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The Effects of Ozone Exposure on Natural and Semi-Natural Vegetation

Interim report to The Department of the Environment Transport and the Regions

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EXECUTIVE SUMMARY

Seasonal variation in ozone sensitivity of beech.
University of Lancaster, Prof. T. A. Mansfield, Dr N. D. Paul, Dr P. S. De Silva

- Ozone pollution early in the growing season (mid-May to mid July) significantly reduced the ability of beech to fix carbon, but comparable pollution later in the season (mid July- mid September) had no significant effect.

- Plants exposed to ozone throughout the growing season (mid May-mid September) were less able than unfumigated plants to fix carbon late in the season. However, carbon fixation late in the season was low compared with that in June and July, and its is not clear whether these late-season effects of ozone will have effects on plant growth.

- Measurements of plant growth will continue until plants become dormant (November) and conclusions concerning any effects of ozone on biomass production cannot be made until these measurements are completed.

- On the basis of data obtained to date, we tentatively suggest that calculation of AOT40 for ozone might be "weighted" to take account for the greater effects of pollution in late spring and early summer

Responses of wetland plant species to ozone
Imperial College London/University of Bradford, Prof. M.R. Ashmore, Dr S.A. Power and Dr K Batty

- Recognisable ozone injury was observed on eight of the 12 species, with the first signs of injury being recorded on *Viola cracca* following an ozone exposure of only 1,950 ppb.h.

- There was a general trend of reduced above- and below-ground biomass in ozone with *Mentha aquatica* being a notable exception.

- In general, below-ground biomass was more affected by ozone than above-ground, as is reflected in the lower root:shoot ratios in ten of the twelve species examined

- Exposure to ozone resulted in large and significant reductions in photosynthetic rate, at some stage of the experiment, for five species.

- The most striking aspect of the experimental results was the number of species (nine of the twelve studied) that were negatively affected by ozone in terms of either visible injury or detrimental effects on growth or physiology.

- There is evidence that factors which increase ozone flux into leaves will tend to increase the sensitivity of plants to a given ozone exposure. This suggests that wetland species with a higher stomatal conductance were more sensitive to ozone.

- The magnitude of biomass reductions observed for the most affected species is large (as high as 58% for *C. arvense* roots), given that the experimental AOT40 values of 10000-15000 ppb.h are within the range reported for the UK.

- The hypothesis that fen and fen meadow communities may be amongst the most sensitive semi-natural plant communities in the UK is confirmed.

Assessment of the relative sensitivity of wetland plant species to ozone
University of Newcastle, Prof. A. W. Davison, Ms H. Haley

- All species tested showed significant within-species differences in response to either acute and/or chronic ozone exposures.

- The population of *Cirsium arvense* obtained from Imperial College(John Chambers seeds) was shown to be more sensitive than other populations tested.

- There are no early indications of a systematic difference in stomatal conductance or index between wet- and dry-land species.

- There are differences in stomatal response to water stress and ozone between populations of *Epilobium hirsutum*

Continuous measurements of ozone dry deposition to wheat, sugar beet, and potatoes, using micrometeorological methods
Institute of Terrestrial Ecology, Prof. D. Fowler and Ms M. Coyle

- Substantial seasonal data sets, of total ozone flux, are available for sugar beat (1305 hours), wheat (1615 hours), oats (403 hours) and potato (2290 hours) crops.

- The data for wheat and sugar beat, show that the non-stomatal uptake of ozone represents > 50% of the total flux over the growing season, but the precision of estimates for the daily measurements is limited.

- Ozone deposition fluxes to potatoes provide estimates of the total seasonal flux to the crop.

- Analysis of the data for all crops is in progress to: quantify the stomatal and non-stomatal components of the total flux; show whether the variables associated with large evaporative demand and water stress are associated with the magnitude of the stomatal ozone flux.

THE SEASONAL VARIABILITY IN SENSITIVITY OF BEECH TO OZONE

(Ref C989 0005 D4 128 003)

Annual report for 1999

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EXECUTIVE SUMMARY

Critical levels of tropospheric ozone pollution are defined by the AOT40 (accumulated exposure over a threshold concentration of 40ppb ozone), calculated using total ozone from 1st April to 30th September. This project aims to determine whether the response of beech trees to ozone varies with the timing of ozone pollution and, hence, whether AOT40 might be refined by taking account of any seasonal variation in ozone sensitivity.

- Ozone pollution early in the growing season (mid-May to mid July) significantly reduced the ability of beech to fix carbon, but comparable pollution later in the season (mid July- mid September) had no significant effect.
- Plants exposed to ozone throughout the growing season (mid May-mid September) were less able than unfumigated plants to fix carbon late in the season. However, carbon fixation late in the season was low compared with that in June and July, and its is not clear whether these late-season effects of ozone will have effects on plant growth.
- Measurements of plant growth will continue until plants become dormant (November) and conclusions concerning any effects of ozone on biomass production cannot be made until these measurements are completed.
- On the basis of data obtained to date, we tentatively suggest that calculation of AOT40 for ozone might be "weighted" to take account for the greater effects of pollution in late spring and early summer

Abstract

Two year old saplings of beech (*Fagus sylvatica*) grown in Solardome glasshouses were exposed to ozone treatments early in the growing season (mid-May to mid July) and/or late in the season (mid July- mid September). Responses were quantified using *in situ* gas analysis, and destructive harvests for plant morphology and biomass. Ozone pollution early in the season (May-July) significantly reduced net photosynthesis, transpiration and stomatal conductance in beech but comparable pollution later in the season (July-September) had no significant effects. The mechanism of this response is not yet known, but seems likely to reflect a direct effect of ozone on stomata. The early season response occurs at cumulative ozone concentrations well below the current critical AOT40 of 10 ppmh. In plants exposed to ozone throughout the season, photosynthesis during August and September was significantly inhibited compared with controls. This response was associated with a significant increase in internal CO_2 concentration, but not with any change in stomatal conductance. However, photosynthetic rates late in the season were low compared with those in June and July, suggesting that the significant reduction in late-season carbon fixation due to long-term ozone fumigation may not have major effects on biomass production. Although confirmation in terms of biomass data is required, these gas exchange data suggest that the current critical level criteria might be improved by "weighting" ozone episodes according to season, with greater weight being given to episodes early in the year.

1. Introduction

The concept of critical levels for tropospheric ozone has been substantially refined over the past ten years. The recognition that potential ozone damage to plants is best described by the cumulative ozone concentration above a defined threshold has led to the adoption of AOT40 (accumulated exposure over a threshold concentration of 40ppb ozone) as a standard measure of ozone pollution. The critical AOT40 for forest trees is set at 10 ppmh for daylight hours over a six month growing period based on an expected response of a 10% reduction in biomass (Anon, 1997). However, it is recognised that the current definition of critical levels is limited since it does not account for the differences between species, or take account of interactions between ozone and other environmental factors, such as soil moisture content, temperature or humidity (Broadmeadow, 1998). Such environmental factors may affect the uptake and/or physiological effects of ozone, and hence modify the damage that is caused. A further constraint on current critical levels is that the effects of cumulative ozone dose are assumed to be independent of plant developmental age or time of year. However, there are a number of reports that suggest that plant responses to ozone are significantly affected by the timing of ozone episodes (e.g. Hawes, 1998; Reich, 1983; Pääkkönen *et al.*, 1995a and 1995b). Studies of beech (*Fagus sylvatica*) conducted at Lancaster under a previous NERC/DETR contract showed that response varied with season. Beech saplings exposed to ozone in late spring-early summer showed significant reductions in net photosynthesis, transpiration and stomatal conductance, but no such responses occurred in saplings exposed in mid-summer (Hawes, 1998). The aim of the current contract is to corroborate and refine these observations and hence to establish whether the response of beech to a given AOT40 varies with the timing of ozone episodes.

2. Preliminary studies

Since funding in 1998 was not confirmed until mid-summer it was not possible to complete a full programme of research during the 1998 growing season. However, resources allowed a preliminary study designed to clarify the pattern of growth of beech saplings over the course of a season. The increase in total plant dry weight with time was broadly log-linear over the season April-October (Figure 2.1a). However, leaf expansion was largely completed by June-July, with only a small additional increase attributable to "lammas growth" later in the season (Figure 2.1b). By contrast, root growth was minimal prior to July, but rapid from July until the end of growth (Figure 2.1b). This demonstration that leaf and root growth were temporally separate provided a useful context for the "early" and "late" ozone treatments used previously (Hawes, 1998). In that experiment the early treatment ozone was provided during a period of rapidly increasing leaf area and rapidly decreasing root:shoot ratio (Figure 2.1c). By contrast, in the late ozone treatment leaf expansion was minimal but root growth was rapid and root:shoot ratio increased substantially (Figure 2.1c). This also relates to one possible mechanism for seasonal variation in ozone response i.e. that ozone early in the season creates an imbalance between water loss (transpiration from the rapidly expanding foliage) and water uptake (by a limited root system). Thus, one priority of the experiment during 1999 was to complement gas exchange data with measurements of root growth and hydraulic conductivity.

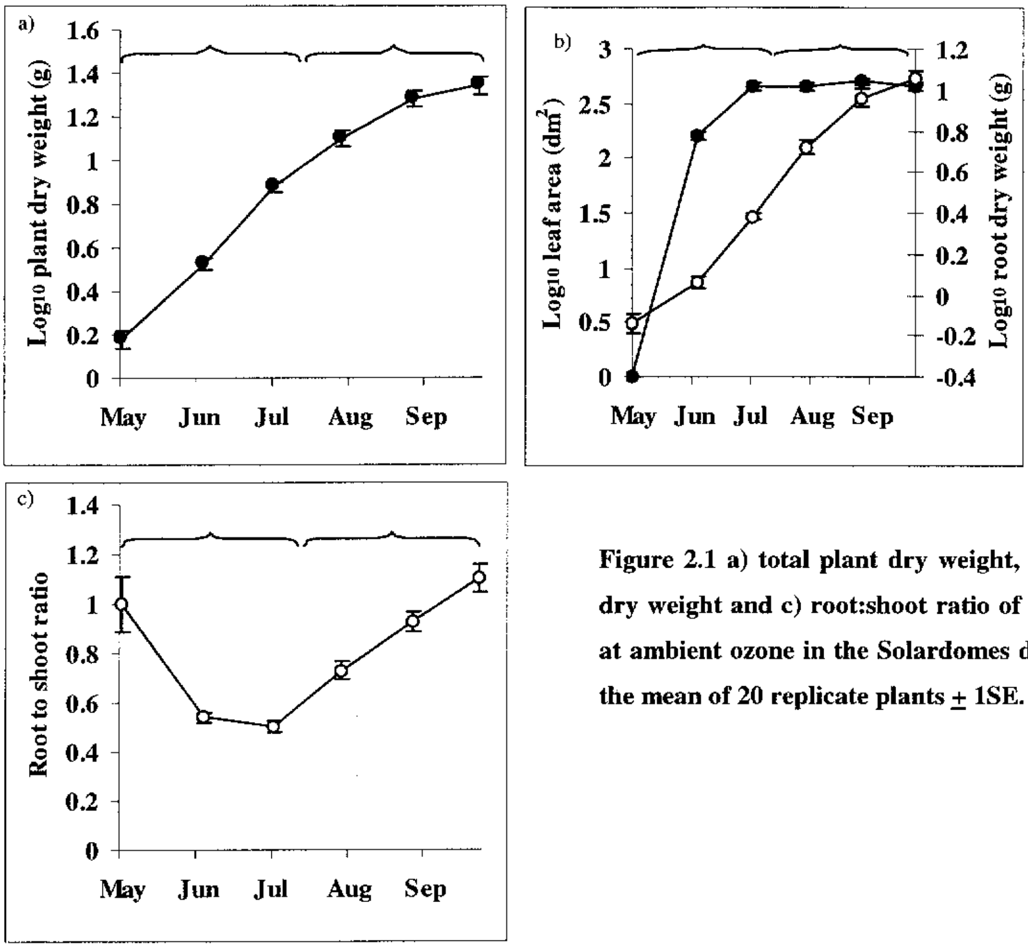


Figure 2.1 a) total plant dry weight, b) leaf area and root dry weight and c) root:shoot ratio of beech saplings grown at ambient ozone in the Solardomes during 1998 Data are the mean of 20 replicate plants ± 1SE.

3. Materials and Methods

The experiment was carried-out using four Solardome glasshouses (Rosedale Engineering, Filey, UK), as described before (Lucas *et al.*, 1987). At any time ozone was supplied to two of the four Solardomes, Strictly, since ozone treatments were imposed on Solardomes, not plants, there were two true replicates (Solardomes) per treatment. Analysis of the growth of beech in 1998, when no ozone treatment was imposed, showed no significant between-dome variation (data not presented). However, to minimise the effect of any remaining "between dome" differences, ambient and ozone treatments were re-allocated between domes at intervals throughout the study period (Table 2.1). Clearly, plants of a particular treatment were moved between domes and, at the same time, plants within treatments were re-randomised between and within domes.

	Treatment			
Date	**Control 1**	**Control 2**	**Ozone 1**	**Ozone 2**
11/05/99	Dome 5	Dome 8	Dome 7	Dome 6
14/06/99	Dome 6	Dome 5	Dome 8	Dome 7
19/07/99	Dome 7	Dome 6	Dome 5	Dome 8
17/08/99	Dome 8	Dome 7	Dome 6	Dome 5

Table 2.1
Assigned of treatments to the four Solardomes over the course of the experiment.

3.1 Ozone treatments

Ozone treatments commenced on May 16th 1999 and continued until 19th September 1999. This was divided in to two periods of nine weeks: "Early" (16th May –18th July) and "Late" (19th July – 19th September), and plants were exposed to ozone according to a fully factorial design, i.e.:

No ozone:	"Control"
Early ozone only	"Early ozone"
Late ozone only	"Late ozone"
Early and late ozone	"Continuous ozone"

Within each period, ozone was provided as a defined series of episodes, each of which lasted one week. Within each episode peak daily ozone concentration was increased from the Monday to Wednesday, then decreased to Friday. No ozone was added on Saturday or Sundays. Peak ozone concentration was 60, 80, or 120 ppm ozone, based on the range of ozone treatments provided in previous seasons. However, ozone treatments given during previous experiments with beech were based on prevailing weather conditions (e.g. Hawes, 1998). Clearly, coupling treatment to weather would not necessarily produce comparable "Early" and "Late" treatments (see Hawes, 1998 for example), so in this experiment ozone treatments were independent of weather. The target ozone episodes were designed to give an AOT40 of 8.4 ppmh, just below the accepted threshold for damage. Clearly, the "Continuous ozone" treatment provided an AOT40 of 16.8 ppmh, well above the critical limit. Control plants received unfiltered air.

3.2 Ozone generation and control

Ozone was generated using an ozone generator (Ozonia CFS-1) supplied with compressed dried air. Ozone was passed through water to remove impurities, in particular N_2O_5 (Bytnerowicz *et al.*, 1995) before being added to the Solardome air supply. Ozone concentration was monitored using a PC based data acquisition and control systems (Lancaster Data Analysis System Version 1.5.2-B6: LanDACS) and the desired concentration was maintained by regular adjustment of the voltage supplied to the ozone generator. LanDACS was also used record temperature, humidity and solar radiation in the domes.

