5. Proportion of symptomatic trees (left) and leaves (right) denoted by damage class observed at site CH2 in September.

Table 3
Results of a detailed survey of ozone-induced symptoms at site IT3.

Species	Ozone symptom score[a]		Observations
	Leaves affected	Leaf area affected	
Viburnum opulus	D	3	Reddening
Viburnum lantana	D	3	Reddening
Cornus sanguinea	D	3	Reddening
Morus nigra	D	2	Interveinal brown stipples (**ozone typical**)
Fraxinus excelsior	B	3	Interveinal brown stipples (o**zone very typical**)
Fraxinus ornus	B	2	Bronzing
Prunus avium	D	2	Reddening
Acer pseudoplatanus	C	3	Interveinal brown stipples (**ozone typical**)
Acer platanoides	B	1	Interveinal brown stipples (**ozone-like**)
Acer campestre	D	2	Interveinal brown stipples (**ozone-like**)
Rhamnus catharticus	D	2	Interveinal brown stipples (**ozone typical**)
Ulmus campestre	C	2	Reddening
Populus nigra	D	1	Interveinal brown stipples (**ozone typical**)
Ligustrum vulgare	C	2	Bronzing

Observations in bold are those injuries were the damage seen is believed to be attributed to ozone alone, and is not compounded by known seasonal effects.

[a] For details of scoring system.

maximum of 40 ppb. Peak concentrations >100 ppb were highest at IT1 (47 h) and lower at IT2 (7 h) and IT3 (5 h).

In Spain, the highest ozone levels occurred in July (Fig. 1c). Ozone exposures also varied with altitude, with the largest concentrations experienced at the highest elevation site (up to 50 ppb for a 2-week period recorded at the highest altitude site ES1), while the lowest altitude (site ES2) experienced the lowest values (32 ppb for a 2-week period). Peak concentrations >100 ppb occurred at all sites. ES1 and ES3 experienced the longest duration (873 and 565 h) with the lower altitude site ES2 experiencing significantly less (24 h).

At the Swiss sites, ozone was monitored using continuous automatic analysers (Fig. 1d). The highest hourly ozone concentration of 165 ppb was recorded at the highest altitude site CH1 which is situated in the mountains above the Italian plain of Milan and is known to have high ozone concentrations with foliar damage frequently observed. The duration of peak hourly concentrations over 100 ppb were also higher (143 h) than the lower altitude site CH2 (4 h) which experienced a maximum concentration of 104 ppb.

3.2. *Injury assessment*

3.2.1. *UK*

In the UK during the first assessment (mid July) *Tilia cordata*, *Carpinus betulus*, *Alnus incana*, *Corylus avellana*, *Prunus avium* and *Fagus sylvatica* displayed a degree of interveinal bronzing. This was identified as being due to a combination of juvenile material and scorching. Stippling was seen on *Liriodendron tulipifera*, *Populus nigra* and *Pinus nigra* subsp. *austrialis*. The symptoms in the first two cases were mostly caused by tissue necrosis but stippling was clearly visible on both sides of the leaves indicating that this was more likely to be pathogen-induced. Damage to *P. nigra* probably represented early symptoms of viral infection. *Viburnum lantana*, *Viburnum opulus*, *A. incana*, *A. glutinosa*, *P. avium* and *Pyrus malus* all displayed reddening of the foliage. This was identified as the natural build up of pigments as the season progressed. However, no evidence was available as to the usual timing of this event.

During the second assessment in late September, ozone damage was confirmed only at site UK1: stippling was observed on 50% of the *L. tulipifera* trees assessed, with 10% of these displaying extreme symptoms on older leaves in full sun; younger leaves were not affected. *F. sylvatica* showed bronzing on 80% of the older leaves on exposed branches, with 80% of the trees affected to some extent. Many leaves also displayed a classical 'shading response' where damage was not observed on parts of the surface obscured by other leaves. Microscopic examination confirmed tissue damage typical of ozone injury in both cases.