3.3 Plant material

Three hundred two year old, similar sized beech trees (*Fagus sylvatica* L.), planted in 10 litre polythene pots using a mixture of sterilized loam, grit and peat (5:3:3 by volume) to which slow release fertiliser (Osmocote: 16:8:12 NPK) was added at 1.8g per 100 l compost. The final compost was in the range pH 5-6. In early May, the trees were allocated randomly between the four ozone treatments (see above) and placed in the Solardomes. The plants were watered two-three times a day, using an automatic dripper system, controlled by a timer.

3.4 Gas exchange

Leaf gas exchanges in forty marked trees, ten per ozone treatment, were measured at intervals of approximately one week (excluding a two week break in late August). The youngest fully expanded leaf of the leading shoot was selected on 10-12th May 1999, and marked by loosely tying a loop of 1 mm electrical wire around the leaf petiole. Gas exchanges were measured using a portable infrared gas analysis system and Parkinson leaf cuvette (CIRAS-1, PP Systems, Hitchin, Hertfordshire). All gas exchanges measurements were made with CO_2 concentration within the leaf cuvette set at 360 ppm ± 10) and PAR (provided by the CIRAS cuvette illumination system) set at 1500 μmole m^{-2} s^{-1}. It was not possible to measure all trees in one day. Therefore, each week measurements were made on successive days. Twenty plants selected at random from all treatments and Solardomes, were recorded on the first day, and remaining plants were on the following day. All measurements were made between the hours of 10.00 and 13.00 BST. Data for net photosynthetic rate (A), internal CO_2 concentration (c_i), transpiration rate (E) and stomatal conductance (G) were recorded.

3.5 Destructive harvests

Trees were harvested at intervals throughout the season. Each harvest included twenty trees per treatment, ten from each of the two domes that provided ambient or elevated ozone. At harvest, all leaves were removed and total leaf area measured before drying to constant weight at 80°C. The root system was excised at soil level, washed and divided into fine and coarse roots. The total lengths of these two root fractions were measured. In half of the trees, a small sub-sample of fine roots were taken for estimation of root hydraulic conductance. Remaining roots were then dried at

80°C. The stem was oven dried at 80°C. The dry weights of all components were recorded, and used for growth analysis.

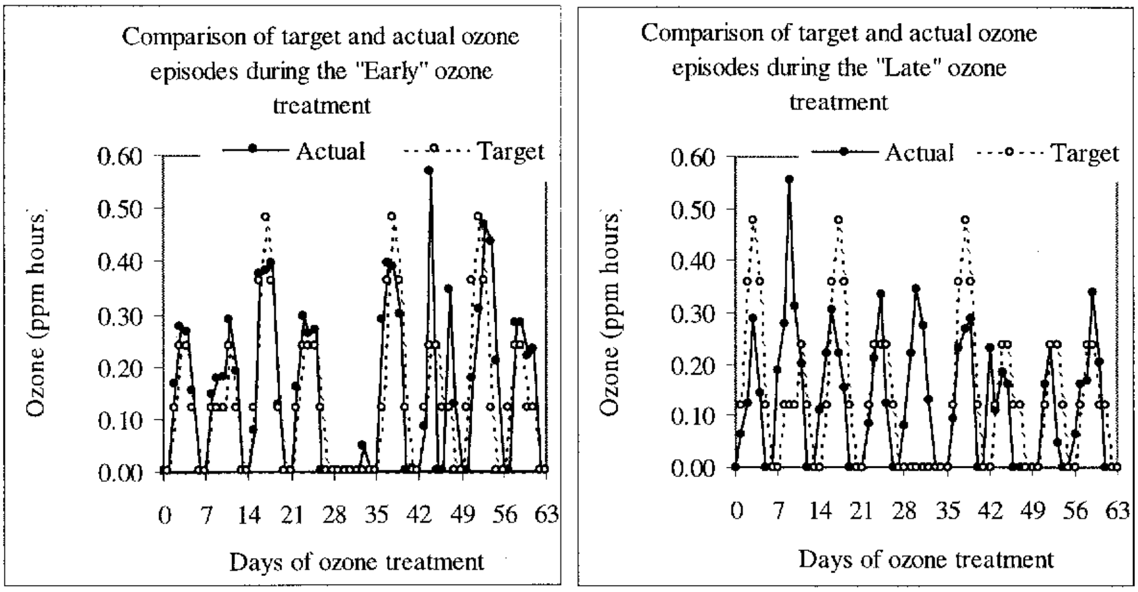
3.6 Statistical Analysis

As noted above, ozone treatments were re-randomised between Solardomes, and trees between Solardomes within treatment, allowing plants to be treated as replicates. On this basis there were 20 per treatment (10 trees per dome with two domes) at each harvest date for destructive harvests, and ten trees per treatment (5 per dome) for gas analysis. Statistical analysis was carried out using a range of analyses of variance (ANOVA). For leaf gas exchange data, the major data set presented here, time was treated as a repeated measure.

4. Results

4.1 Ozone Pollution Regime

In terms of the planned series of ozone episodes, the treatment provided during the early period was generally close to the target (Figure 4.1a). During the "late ozone" treatment (Figure 4.1b, there was greater deviation from the intended pattern of exposure, due to sporadic problems with the ozone generator, which led to periods when treatments were adjusted to compensate for earlier problems. The maximum ozone concentration was 121 ppb in the early part of the season, and 133 ppb in the late period. In comparison with the target AOT40s (8.4 ppmh for both early and late ozone), the actual ozone treatment provided slightly more ozone: AOT40 was 9.3 ppmh for the "Early ozone" treatment and 9.0 ppmh for the "Late ozone" treatment (Figure 4.2). The total AOT40 for the continuous ozone treatment was 18.3ppmh (compared with the target of 16.8 ppmh).



Comparison of target and actual ozone episodes during the "Early" ozone treatment

Comparison of target and actual ozone episodes during the "Late" ozone treatment

Figure 4.1 **Ozone episodes over the study period**

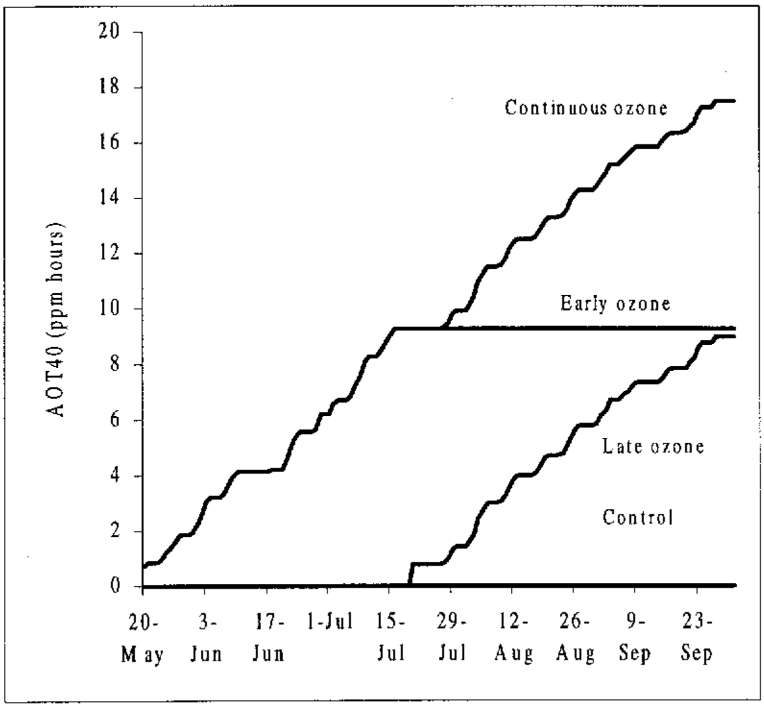


Figure 4.2 **Cumulative ozone concentration across the four treatments provided during 1999, expressed as AOT40s.**

4.2 Gas exchanges

4.2.1 Responses during "early ozone" treatment, prior to "cross-over" (16th May – 18th July)

Net photosynthesis increased over the initial period of exposure in both control and fumigated trees (significant effect of time, $p< 0.001$, no significant time x treatment interaction). The main effect of ozone treatment was also significant ($p<0.01$), since net photosynthesis was consistently lower in fumigated and control trees (Figure 4.3). The magnitude of this reduction in net photosynthesis varied (2-29% compared with controls), and there was a tendency for the greatest effects to occur early in the course of ozone treatment. For example, photosynthesis was 15% lower in fumigated than control trees after one week of ozone fumigation. Changes in stomatal conductance during "early ozone" (Figure 4.4) were broadly similar to those in photosynthesis. Thus, conductance increased with time, independent of treatment (main effect of time significant at $p<0.001$, no significant time x treatment interaction) and was significantly ($p<0.01$) lower in ozone treated than control trees. Despite the significant main effect of fumigation, the effects of ozone on conductance varied markedly from week to week, but it was notable that a large response occurred within one-two weeks of treatment.

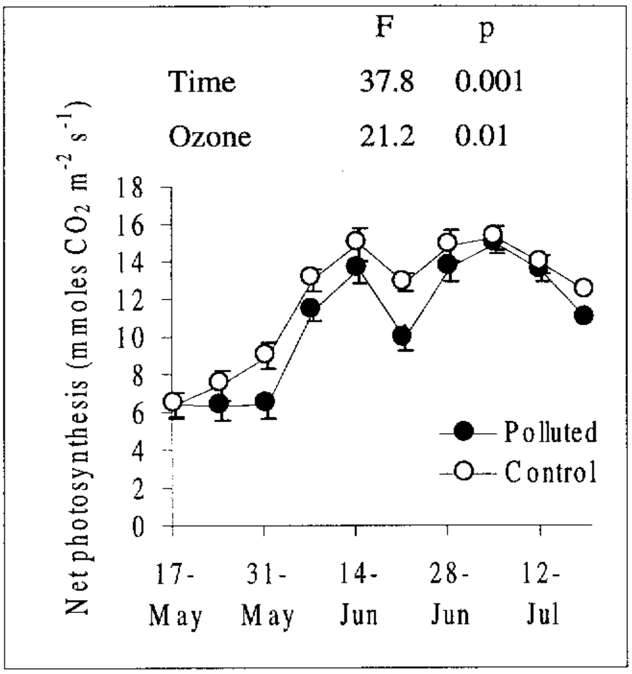


Figure 4.3 Net photosynthesis during the "Early ozone" period (16th May – 18th July) in control (open symbols) and ozone-fumigated plants (filled symbols). Data are the mean of 40 replicate plants ± 1SE. The results of two-way ANOVA (time x ozone treatment, with time treated by repeated measures) are summarised.

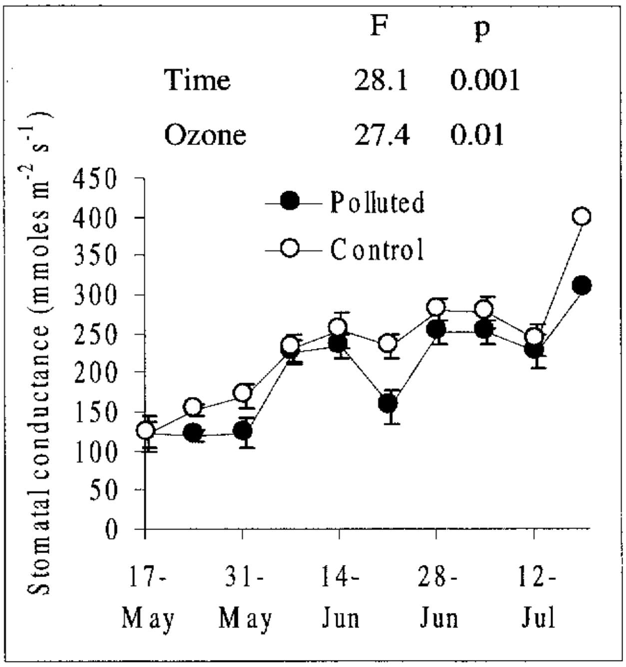


Figure 4.4 Stomatal conductance during the "Early ozone" period (16th May – 18th July) in control (open symbols) and ozone-fumigated plants (filled symbols). Data are the mean of 40 replicate plants ± 1SE. The results of two-way ANOVA (time x ozone treatment, with time treated by repeated measures) are summarised.

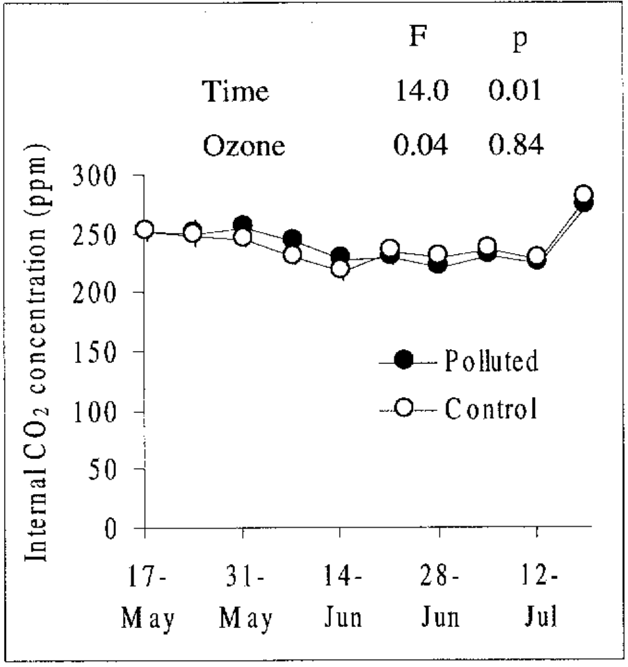


Figure 4.5 Internal CO_2 concentration during the "Early ozone" period (16th May – 18th July) in control (open symbols) and ozone-fumigated plants (filled symbols). Data are the mean of 40 replicate plants ± 1SE. The results of two-way ANOVA (time x ozone treatment, with time treated by repeated measures) are summarised.

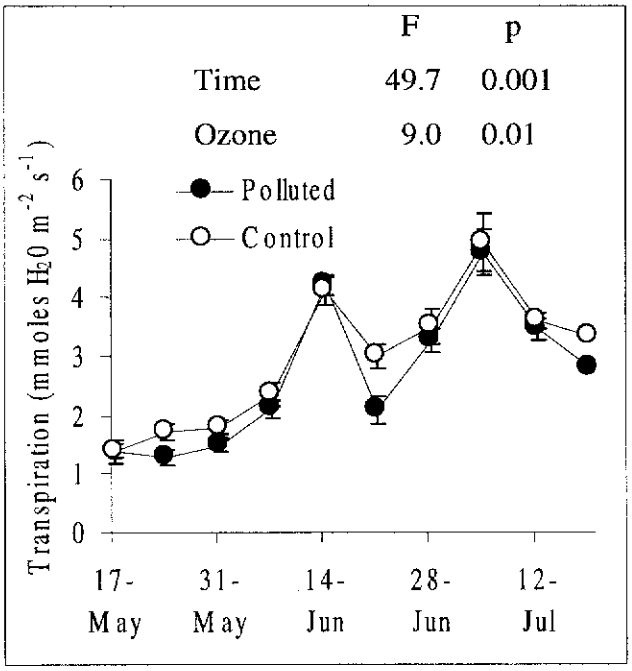
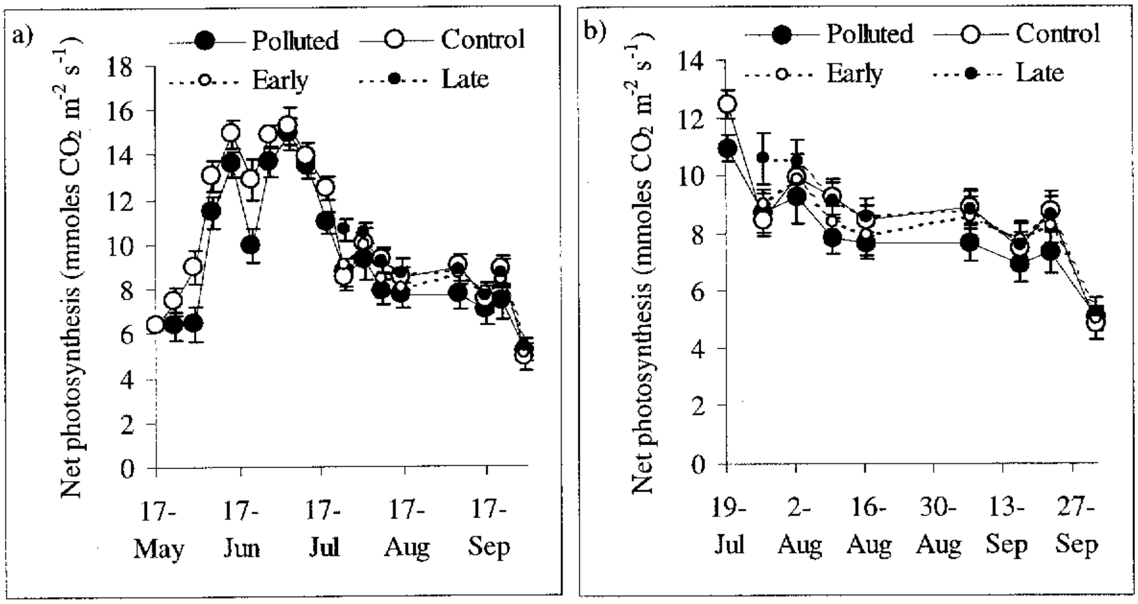


Figure 4.6 Transpiration rate during the "Early ozone" period (16th May – 18th July) in control (open symbols) and ozone-fumigated plants (filled symbols). Data are the mean of 40 replicate plants ± 1SE.The results of two-way ANOVA (time x ozone treatment, with time treated by repeated measures) are summarised.

By contrast with photosynthesis and stomatal conductance, internal CO_2 concentration (Ci) was not significantly affected by ozone fumigation, nor was there a significant ozone x time interaction (Figure 4.5). The main effect of time of internal CO_2 concentration was significant ($p<0.01$), reflecting a gradual decline in Ci until late June, followed by an increase for the remainder of this early part of the season. Transpiration rate fluctuated during the early part of the season (main effect of time significant at $p<0.001$, no significant time x treatment interaction) but, in broad terms, tended to increase with time between mid-May and mid July (Figure 4.6). The transpiration rate of ozone-fumigated trees was significantly lower than that of controls (main effect of treatment: $p<0.01$) although the magnitude of this effect varied, with minimal differences between treatments at some sample dates (Figure 4.6).

4.2.2 Responses during following the "cross-over" (19th July-)

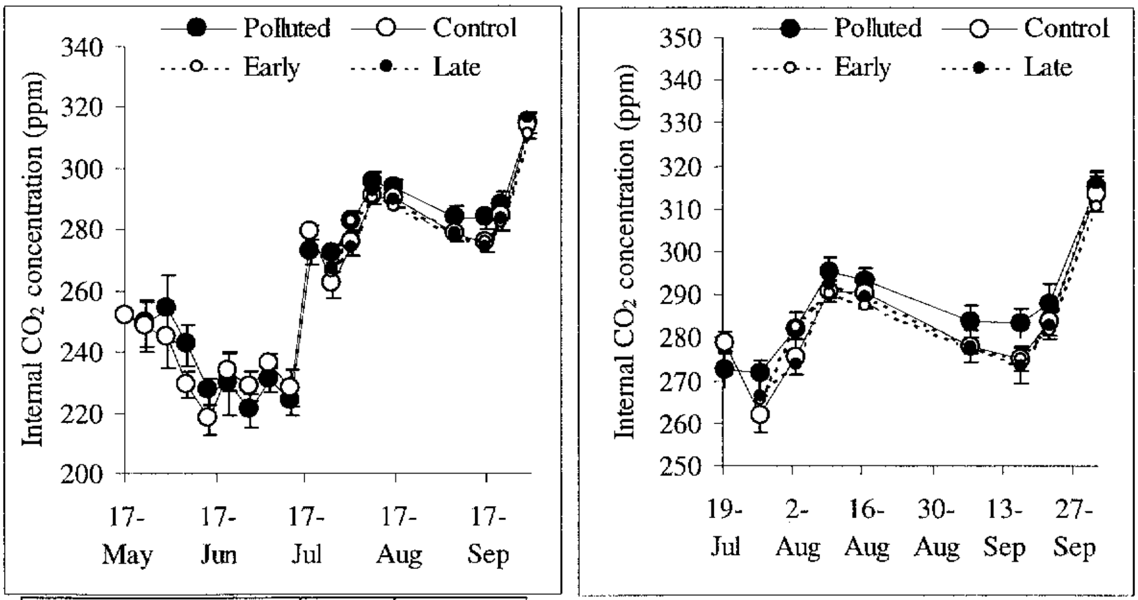


Source	F	p
Time	26.2	<0.001
Early ozone	5.7	0.02
Late ozone	0.69	0.41
Early x late ozone	5.4	0.03

Figure 4.7 Net photosynthesis following the "cross-over" between early and late ozone treatments (19th July). Data are the mean of 10 replicate plants ± 1SE. Summary table of the results of three-way ANOVA (early ozone x late ozone x time, with time treated by repeated measures). Only significant terms are shown.

The decline in photosynthesis apparent in all plants during the latter part of the "early" part of the season continued throughout the "late" period (Figure 4.7a). The main effect of time during the late period was significant ($p<0.001$) but there were no significant interactions between time and the effects of ozone treatments. "Late ozone" had no significant effect on net photosynthesis and while the effect of "early ozone" was significant ($p<0.05$) there was also a significant interaction between early and late ozone ($p<0.05$). This significant interaction occurred since the only consistent effect of ozone treatments on net photosynthesis was a reduction in plants that had been fumigated during both the early and late treatments (Figure 4.7b). Net photosynthesis in plants that had been exposed to ozone only during the "early" period was not significantly different from that in controls.

The significant decline in photosynthesis during the latter part of the season was associated with a significant increase in internal CO_2 concentration (main effect of time significant at $p<0.001$: Figure 4.8a). There were no significant interactions between the effects of time and those of ozone treatments. However, the main effects of both "early ozone" and "late ozone" treatments, and their interaction were all significant ($p<0.05$, $p<0.05$, and $p<0.01$ respectively). These ANOVA results were a function of a small but significant increase in Ci in plants that had been exposed to ozone throughout the season (Figure 4.8b). By contrast Ci in plants exposed to ozone only during the "early" or "late" periods was not significantly different from that in controls. Although the main effects of time on stomatal conductance was statistically significant ($p<0.001$) there was no systemic change after the transient high conductance observed at the time of cross-over in mid-July (Figure 4.9a). Conductance was in the range 200-300 mmole m^{-2} s^{-1} in all treatments and there were no significant effects of "early" or "late" ozone treatments (Figure 4.9b). As in the early part of the season, transpiration after cross-over fluctuated markedly (Figure 4.10a). The only factor to significantly affect transpiration in the post cross-over period was time (main effect of time significant at $p<0.001$, all other factors and interaction $p>0.05$).



Source	F	p
Time	51.4	<0.001
Early ozone	5.6	0.023
Late ozone	6.42	0.016
Early x late ozone	9.16	0.005

Figure 4.8 Internal CO_2 concentration following the "cross-over" between early and late ozone treatments (19th July). Data are the mean of 10 replicate plants ± 1SE. Summary table of the results of three-way ANOVA (early ozone x late ozone x time, with time treated by repeated measures). Only significant terms are shown.

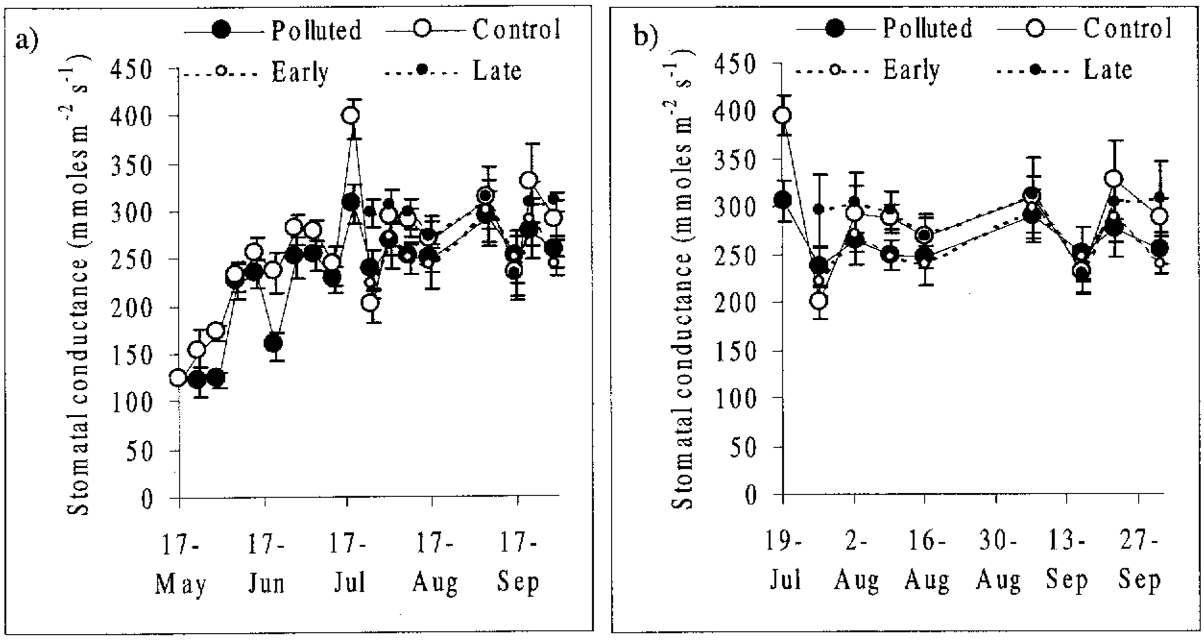


Figure 4.9 Net photosynthesis following the "cross-over" between early and late ozone treatments (19th July). Data are the mean of 10 replicate plants ± 1SE. Three-way ANOVA (early ozone x late ozone x time, with time treated by repeated measures) showed that the only significant factor affecting stomatal conductance during the "late period" was time ($p<0.001$).

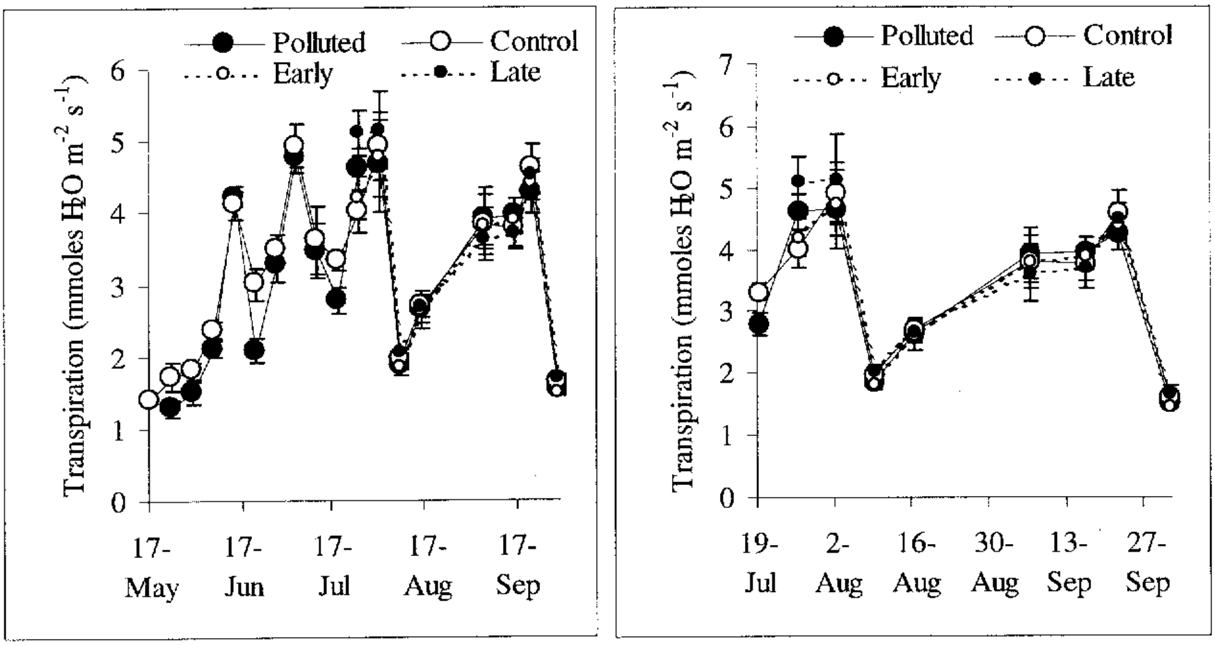


Figure 4.10 Transpiration rate following the "cross-over" between early and late ozone treatments (19th July). Data are the mean of 10 replicate plants ± 1SE.

Three-way ANOVA (early ozone x late ozone x time, with time treated by repeated measures) showed that the only significant factor affecting stomatal conductance during the "late period" was time ($p<0.001$).

4.3 Destructive harvests

Note. At the time of preparing this annual report, four of the six destructive harvests have been completed and the data fully analysed. The fifth harvest has just been completed, and some data are will be considered here, but analysis is not yet complete. The final harvest will take place once leaf senescence is complete, and plants are in their overwintering state, typically early November.