3.2.2. *Italy*

In Italy, assessments were carried out in early July and again in late August. At the first assessment, many tree species pre-

Table 4
Ozone exposure for 2006 for the 13 sites assessed. Exposure is reported as AOT40, stomatal flux above a threshold of 1.6 nmol m^{-2} s^{-1}, mean concentration and peak concentration >100 ppb.

Country	Nursery	Accumulated stomatal ozone flux (AF_{st}). Calculated by DO_3SE model (mmol m^{-2})	AOT40 (ppm h)	Mean ozone concentration measured over monitoring period (ppb)	Peak concentration (number of hourly means >100 ppb) [maximum peak ppb]
United Kingdom	UK 1	13.0	15.4	32.6	23 [123]
	UK 2	11.3	4.6	33.6	225 [100]
	UK 3	10.4	1.9	28.9	0 [83]
	UK 4	8.8	5.4	28	0 [80]
	UK 5	16.0	9.3	34.5	107 [103]
Switzerland	CH 1	24.9	38.1	49.8	143 [165]
	CH 2	14.0	17.4	36.0	4 [104]
Spain	ES 1	24.9	20.0	41.6	873 [174]
	ES 2	7.8	1.2	24.1	24 [110]
	ES 3	15.7	12.7	32.6	565 [149]
Italy	IT1	18.4	18.1	43.3	47 [142]
	IT2	13.4	24.1	35.2	7 [105]
	IT3	23.6	36.4	40.5	5 [110]

sented ozone-like symptoms at all three nurseries. In most of these species, the observed symptoms were interpreted as natural accumulation of anthocyanins in response to the high irradiance typical of the Mediterranean climate during the summer. Nevertheless, these symptoms appeared earlier than expected on the basis of past observations. At the first assessment reddening on *Cornus sanguinea*, *C. mas*, *Prunus serotina*, *Crataegus oxyacantha*, *V. opulus* and *V. lantana* was observed, while bronzing was seen on *Populus nigra* and *C. avellana*. During the second assessment in late August, for *P. serotina*, *C. oxyacantha* and *Populus nigra*, some of the plants that were symptomatic at the previous assessment had lost their leaves prematurely. Pest and disease outbreaks prevented a valid second assessment being carried out for some species such as *Quercus robur*, *Laburnum anagyroides* and *Acer pseudoplatanus*. For other species, the leaf reddening observed at the first assessment increased in intensity and in the proportion of plants affected. The early onset of these 'symptoms' observed at the first assessment suggests a response to ozone pollution. In order to clarify these findings, a more comprehensive survey was carried out at site IT3, and symptoms were assessed in plants throughout the whole nursery. The results are summarised in Table 3.

Microscopic examination confirmed that *Fraxinus excelsior* (IT2), *Populus nigra* (IT2 & IT3), *A. pseudoplatanus* and *Rhamnus catharticus* (IT3) displayed the characteristic collapse of the palisade tissue cells, indicating a hypersensitive response of the palisade cells which is considered the clearest manifestation of ozone-induced stress. For *V. lantana* and *V. opulus* at sites IT2 & IT3 and *Cornus* spp. at all sites, ozone injury was not confirmed because microscopic symptoms consisted of non-specific accumulation of anthocyanins both in the mesophyll and in the epidermis.

3.2.3. Spain

At site ES1 *Prunus spinosa* (Fig. 2) and *Fraxinus ornus* showed visible injury. At site ES2 no visible ozone-induced injury was observed, while at site ES3, injury was observed on *V. lantana* (Fig. 3). Ozone-induced symptoms previously observed in fumigation experiments at the La Peira Open Top Chamber (OTC) facility (2005–2006) – see http://www.gva.es/ceam/ICP-forests/index.htm – were compared with ozone-like symptoms observed in the field to ascribe injury to ozone. In all cases symptoms first appeared in July and increased in severity during August. Symptoms were validated microscopically to confirm that ozone was likely to be the causative agent. Ozone damage was confirmed in *V. lantana* and *P. spinosa*, but not in *F. ornus*.

3.2.4. Switzerland

Plants were assessed three times during July, August and September at site CH1 and twice (August, September) at CH2. At both sites, ozone-induced injury was observed on many of the species assessed. At site CH1, damage was observed on *Prunus mahaleb*, *Populus nigra*, *Salix daphnoides*, *F. sylvatica*, *C. betulus*, *Ligustrum vulgare*, *Sambucus nigra* and *Viburnum opulus* from early August, increasing in severity over the following two months (Fig. 4).

At site CH2, *Betula pendula*, *Robinia pseudoacacia*, *C. avellana*, *R. catharticus*, *Ulmus glabra*, *P. serotina*, *F. sylvatica* and *Populus tremula* all showed signs of ozone injury in September. The most seriously affected species was *P. serotina*, confirming its position as a highly sensitive bioindicator of ozone pollution (Fig. 5). Symptoms were validated by comparison with the findings from open top chamber studies (VanderHeyden et al., 2001; Novak et al., 2003; Gravano et al., 2004) and of symptoms with photographic evidence from the literature (Innes et al., 2001; Schaub et al., 2002).

Full details of the results obtained in the study are given in Benham et al. (2007).

4. Discussion

Our study has shown that although ozone-induced symptoms are not serious, they were extensive across those commercial tree nurseries in Europe that were assessed. Positive records of ozone injury were reported for all three geographical regions in this study. This indicates that visible ozone injury is a widespread and reoccurring phenomenon. The timing of "natural" responses such as leaf reddening or senescence can be influenced by ozone exposure but can be difficult to interpret unambiguously.

Peak concentrations were highest in Spain (site ES1 and ES3) but injury was most extensive at site CH1 in Switzerland, where the highest mean ozone concentrations were monitored. This was also the site with the highest ozone exposure when expressed as AOT40 (see Table 4). Ozone-induced symptoms were least evident in the UK, which is in line with recorded exposures using all four indices. However, plants at the Spanish sites also expressed relatively low levels of ozone-induced injury although ozone exposure was significantly higher than in the UK. This corroborates the assertion of Karlsson et al. (2007) that the extent of ozone damage to vegetation in Europe is greater than would be expected using the original critical level for ozone of 10 ppm h.

In Spain and Italy, injury was greater at higher altitudes, reflecting higher ozone concentrations at higher elevations. In Spain, confirmed ozone injury was restricted to two species. Furthermore, injury was not observed at site ES2 (low altitude), where ozone exposure measured as mean concentration, AOT40 or AF_{st} was significantly lower than at the other two sites.

Within the limitations of the project design, the extent of injury correlated with ozone exposure expressed as both AOT40 and AF_{st} better than as mean or peak ozone concentration. Evidence from this study has shown the use of AF_{st} to be more accurate in predicting ozone damage than that of AOT40, particularly where less polluted air leads to higher night-time ozone concentration such as those seen in the UK in Central Scotland.

Injury was not detected at any site with an AOT40 of less than 12.7 ppm h (site ES3), with 13.7 mmol m^{-2} (site UK1) the minimum AF_{st} at which injury was observed. In both cases, these observations are compatible with the current critical load of 5 ppm h or 4 mmol m^{-2} (UNECE, 2007) which assumes that growth may be reduced below these levels, without visible injury.

5. Conclusion

The study demonstrates that the impacts of ozone are not restricted to Southern and Central Europe, where higher ozone concentrations are experienced. Longer day-length and greater moisture availability in Northwest Europe means that although ozone concentrations are lower enhanced stomatal uptake under these circumstances may lead to ozone-induced symptoms. Implementing a comprehensive assessment of ozone-induced injury in commercial tree nurseries as part of a bioindicator monitoring network could produce hard evidence for ozone-induced damage. Such evidence could have a role to play in communicating the impacts of ozone pollution, leading to acceptance of the need for, and the implementation of, emissions control policies. The importance of bioindicator networks in informing policy has been shown for other forms of vegetation recently (Hayes et al., 2007), and demonstrates that credible and trustworthy information can be obtained in this way.

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