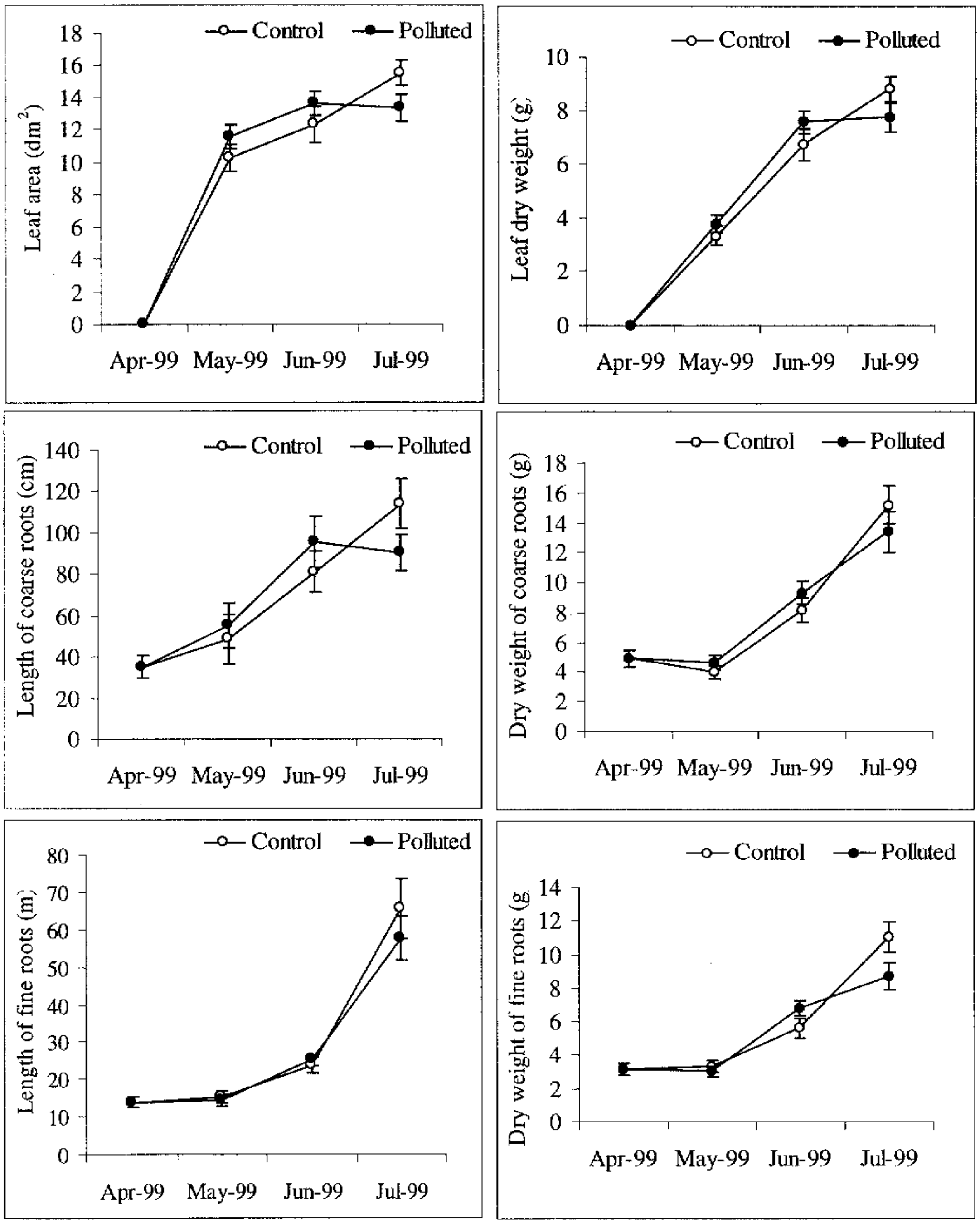
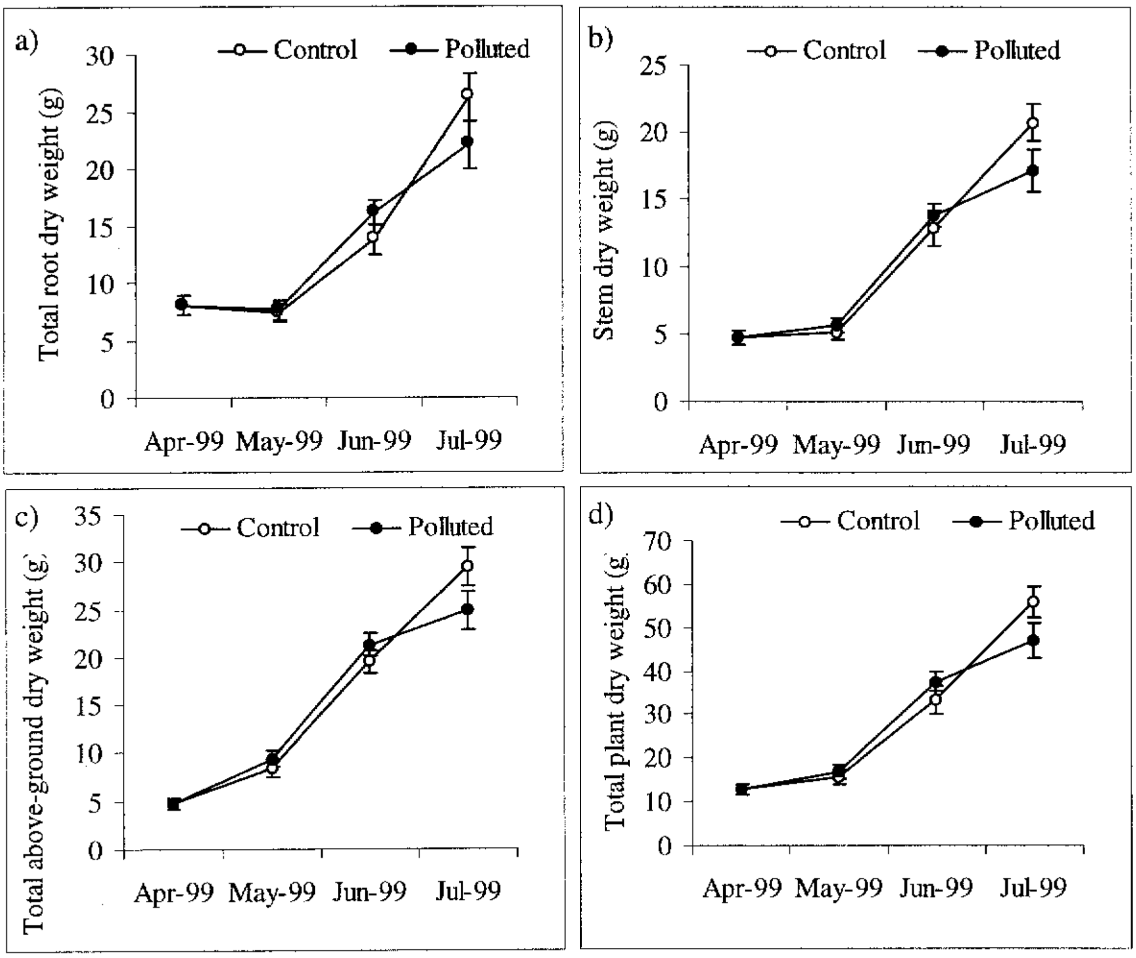


Figure 4.11 Area and dry weight of leaves, length and dry weight of coarse and fine roots of beech saplings exposed to ambient ozone (open symbols) or elevated ozone concentrations (filled symbols). Data are the mean of 20 replicate plants ± 1SE.

From the time of bud-burst (mid-late April) leaf expansion was rapid until mid-May, but then slowed substantially (Figure 4.11a). By contrast, leaf dry weight increased progressively between April and June and into July in control plants (Figure 4.11b). Unlike the initial flush of leaf growth, no significant root growth occurred until May, but after this time both root length and root weight increased rapidly (Figure 4.11c-f, Figure 4.12a). Root:shoot ratio declined rapidly from approx. 1.7 at the start of growth, to 0.75 in June (data not presented). The hydraulic conductivity of fine roots increased after May, perhaps reflecting the production of new roots, but was not significantly affected by ozone fumigation (data not presented) Stem dry weight (Figure 4.12b) increased significantly only after May.

Figure 4.12 a) total root dry weight, b) stem dry weight, c) total above ground dry weight and d) total plant dry weight of beech saplings exposed to ambient ozone (open symbols) or elevated ozone concentrations (filled symbols).



Data are the mean of 20 replicate plants + 1SE.

There were no significant effects of the "early ozone" treatment on any measured dry weight component, leaf area or root length at any harvest between May and July. However, it was noticeable that at the July harvest there was a consistent tendency for fumigated plants to be smaller than controls (Figure 3.11 and 3.12). Reductions were as great as 20% (fine root dry weight) and some approached formal statistical significance (e.g. $p=0.056$ for fine root dry weight, and $p<0.1$ for leaf area, stem dry weight, total above ground dry weight and total plant dry weight). This trend for reduced biomass in at the July harvest reflected a marked inhibition of growth in fumigated plants between June and July. Relative growth rates for this period were 7.3 ± 0.9 mg g^{-1} d^{-1} and 2.2 ± 0.5 mg g^{-1} d^{-1} for control and ozone treated plants respectively; while for the entire April-July period comparable data were 7.1 ± 0.4 and 6.2 ± 0.3 (a reduction of 14%).

4.4 Other measurements.

Plant water use has been measured continuously using sap-flow gauges from the time of bud-burst, and will continue until leaf senescence is complete. This is an extremely large data set that will be analysed in detail over the winter. However, initial inspection of the data suggests that water use is reduced in fumigated plants early in the season, consistent with the *in situ* gas exchange measurements.

5. Discussion

In the early part of the season exposure to environmentally relevant ozone concentration resulted in a significant reduction in net photosynthesis within seven days (Figure 4.3). This response occurs at a very low cumulative ozone dose (AOT40 < 1ppmh) and persisted throughout the "early ozone" treatment (mean reduction 13 ± 2%), although there was a tendency for the magnitude of the reduction to decline with time (Figures 4.3 and 5.1a). However, there was little evidence that this effect persisted in plants that were removed from ozone treatment since "early ozone" treatment had no significant effect on conductance after the cross-over (Figure 4.7). This rapid response to ozone did not occur in plants exposed when their leaves were fully expanded: the mean reduction in stomatal conductance due to the "late ozone" treatment was 3 ± 2% (Figure 5.1a). With "early ozone" the rapid decrease in photosynthesis in the first 1-2 weeks of exposure was associated were significant decreases in stomatal conductance (Figures 4.4 and 5.1b) but internal CO_2 concentration was not significantly affected by ozone during this period (Figures 3.5 and 5.1c). Thus, it seems likely that the observed reduction in photosynthesis was the result of ozone induced stomatal closure.

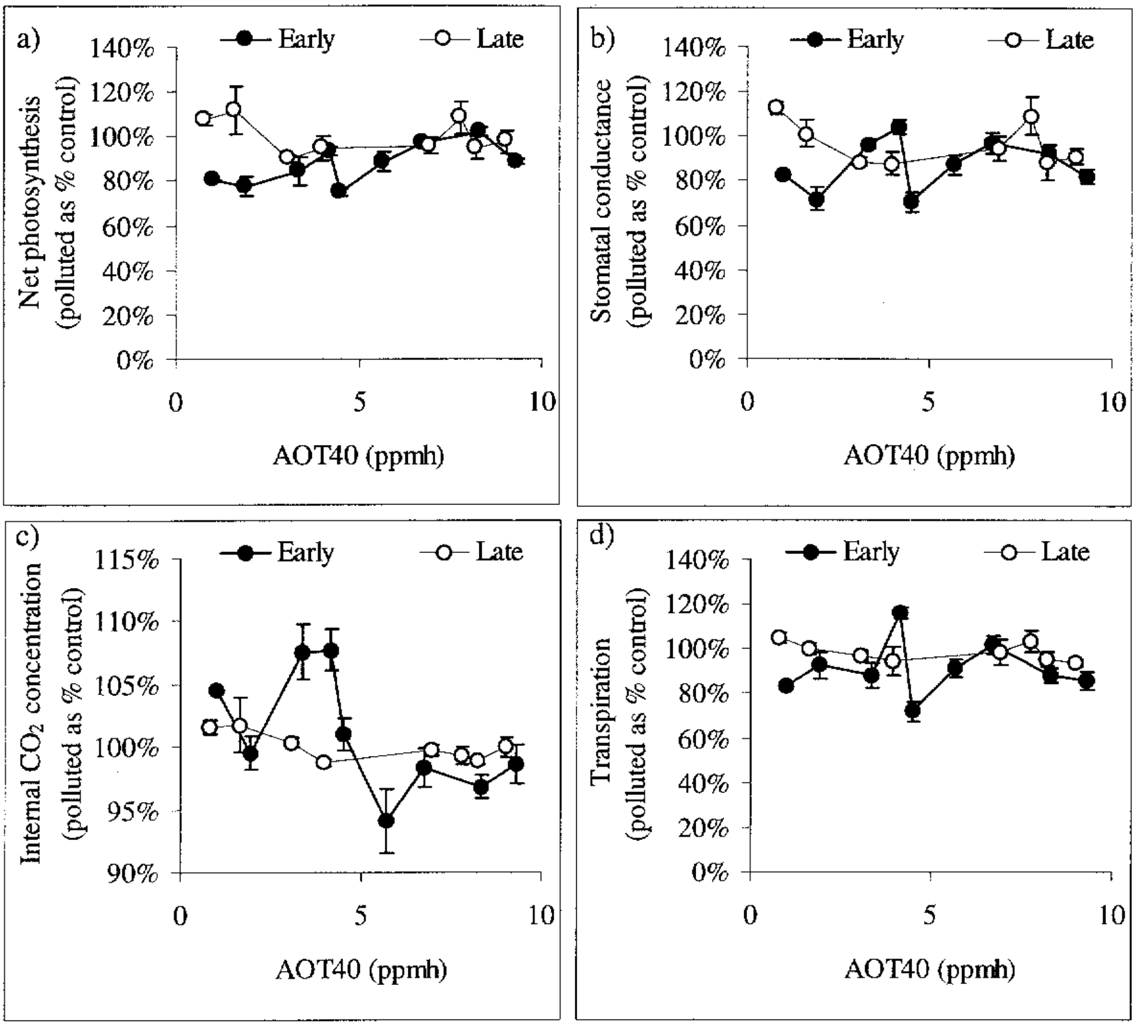


Figure 5.1 Contrasting effects of ozone on a) net photosynthesis, b) stomatal conductance, c) internal CO_2 concentration and d) transpiration in plants exposed to ozone either from May-July ("early") or July-September ("late"). Data ozone fumigated plants are expressed as a percentage of control values.

This detailed programme of gas exchange measurement carried out during 1999 confirmed the initial observation of Hawes (1998) that ozone treatment had greater effects on leaf gas exchange early in the season. It remains unclear whether the contrasting response of beech to early and late ozone is a function of plant developmental age or the environmental conditions that occurred during the two periods. Although detailed assessment of the environmental records is not yet complete, it generally appeared that conditions were typically warmer during the "late" period than the "early" period. Thus, it remains possible that environmental differences contributed to the observed difference in response. On the other hand, changes in ozone sensitivity during development might result from the contrasting morphology of plants during the early and late periods (Figure 2.1, 4.11, and 4.12), and/or alterations in the direct effect of ozone on stomata. Since there was no evidence that ozone influenced root:shoot ratio or root hydraulic conductivity during the "early ozone" treatment, a direct effect on stomata seems most likely, and is consistent with previous studies (Dobson et al., 1990; Pearson & Mansfield, 1993; Thiec et al., 1994).

While plants that were exposed to ozone only during the late period showed no significant physiological responses, marked effects occurred in trees that were fumigated during both the "early" and "late" treatments . In these trees there was a progressive reduction in photosynthesis compared with control plants from late July (Figure 4.7). After this time photosynthesis in fumigated plants declined to around 80% of that in control plants for the remainder of the season (Figure 5.2a). It was notable that this "long-term" effect on photosynthesis occurred above a threshold AOT40 of approx. 10ppmh, i.e. close to the accepted limit for marked ozone effects on biomass production. This photosynthetic response was not correlated with any effect of ozone on stomatal conductance, which was not significantly different in control and ozone fumigated plants during this period (Figures 4.9 and 5.2b). However internal CO_2 concentration was slightly but significantly increased in fumigated plants (Figures 4.8 and 5.2c), suggesting that the long-term effect of ozone on photosynthesis in beech is the result of changes in the inherent capacity of leaf tissues to fix carbon. Although the underlying mechanism(s) of this response remains unclear, it may be consistent with a more rapid onset of senescence in fumigated trees, which is a common response to ozone in many species, including beech (Braun & Fluckiger, 1994; Krause & Hockel, 1995; Langebartels *et al.*, 1997).

Since the full programme of destructive harvests will not be completed until later in the autumn, it is not yet possible to state whether the observed changes in photosynthesis per unit leaf area is reflected in reduced biomass in ozone-fumigated trees. However, in the most recent harvest to have been fully analysed (mid-July: AOT40 = 9.6 ppmh) total plant dry weight in plants exposed to "early ozone" was approx. 10% less than that of controls (Figure 4.12). Although not significant (p=0.11) this reductions in biomass is comparable in magnitude to the reduction in cumulative photosynthesis between May and mid July, also around 10%. Since rates of photosynthesis during May-July were substantially greater than those observed later in the season (Figure 4.7), reductions due to "early ozone" might have long-term effects on total biomass gain over the whole season, even though photosynthesis later in the season was not significantly affected by previous exposure to ozone (Figure 4.7). The progressive decline in the rate of photosynthesis later in the season (Figure 4.7) may have wider implications. On the basis of photosynthesis measured between mid-May and mid-October, approximately 65% of the potential cumulative carbon fixation occurred before mid-July. This pattern is clearly subject to modification by changes in environmental conditions, notably PAR, over the course of the season. However, at least on the basis of potential photosynthesis, the reduction in late-season photosynthesis in plants exposed to both early and late ozone, although marked and significant, may not result in large effects on biomass production. Although caution is required in extrapolating from *in situ* gas exchanges

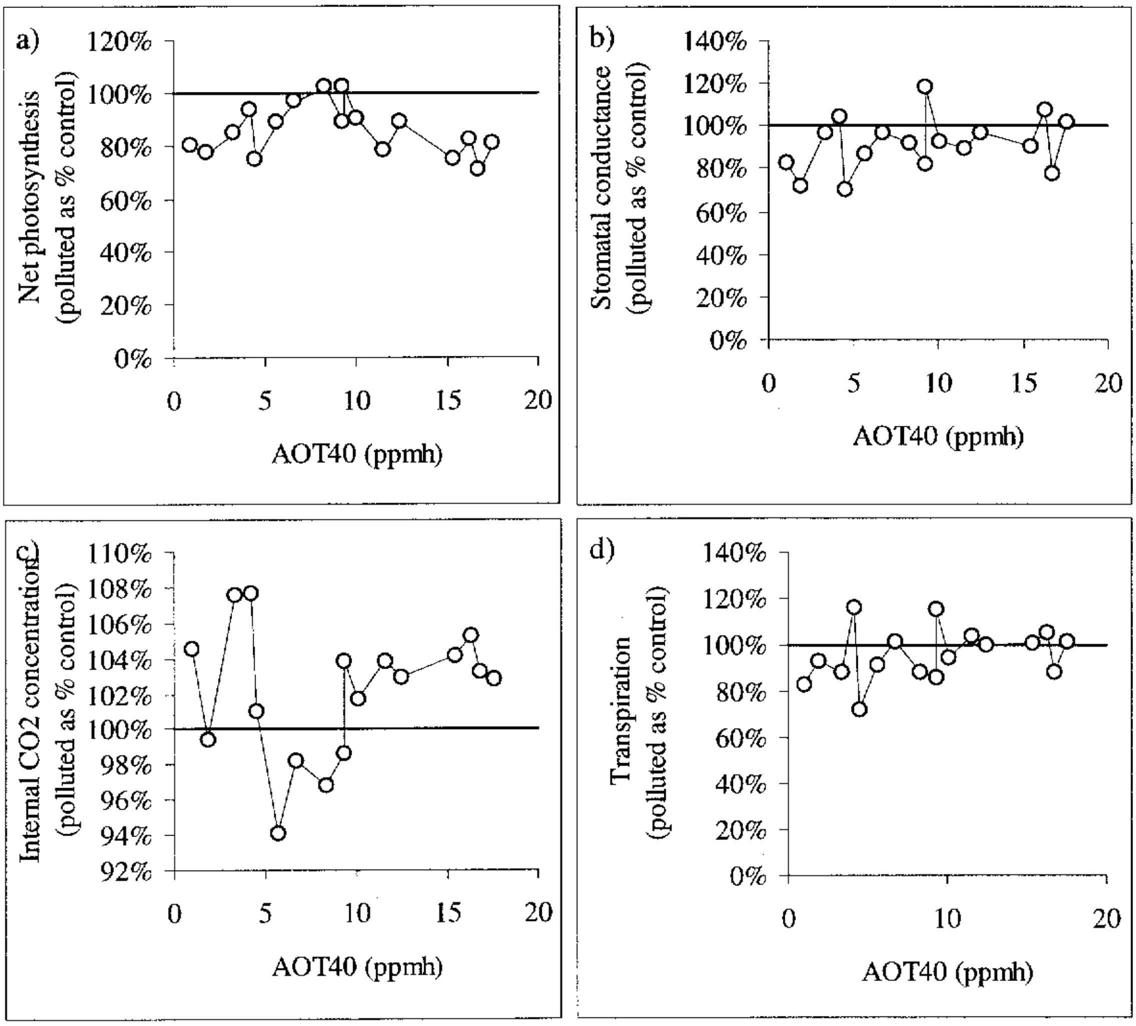


Figure 5.2 a) net photosynthesis, b) stomatal conductance, c) internal CO_2 concentration and d) transpiration in ozone fumigated plants expressed as a percentage of control values. Note that data refer to plants exposed to ozone during <u>both</u> the "early ozone" and "late ozone" treatments.

measured on small areas of foliage, on the basis on these data plants exposed to ozone throughout the season might suffer a loss in carbon fixation of around 11%. The comparable expected loss in plants subjected only to early ozone is 7%.

In conclusion, the current method of calculating AOT40 uses cumulative ozone exposure between 1st April and 30th September. The gas exchange data obtained here show that late season ozone (broadly from mid July) has little or no effect on beech. Hence, in considering refinements of AOT40, one possibility may be to calculate cumulative ozone only between 1st April and, say, mid August. This conclusion requires confirmation, not least using the biomass production data that will be obtained from remaining destructive harvests of this year's experiment.

Acknowledgements

We are grateful to Sally Harrop who carried out the majority of gas exchange measurements, Maureen Harrison, Anne Keates and Phil Nott for technical assistance and Dr Amanda Bamford for many valuable discussions.

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Responses of Wetland Plant Species to Ozone

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Responses of wetland plant species to ozone

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Data analysis from the experiment carried out in the summer of 1998 to investigate the responses of eight species charactersitic of fen and fen-meadow communities (NVC community types S24, S25, S26, S27, M22, M24) was carried out, together with that from an experiment carried out at Imperial College in 1997 under an earlier contract to investigate the responses of six species of similar communities. The species used are summarised in Table 1. Plants were exposed in a system of 8 open top chambers at Imperial College's field station in Ascot, Berkshire. Half of the chambers were ventilated with charcoal filtered air, while the other half received charcoal filtered air with additional ozone. Ozone was delivered to the chambers between 09.00 and 18.00 daily, with target concentrations of 90 nl l^{-1}. Ozone exposure was restricted to dry, still days, where maximum temperatures exceeded 17°C. Destructive harvests of above and below ground biomass were carried out at the end of each experiment. Plant species were harvested sequentially, giving slightly different AOT40 exposures for each species (Table 1). The seasonal exposures were significantly lower in 1998 than 1997, due to the cooler weather allowing less days for fumigation.

	AOT 40
1997:	
Symphytum officinale	11,600 ppb.h
Valeriana officinalis	13, 200 ppb.h
Iris pseudacorus	13,200 ppb.h
Lythrum salicaria	13,900 ppb.h
Mentha aquatica	14,300 ppb.h
1998:	
Vicia cracca	9,200 ppb.h
Lathyrus pratensis	9,200 ppb.h
Rumex acetosa	9,200 ppb.h
Cirsium arvense	10,000 ppb.h
Lychnis flos-cuculi	9,300 ppb.h
Lotus uliginosus	10,100 ppb.h
Filipendula ulmaria	10,600 ppb.h
Valeriana officinalis	10,300 ppb.h

Table 1. Cumulative ozone exposures for each plant species.

Recognisable ozone injury was observed on eight of the 12 species, with the first signs of injury being recorded on *V. cracca* following an ozone exposure of only 1,950 ppb.h. The development of visible injury in relation to ozone exposure is illustrated in Figure 1.

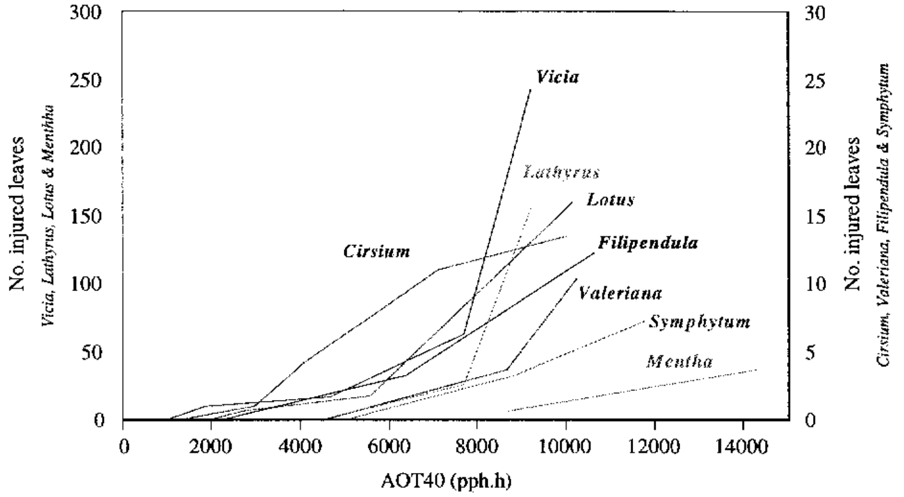


Figure 1. Development of visible injury in relation to ozone exposure

There was a general trend of reduced above- and below-ground biomass in ozone (Table 2), with *M. aquatica* being a notable exception. Significant reductions in above-ground biomass were found for *S. officinale*, *V. officinalis* and *C. arvense*. Three species, including *V. offinalis*, showed a significant reduction in root weight. In general, below-ground biomass was more affected by ozone than above-ground, as is reflected in the lower root:shoot ratios in ten of the twelve species examined. The greater weights recorded for the first five species listed reflects the longer experimental period in 1997 compared with 1998.

Table 2. Above- and below-ground biomass (g dry weight) and root:shoot ratios for all species

	Live (leaf + stem) weight			Root weight			Root:shoot ratio		
	O_3	FA	F ratio	O_3	FA	F ratio	O_3	FA	F ratio
S. officinale	**18.3**	**23.7**	**9.82***	42.7	54.2	3.56	1.71	1.85	0.24
V. officinalis	**14.3**	**18.2**	**6.50***	**25.0**	**36.5**	**54.6****	**1.58**	**1.95**	**10.0***
L. salicaria	48.3	52.4	0.96	45.8	52.1	3.41	0.89	0.92	0.25
I. pseudacorus	7.2	7.4	0.06	7.8	8.8	4.41	1.04	1.16	3.91
M. aquatica	**13.4**	**8.5**	**11.12***	3.9	3.4	1.28	0.27	0.36	4.48
R. acetosa	6.8	7.1	0.36	4.3	4.4	0.08	0.62	0.61	0.01
V. cracca	2.0	2.5	1.69	1.1	1.5	3.09	0.58	0.63	2.12
L. pratensis	1.4	1.3	0.43	**0.9**	**1.1**	**7.22***	**0.66**	**0.83**	**14.6****
C. arvense	2.7	4.0	5.48	**0.9**	**2.2**	**7.12***	**0.33**	**0.52**	**17.1****
L. flos-cuculi	4.2	3.6	3.78	1.2	1.2	0.48	0.30	0.30	0.13
L. uliginosus	4.3	3.8	1.90	1.1	1.2	0.22	0.26	0.33	2.15
F. ulmaria	**1.1**	**1.4**	**6.13***	0.8	0.8	4.82	**0.71**	**0.65**	**6.57***

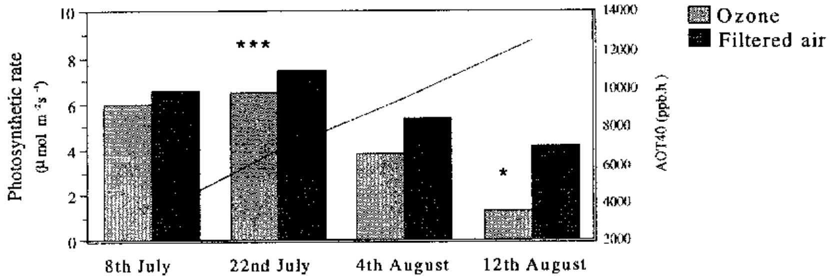
Live (leaf+stem) weights exclude senescent/dead leaves (and flower stalks for *L. salicaria* and *M. aquatica*)

*/** represent significant treatment effects at the P<0.05/0.01 level of probability

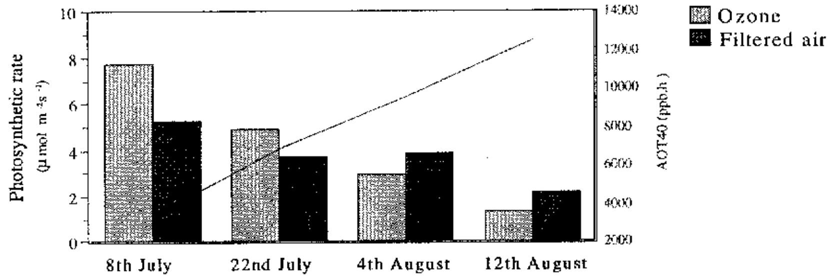
Exposure to ozone resulted in large and significant reductions in photosynthetic rate, at some stage of the experiment, for five species. For three species, *(V. officinalis, I. pseudacorus* and *S. officinale)*, the effect of ozone on photosynthetic rate increased over the course of the experiment . The pattern of response to ozone differed in the other species, which showed an initial stimulation followed by a reduction in photosynthesis (*M. aquatica*), and a significant reduction from the first measurement period (*C. arvense*). Figure 2 illustrates these differences in temporal changes in plant photosynthetic response to ozone exposure, for three species.

Figure 2. Relationship between AOT40 exposure and effects on plant photosynthetic rate for a) *V. officinalis*, b) *M. aquatica* and c) *C. arvense*

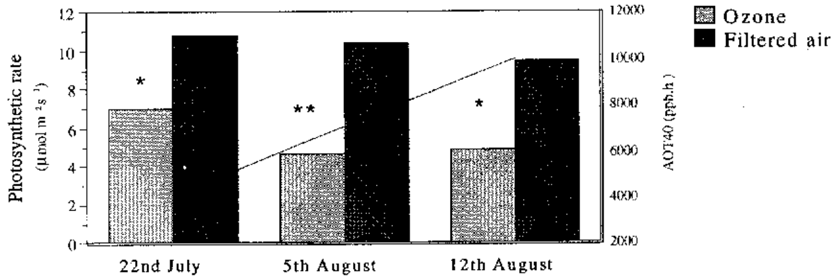
a) Valeriana officinalis



b) Mentha aquatica



c) Cirsium arvense



The most striking aspect of the experimental results was the number of species (nine of the twelve studied) that were negatively affected by ozone in terms of either visible injury or detrimental effects on growth or physiology. Initial species selection did not involve any prior knowledge about relative sensitivities to ozone and was largely constrained by seed supply and germination success. Visible injury is not generally regarded as a good indicator of ecological effects, but in this study 5 of the 8 species showing injury symptoms also had statistically significant reductions in biomass in ozone. The extent of visible injury and biomass reduction was noticeably greater than in previous experiments at Imperial College with grassland species, and is consistent with earlier work which suggested that grassland forb species characteristic of more mesic environments might be more likely to be affected by ozone.

There is evidence that factors which increase ozone flux into leaves will tend to increase the sensitivity of plants to a given ozone exposure. Mean stomatal conductance values for the wetland species used in this experiment about 50% higher than those measured for grassland species in earlier studies at Imperial College. There was a very weak relationship between stomatal conductance and reductions in above-ground weight in this experiment, ($r^2 = 0.059$), but the positive relationship between stomatal conductance and reductions in ozone of both root weight ($r^2= 0.409$) and root:shoot ratio ($r^2= 0.344$) was stronger. This suggests that wetland species with a higher stomatal conductance were more sensitive to ozone.

Since this was not designed as a dose-response experiment, it is not possible to comment on the appropriateness of the current critical levels for semi-natural communities. However, the magnitude of biomass reductions observed for the most affected species is large (as high as 58% for *C. arvense* roots), given that the experimental AOT40 values of 10000-15000 ppb.h are within the range reported for the UK. This fact, together with together with the fact that the first signs of visible injury appeared at AOT40 values of only 1,950 ppb.h, is consistent with the hypothesis that fen and fen meadow communities may be amongst the most sensitive semi-natural plant communities in the UK.

In the summer of 1999, an further experiment was planned to investigate the effects of ozone on species of fen communities. Two reed species (*Phragmitis australis* and *Typha latifolia*) and four forb species (*Eupatorium cannabinum*, *Epilobium hirsutum*, *Lychnis flos-cuculi* and *Filipendula ulmaria*) were selected for study, with the latter two species selected for comparison with the previous year's experiment . The experiment was planned in collaboration with ITE Bangor, who were carrying out investigations of the responses of candidate wild species for use in the ICP-Vegetation network across Europe. Unfortunately, delays were experienced in establishing the ozone fumigation in the ITE solardome chambers, which means that no results are available from this experiment to date.

Assessment of the Relative Sensitivity of Wetland Plant Species to Ozone

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University of Newcastle

Assessment of the relative sensitivity of wetland plant species to ozone.

Summary

Outline of work since November 1998.

- Seed collection and acquisition completed December 1998.
- Screening species and populations using acute and chronic exposures (December 1998-August 1999).
- Is ozone flux greater in wet- than dry-land species? Comparison of stomatal conductance and stomatal index in wet- and dry-land species and populations. Started August 1999, continuing until February 2000.
- Within-species comparison of stomatal conductance (ozone flux)..

Conclusions:

- All species tested showed significant within-species differences in response to either acute and/or chronic ozone exposures. Therefore it is essential that the relative resistance/sensitivity of taxa used in critical levels should be defined.
- The IC/John Chambers population of *Cirsium arvense* was more sensitive than other populations.
- Data are still being analysed and stomatal indices will be estimated during the winter, but at present it does not appear that there is a systematic difference in stomatal conductance or index between wet- and dry-land species.
- Data are still being analysed but it appears that there are no great differences in stomatal conductance between populations of *Epilobium hirsutum.* There are differences in stomatal response to water stress and ozone. These will be reflected as differences in ozone flux. Water stress causes a lasting reduction in stomatal conductance that will restrict ozone flux.

Assessment of the relative sensitivity of wetland plant species to ozone.

Progress Report.

Introduction.

The principal aim of the Newcastle project is to determine if there are differences in O_3 response between populations of wetland species, especially those species that are being used by Imperial College. This will put the IC data into a better defined context. It will also raise important questions about how variation in response can be incorporated into critical levels.

During 1999 three changes were made to the work plan. The first was because of severe problems germinating seeds used by IC. This delayed the work and was discouraging for Ms Haley. Some of the important IC species were examined but the work will have to be continued when good seed lots become available.

The second change was a consequence of the delay. We were unable to use the OTCs as planned so the work on rapid screening of plants for ozone response will be started in 2000.

The third change was because the Head of Department funded the purchase of some sap flow gauges. This gave us the unexpected opportunity to investigate whole plant ozone flux in wet- and dry-land species. Preliminary work was done in 1999 and it will be developed in 2000. If the work is successful we should be able to produce data on inter and intra-specific variation in ozone flux.

Overall, the changes in timing will not affect the final outcome of the programme and the availability of the sap flow gauges will add valuable data that should contribute to Level II Critical Levels.

Outline of work since November 1998.

- Seed collection and acquisition completed December 1998.
- Screening species and populations using acute and chronic exposures (December 1998-August 1999).
- Is ozone flux greater in wet- than dry-land species? Comparison of stomatal conductance and stomatal index in wet- and dry-land species and populations. Started August 1999, continuing until February 2000.
- Within-species comparison of stomatal conductance (ozone flux)..

Results.

1. Species responses.

The commercial seeds used by IC showed poor and erratic germination. Examination showed that the larger seeded species were damaged, probably by mechanical handling and cleaning. This limited the work that could be done on the IC species. The most important species that we have been unable to investigate is *Eupatorium cannabinum*. We will try to obtain better seeds of this reportedly sensitive species because it has been used by IC and by both Dutch and German groups. Intra-specific comparisons of IC species will be continued as seeds become available.

Apart from the IC species, we focussed on those that have been described in the literature as having a degree of ozone sensitivity.

Conclusion: all species tested showed significant within-species differences in response to either acute and/or chronic ozone exposures. Therefore it is essential that the relative resistance/sensitivity of taxa used in critical levels should be defined.

Three examples are shown in Figures 1-6.

Cirsium arvense has been reported as being ozone sensitive. IC are using seeds supplied by John Chambers Seeds. There was no difference between populations in visible symptoms produced by an acute exposure ranging from 1-4 days of 7h per day at 150 ppb. However, there were significant differences between populations in terms of growth rate and biomass (Figs 1 & 2). The IC/John Chambers population was more sensitive than other populations.

Foxglove, Digitalis purpurea was reported as sensitive by Gina Sanders at Trent. Figure 3 shows variation in response to a chronic exposure between population.

The ubiquitous wetland species *Epilobium hirsutum* proved to be one of the most amenable species so it was decided to focus on it for more detailed investigation of variation between populations. Most populations showed about the same sensitivity to an acute exposure (Figs 4 & 5) but there were differences in response to a chronic exposure (Figure 6). Most populations were quite sensitive but the Sheffield population was resistant to 70 ppb.

2. Do wet- and dry-land species differ in stomatal conductance (and therefore ozone flux)?

The approach used was to compare wet and dry habitat pairs of species in 12 families: Polygonaceae, Lamiaceae, Boraginaceae, Poaceae, Onagraceae, Ranunculaceae, Rosaceae, Asteraceae, Scrophulariaceae, Iridaceae, Cyperaceae and Apiaceae.

Conclusion. The data are still being analysed and stomatal indices will be estimated during the winter, but at present it does not appear that there is a systematic difference in stomatal conductance or index between wet- and dry-land species.

3. Within-species comparison of stomatal conductance (ozone flux).

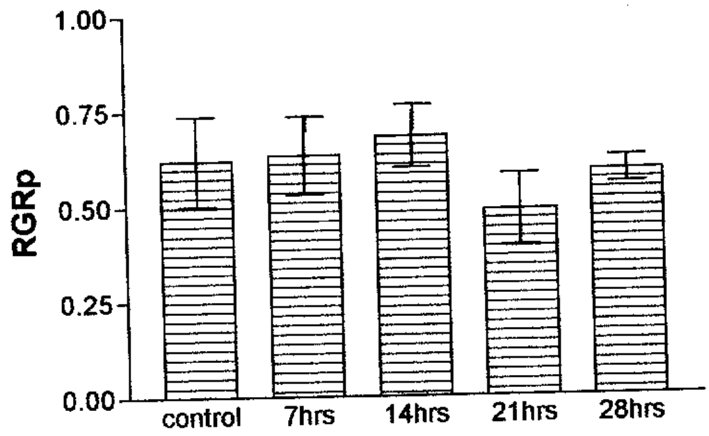
Since August work has concentrated on *Epilobium hirsutum* because this widespread species has the attributes to make it an excellent model for investigation of critical levels. *Epilobium* will be used with the sap flow gauges to estimate whole plant ozone flux.

Conclusion. Data are still being analysed but it appears that there are no great differences in stomatal conductance between populations of *Epilobium hirsutum*, but there are differences in stomatal response to water stress and ozone. These will be reflected as differences in ozone flux. Water stress causes a lasting reduction in stomatal conductance that will restrict ozone flux.

Finally, coordination of the work for the coming year will be discussed with Dr Power during the Critical Loads meeting in Copenhagen later this month.

AW. Davison
9th November 1999

Relative Growth Rate of Whole Plant (RGRp) in St. Andrews Population of *Cirsium arvense* in Acute Ozone.

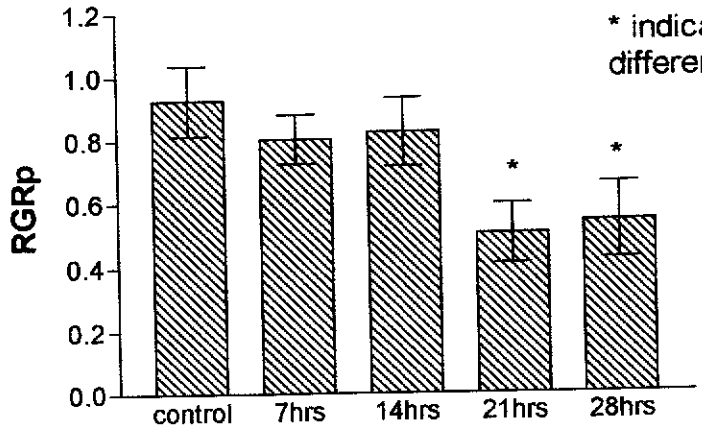


* indicates significant difference from control

Figure 1 Effects of acute exposure to ozone on mean growth rate of St Andrews population of *Cirsium arvense*.

Control plants kept in charcoal filtered air (CF) other treatments kept in CF + 150ppb Ozone 7hd^{-1} for 1, 2, 3 or 4 days. Legend shows total time treatments exposed to ozone.

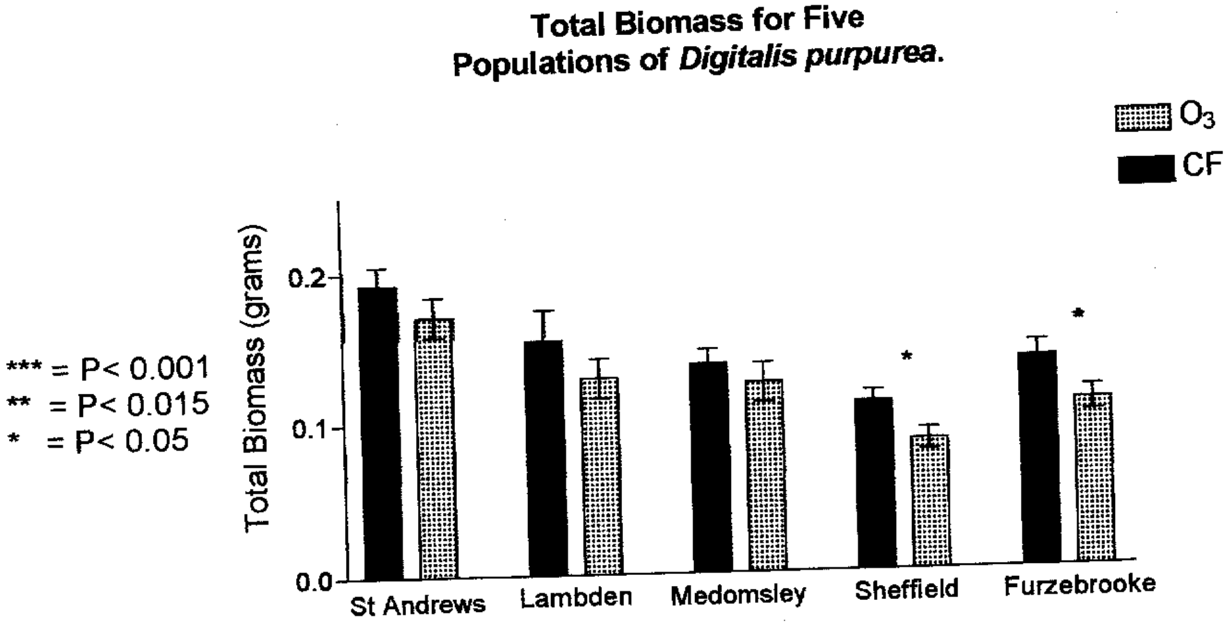
Relative Growth Rate of Whole Plant (RGRp) in John Chambers Population of *Cirsium arvense* in Acute Ozone.



* indicates significant difference from control

Figure 2 Effects of acute exposure to ozone on mean growth rate of John Chambers population of *Cirsium arvense*.

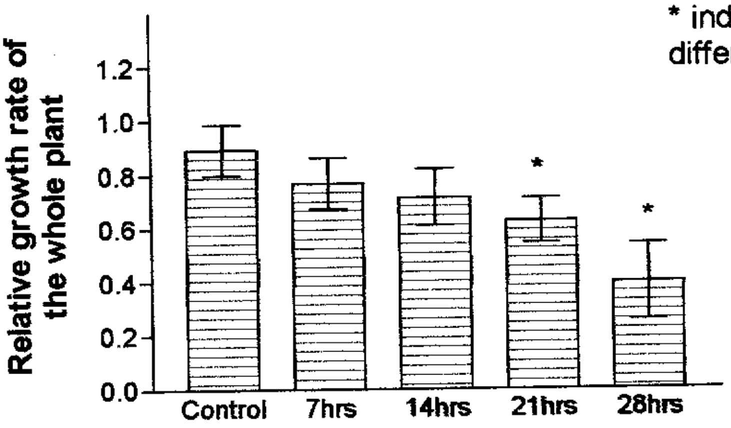
Control plants kept in charcoal filtered air (CF) other treatments kept in CF + 150ppb Ozone 7hd^{-1} for 1, 2, 3 or 4 days. Legend shows total time treatments exposed to ozone.



Total Biomass of five populations of *Digitalis purpurea* following 21 days in either charcoal filtered air (CF), or CF + 70ppb O_3 7h d^{-1} (O_3)

Figure 3. Variation in effects of chronic exposure to ozone on five populations of foxglove. *Digitalis purpurea*.

RGRp (whole plant) for *Epilobium hirsutum*
from St. Andrews following a range of acute ozone exposures

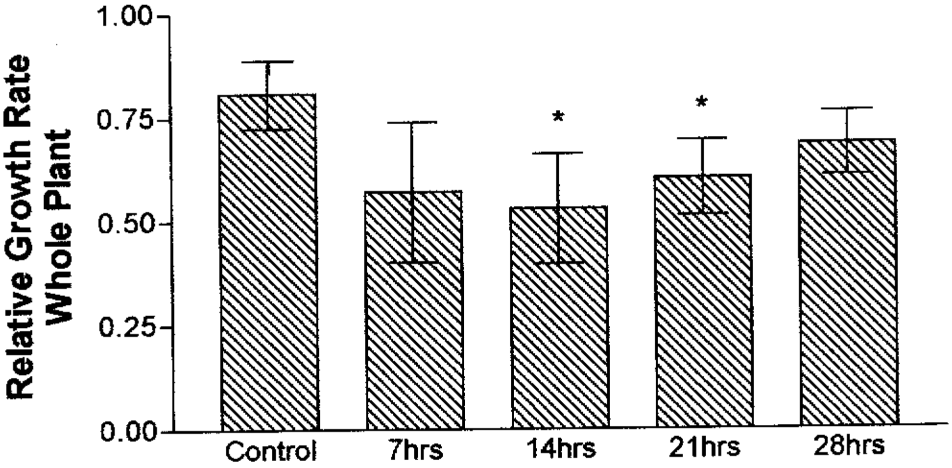


* indicates significant difference from control

Figure 4 Effects of acute ozone exposure on St Andrews population of *Epilobium hirsutum.*

Control plants kept in charcoal filtered air (CF) other treatments kept in CF + 150ppb Ozone 7hd^{-1} for 1, 2, 3 or 4 days. Legend shows total time treatments exposed to ozone.

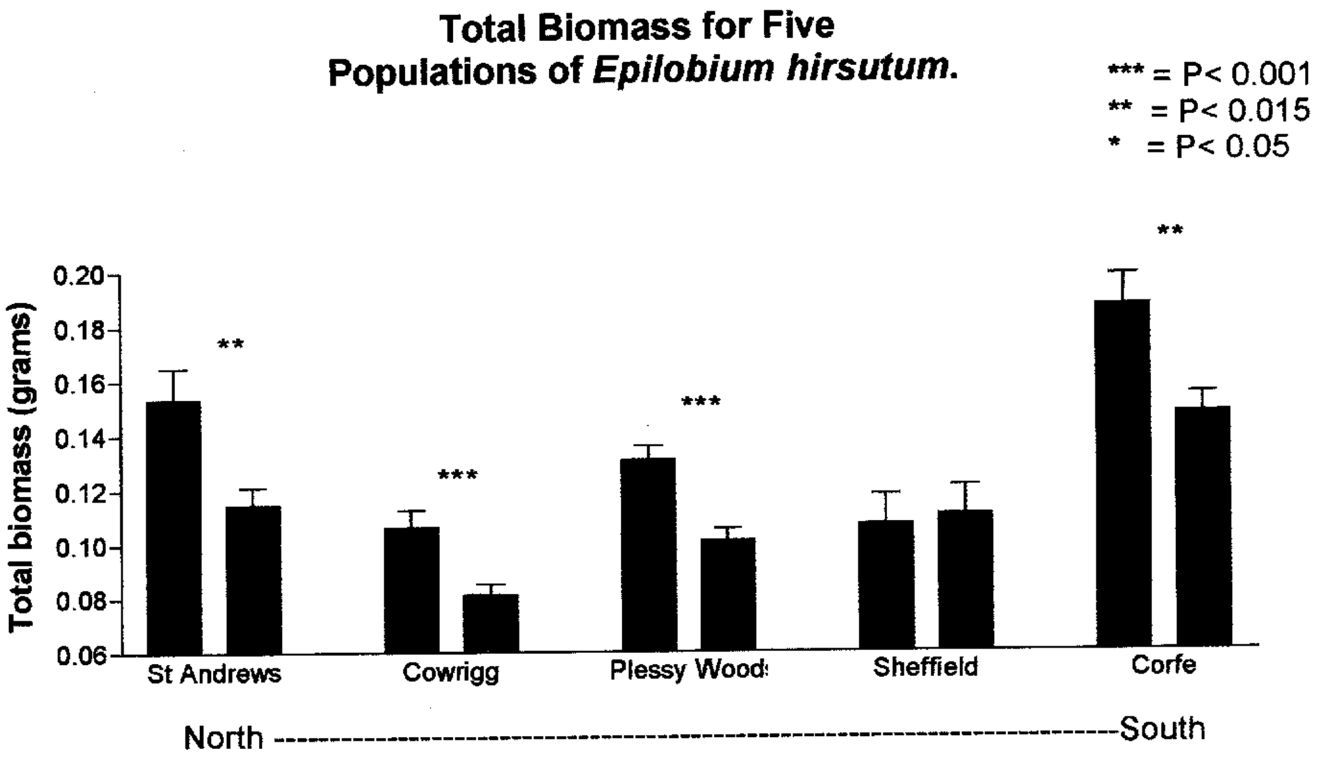
RGRp (whole plant) for *Epilobium hirsutum* from Sheffield following a range of acute ozone exposures.



* indicates significant difference from control

Figure 5 Effects of acute ozone exposure on Sheffield population of *Epilobium hirsutum.*

Control plants kept in charcoal filtered air (CF) other treatments kept in CF + 150ppb Ozone 7hd^{-1} for 1, 2, 3 or 4 days. Legend shows total time treatments exposed to ozone.



Total biomass for five populations of *Epilobium hirsutum* following 21 days in either charcoal filtered air (CF), or CF + 70ppb O_3 7h d^{-1} (O_3)

Figure 6. Variation in effects of chronic exposure to ozone on five populations of hairy willow herb, *Epilobium hirsutum*.

Continuous Measurements of Ozone Dry Deposition to Wheat, Sugar beet and Potatoes, Using Micrometeorological Methods

1999 Annual Report
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Contents

Introduction

Objectives

The aim of this research is to measure the dry deposition flux of ozone to agricultural crops and other vegetation in the field, and to:

- partition the total flux between stomatal and non-stomatal uptake
- examine the relationship between the absorbed (stomatal) ozone dose and AOT40 (accumulated concentration over a threshold of 40 ppb) levels

Effects of ozone on vegetation and critical levels

There are 4 processes that influence the instantaneous concentration of ozone in the boundary layer:

1. photochemical production (for a full description see PORG, 1998)
2. chemical destruction (mainly reaction with NO)
3. atmospheric transport (horizontal advection and vertical transport by diffusion or turbulence)
4. surface dry deposition (direct removal at the Earth's surface by reaction with materials or absorption by vegetation)

These processes lead to ozone concentrations being highly variable both spatially and temporally, for example: in rural areas of the UK a typical daily maximum hourly mean would be around 30 ppb whereas in urban areas it may be only 10 ppb due to the depletion of ozone by titration with NO.

Dry deposition causes a significant decrease in ozone concentrations in the lowest few meters of the boundary layer as large amounts are removed by oxidation on materials at the surface or absorption through the stomata of plants when they are actively transpiring. The deposition of ozone can have significant effects on vegetation, from the reduction of agricultural crop yields to the visible injury and death of leaves (Guderian 1985, PORG 1997). It has been shown that concentrations as small as 30 to 40 ppb can have adverse effects on plant physiological processes.

Studies of the effects of ozone on vegetation often take place in open-top chambers where the ozone concentration is easily maintained at a specific concentration. However other factors within the chambers, such as temperature and humidity, do not accurately reflect field conditions so the plants may not respond to ozone in the same manner as they would in a natural environment. In open-top chamber experiments well defined dose-effects relationships are established (PORG, 1997) but field experiments often show damage to the cultivar at a wide range of concentrations (Grűnhage *et al* 1993). This inconsistency between chamber and field experiments is probably due to the plants having different stomatal fluxes of ozone. It is generally accepted that the ozone absorbed through a plant's stomata is more damaging than that deposited on the surface. At high concentrations the plant's detoxification mechanisms are overwhelmed, allowing the ozone to cause harm. Within an open-top chamber all plants will tend to absorb the same ozone dose as the atmosphere is well-mixed, ensuring the ozone concentration is consistent across the canopy and efficient deposition occurs and the plants are usually well watered and so they will maintain a higher stomatal conductance. The amount of ozone being deposited on the canopy as a whole also varies with the amount of boundary layer turbulence. Therefore, although the AOT40 index can indicate the potential for effects on vegetation it does not correlate well with the magnitude of effects making it difficult to make economic assessments of ozone damage.

Another disadvantage with using the AOT40 is that the critical level assumes the concentrations are those measured in the quasi-laminar boundary layer, just above the vegetation canopy, whereas most air quality monitoring measurements are made at a height of 3-4 m well above this layer. Measurements of ozone concentration at several heights above vegetation usually show a large positive gradient with concentrations increasing by 10 - 20% from the top of the canopy to 3 - 4 m above. Hence data from air quality monitoring networks may significantly overestimate the exceedance of critical levels.

Theory and methods

Micrometeorological theory

Deposition occurs at the Earth's surface in the lowest part of the troposphere, known as the planetary boundary layer, where air flow is modified by aerodynamic friction with the surface and thermal stratification which determines the air density gradient. Within the boundary layer entities such as momentum, heat, water vapour and trace gases are mainly transported horizontally by wind and vertically by turbulence. Although it is possible to write down a complete set of equations describing the dynamics and thermodynamics of the boundary layer, they are very complex. To measure fluxes of trace gases in the lower part of the boundary layer, several assumptions and mathematical techniques are employed to reduce the problem to a relatively simple set of equations.

It is only the bottom few metres of the boundary layer, where the atmosphere is closely coupled to the surface, in which we are interested. This region, termed the surface layer, is normally defined as where fluxes vary by less than 10% with height. It is often called the constant flux layer, as fluxes within it can be described by measurements at a single height. To describe this surface layer in detail, similarity theory (where variables are organised into dimensionless groups) and Buckingham Pi theory are used to develop a series of relationships. The application of similarity theory used for the surface layer is called Monin-Obukhov similarity and this works only when the winds are not calm and the friction velocity, u_*, is not zero. The relevant scaling parameters and their typical orders of magnitude are defined below.

Common variables and constants:

u' = turbulent component of horizontal wind velocity, ie $u' = U - \bar{U}$ where U is the instantaneous velocity and $\bar{U}$ is the mean velocity
w' = vertical wind velocity (as above)
T = absolute temperature
θ = potential temperature
θ_v = virtual potential temperature
k = 0.41, von Karman's constant
g = 9.81 ms^{-2}, gravitational acceleration
ρ = air density
c_p = specific heat at constant pressure for moist air
λ = latent heat of vaporisation of water
χ = gas concentration
z = height above ground
h = crop height
d = zero plane displacement height, where the canopy effectively becomes closed and all momentum is dissipated
z_0 = aerodynamic roughness length, the height at which u = 0, typically 1 mm to 1 m.
NB over bars denote time averages

Scaling parameters:

Monin-Obukhov length, $$L = -\frac{\overline{(u'w')}^{\frac{3}{2}}}{k\left(g/\bar{\theta}_v\right)\overline{\left(w'\theta'_v\right)}} \qquad (1\text{ m to }200\text{ m}) \tag{1}$$

friction velocity, $$u_* = \overline{(u'w')}^{\frac{1}{2}} \qquad (0.05\text{ to }0.3\text{ ms}^{-1}) \tag{2}$$

potential temperature, $$\theta_* = -\frac{\overline{\left(w'\theta'_v\right)}}{u_*} \qquad (0.1\text{ to }2.0\,^{\circ}\text{C}) \tag{3}$$

humidity, $$q_* = -\frac{\overline{(w'q')}}{u_*} \qquad (0.1\text{ to }5\text{ g}_{H_2O}\text{ kg}_{air}^{-1}) \tag{4}$$

The instantaneous vertical flux of momentum, or shearing stress, τ, within the inertial sub-layer may be defined as:

$$\tau = \rho\, u'\, w' = \rho\, u_*^2 \tag{5}$$

and by analogy the fluxes of sensible heat (C), latent heat (E) and a trace gas (F) may be written as:

$$C = \rho c_p\, w'\theta' \qquad (6)$$

$$E = \lambda\, w'q' \qquad (7)$$

$$F = w'\chi' \qquad (8)$$

These equations show that in a turbulent atmosphere the vertical flux of an entity is related to the vertical velocity and this is the basis of the eddy-correlation technique of measuring fluxes. This technique is described briefly in the following section but it was not used for this project as the very fast response equipment required was not available.

To determine the fluxes described above, the turbulence parameters u', w', θ', q' and χ' must also be described. To simplify the equations governing turbulent flow in the surface layer the first-order closure technique, K-theory, is used. This makes the assumption that the time averaged flux of an entity is related to its local gradient, ie:

$$F(z) = a_s\, K(z)\, ds/dz \qquad (9)$$

where: $F(z)$ = vertical flux density
$K(z)$ = turbulent transfer coefficient or eddy diffusivity (units, m^2s^{-1})
s = concentration of entity S
z = height above the surface
a_s = scaling factor for S

Applying this formula (9) to the fluxes of momentum, sensible heat, latent heat and a trace gas, subscripted m, C, E, and χ respectively, gives:

$$\tau = \rho\, K_m\, du/dz \qquad (5')$$

$$C = -\, K_C\, \rho c_p\, dT/dz \qquad (6')$$

$$E = -\, K_E\, \lambda dq/dz \qquad (7')$$

$$F = -\, K_\chi\, d\chi/dz \qquad (8')$$

Hence, fluxes can be obtained by measuring gradients of the respective variables and determining their eddy diffusivities. By convention the momentum flux is positive in the downward direction and so C, E and F are negative.

Profiles, gradients, and stability in the surface layer

The change in an entity with height above the surface of a crop, or other uniform vegetation, is called its profile. Measurements of profiles of u, T, q and χ can be used to determine the fluxes of momentum, sensible heat, latent heat and trace gases by using the Monin-Obukhov similarity theory and K-theory outlined above. The surface layer is often described as being neutral, unstable or stable depending on which factors are controlling the degree turbulence within the layer and so the shape of the wind speed profile. The main factors that induce turbulence are wind shear and thermal stratification of the surface layer. Changes in thermal stratification occur when the surface is heated by short wave solar radiation in the daytime or looses heat by long-wave radiative cooling during the night.

Neutral

Neutral conditions typically occur on windy and overcast days when thermal stratification is at a minimum and turbulence is mainly driven by wind shear and surface friction. This is termed fully-forced convection, wind speed increases logarithmically with height and there is no gradient in air temperature ($d\theta/dz = 0$). The rates of turbulent diffusion of heat, water vapour and trace gases will be the same as momentum because all 4 entities are transported vertically by eddies alone, ie:

$$K_m = K_H = K_E = K_\chi \qquad (10)$$

Unstable

During a sunny day the surface is heated and there is a negative vertical gradient in air temperature ($d\theta/dz < 0$). If this gradient exceeds the dry adiabatic lapse rate (≈ 1 K per 100 m), then a parcel of warm air rising from the ground will maintain its temperature. Hence it will be warmer and lighter than the surrounding air and continue to rise through buoyancy. Conversely, a parcel of cool air falling from a higher level will continue to fall until it reaches the surface. Under these conditions vertical transport is enhanced by buoyant rising of air from the ground. The amount of enhancement increases as wind shear decreases and the eddies are progressively stretched, as illustrated in Figure 2b. In this case $K_H = K_E = K\chi$ and $K_m < K_H$, as there is a preferential upwards transport of heat.

Stable

Stable conditions most commonly occur on clear nights with light winds, as the surface cools and indirectly cools the air closest to the ground, giving a positive temperature gradient ($d\theta/dz > 0$) often called an inversion. Vertical transport is reduced as any air moving up or down tends to revert to its former position and eddies become progressively flatter with height. The relationship between the diffusivities in stable conditions is uncertain but it has been inferred that $K_H = K_E = K\chi$ and $K_m \approx K_H$ (Monteith and Unsworth, 1990).

In neutral conditions when windspeed increases logarithmically the profile can be described by:

$$\frac{du}{dz} = \frac{u_*}{k(z-d)} \qquad (11)$$

Where the friction velocity, u_* quantifies the turbulent velocity fluctuations as shown by equation (2) and $u' = w' = u_* = l du/dz$. The momentum flux transmitted to surface is assumed to be the same in each of the regimes illustrated in Figure 2. Hence u_* is constant and the wind speed gradient is the same at the lowest levels of the profiles. As height increases the windspeed gradient becomes smaller in unstable conditions and larger in stable conditions. Equation (11) can be rewritten as:

$$\frac{du}{dz} = \frac{u_*}{k(z-d)} \Phi_m \qquad (11')$$

Where Φ_m is a dimensionless stability function that accounts for the modification in the profile in stable ($\Phi_m > 1$) or unstable ($\Phi_m < 1$) conditions. From equations (5) and (5') it can be shown that:

$$K_m = k\, u_*\, (z-d)\, \Phi_m^{-1} \qquad (12)$$

and similar functions can be derived for K_H, K_E, $K\chi$ from (6'),(7') and (8') with the stability functions Φ_H, Φ_E and $\Phi\chi$ respectively.

The stability function, Φ, is generally defined using parameters that depend on the ratio of buoyancy forces to mechanical turbulence. The most commonly used parameters are the Monin-Obukhov length, L (equation (1)) and the Richardson number defined below.

$$L = -\frac{\overline{(u'w')}^{\frac{3}{2}}}{k\left(g/\bar{\grave{e}}_v\right)\left(\overline{w'\theta'_v}\right)} = -\frac{\tilde{n} c_p T u_*^3}{kgC} \quad \text{where T = absolute temperature, K} \qquad (13)$$

$$\mathrm{Ri} = \frac{gT^{-1}\dfrac{dT}{dz}}{\left(\dfrac{du}{dz}\right)^2} \qquad (14)$$

Empirical formula defining Φ from L and Ri have been derived from several experiments and those generally used are:

In unstable conditions, Dyer and Hicks (1970) found that

$$\Phi_m^2 = \Phi_H = \Phi_E = [1 - 16(z-d)/L]^{-0.5} = (1-16\mathrm{Ri})^{-0.5} \quad \text{where Ri} < 0.1 \qquad (15)$$

In stable to slightly unstable conditions, Webb (1970) found

$$\Phi_m = \Phi_H = \Phi_E = [1 - 5(z-d)/L] = (1 - 5\mathrm{Ri})^{-1} \quad \text{where } -0.1 \le \mathrm{Ri} \le 1 \qquad (16)$$

Measuring ozone deposition in the field

There are 3 methods commonly used to measure the deposition flux of atmospheric trace gases over uniform vegetation:

1. eddy-correlation
2. Bowen ratio
3. aerodynamic gradient

Each technique measures fluxes in the surface layer where fluxes of momentum, heat, water vapour and trace gases are constant with height, as described above. There are also conditions that must be met to allow the application of these methods:

1. There must be sufficient upwind fetch from the measurement system to allow the surface layer to develop. A ratio if 100 m of fetch to a 1 m deep surface layer is commonly used although this may be to large according to measurements made over a heathland to forest transition (Monteith and Unsworth, 1990).
2. The flux of the entity being measured should have stationarity ($d\chi/dt = 0$) which implies that there are no sources or sinks of the entity other than the surface and no chemical reactions with the entity in the air column.

Bowen Ratio

The Bowen Ratio method uses the formula describing the energy balance of the surface to derive fluxes:

$$R_n - G = C + \lambda E \qquad \Rightarrow \qquad \lambda E = (R_n - G)/(1+\beta) \qquad (17)$$

where R_n = net radiation
G = soil heat flux
C = sensible heat flux
λE = latent heat flux
β = Bowen Ratio, $C/\lambda E$

Assuming that the transfer coefficients of heat and water vapour are the same β can be found from measurements of temperature (T) and vapour pressure (e) at a series of heights, using: $\beta = C/\lambda E = \gamma\, dT/de$ where γ = psychrometer constant (66 Pa K^{-1} at 0°C, 101.3 kPa, (Monteith and Unsworth, 1990)).

Using K-theory the latent heat flux may be written as:

$$\lambda E = - \frac{\rho c_p}{\gamma} K_E\, de/dz \qquad (18)$$

From equations (14') and (24) the energy balance (23) can be written as:

$$R_n - G = -\rho\, c_p\, K_H \left(\frac{d\theta}{dz} + \frac{de}{\gamma dz}\right) \qquad (19)$$

Hence from measurements of Rn, G, temperature and vapour pressure, K_H can be determined and used to estimate $K\chi$. The Bowen Ratio method performs best in conditions of low wind speed and large energy fluxes but does not perform well during overcast days or night-time when (R_n-G) tends towards zero.

Aerodynamic Gradient Method

This method uses the K-theory formulas, relating the flux on an entity to its gradient, (5') to (8') and the similarity hypothesis that in neutral conditions:

$$K_m = K_H = K_E = K\chi \qquad (20)$$

From these formulae it follows that:

$$\frac{-\rho c_p \frac{dT}{dz}}{C} = \frac{-\rho \frac{du}{dz}}{\tau} \qquad (21)$$

and similar equalities may be written between E, C, F or τ. By rearranging (21) and using $\tau = \rho\, u_*^2$ it can be shown that:

$$C = - -\rho c_p \frac{dT}{du} u_*^2 \text{ and similarly } E = - -\frac{dq}{du} u_*^2,\ F\chi = - -\frac{d\chi}{du} u_*^2 \qquad (22), (23), (24)$$

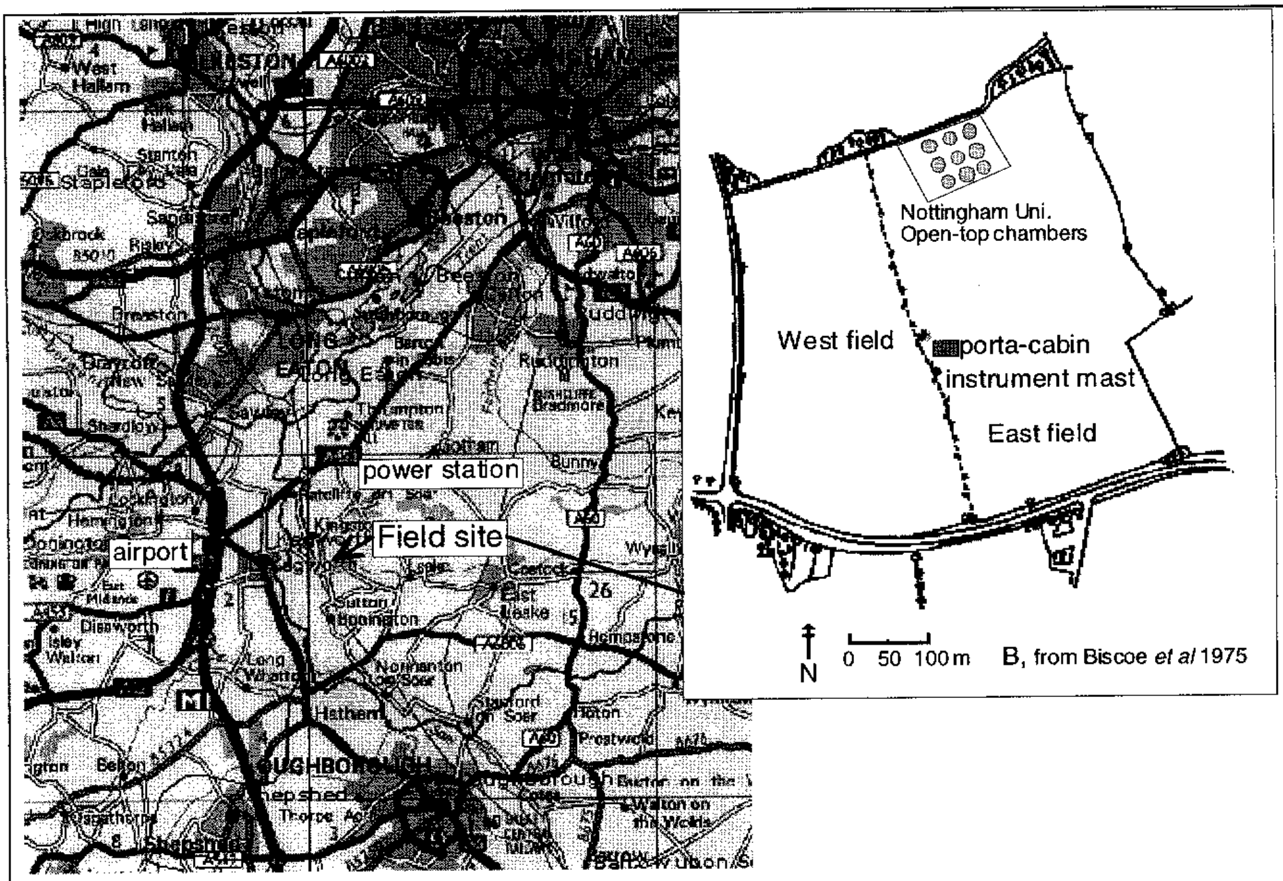
In neutral stability u_* can be determined from the wind speed profile alone and so fluxes can be found by measuring wind speed, temperature and gas concentration at a series of heights above the vegetation. In non-neutral conditions corrections must be made for the non-logarithmic wind profile, as described above.

Field Sites and Instrumentation

Continuous measurements have been made at two sites, using the gradient method as described briefly above.

Sutton Bonnington

The main site is called Sutton Bonnington, a 4 ha field 15 km south west of Nottingham, just off the M1 motorway. The area is predominately agricultural although there are several sources of NO_x and SO_2 near to the field, such as Ratcliffe coal fired power station 3 km north, the M1 motorway to the west and the East Midlands Airport about 4 km to the south west (see Figure 1a). The region is also quite densely populated, with major conurbations less than 100 km away, and so the background concentration of NO_x is between 8 to 16 ppb (AEAT, 1996). This level of NO_x and episodes of higher concentrations lead to significant reductions in the ozone concentration observed at Sutton Bonnington, potentially causing errors in the calculated fluxes. Hence the NO_x concentration must also be monitored to allow corrections to be made to the ozone flux.



B, from Biscoe *et al* 1975

A, Bartholemews UK Road Map CD v 3 (50 km x 50 km grid)

Figure 1. Location of the Sutton Bonnington field site.

The field is owned and managed by the Nottingham University commercial farm, adjacent to the Sutton Bonnington Campus. It has been used for several field experiments over the years: from 1968 to 1973 Biscoe *et al* (1975) performed a series of experiments measuring CO_2 and water exchange above barley; Fowler (1976) studied the deposition of SO_2 to crops and the soil; ITE Edinburgh commenced measurements of SO_2 deposition in spring 1993 when NH_3 fluxes were also measured; the DETR commissioned research into SO_2 deposition at the site during 1994 and 1995 (Fowler *et al*, 1996).

The SO_2 measurement system has been kept in continuous operation since 1995, allowing the instrumentation to measure ozone deposition to be added in 1998. The field itself is split into two halves, labelled west and east on figure 1b, which are planted in rotation with different commercial crops, although they are not physically separated. In 1998 the west field was planted with sugar beet and the east with wheat whereas this year (1999) wheat is in the west field and oats in the east, table 1 summarises the crop plantings. An overhead power line forms the boundary between the two halves and provides a convenient source of power for the instrumentation. A porta-cabin, located approximately 200 m along the line of the power cables from the southern field boundary, contains the equipment and the instrument mast is 18 m south of the cabin, as shown in Figure 1b.

Table 1. Timetable of crop plantings at the two measurement sites.

Crop plantings		
Sutton Bonnington		**Auldhame Farm**
West	**East**	
1998		
Saxon sugar beet drilled 30/4/98 harvested 12/11/98	Consort wheat drilled 2/11/97 harvested 30/8/98	
1999		
Rialto wheat drilled 1/12/98 harvested 17/8/99	Gerald oats drilled 12/10/98 harvested 20/8/99	Desiré potatoes sown end March-early April harvested 21/9/99
2000		
oats sown 14/10/99	wheat sown 17/9/99	

Fetch requirements are well met to the west/south west and east/north east of the mast. However the cabin to the north and the access road to the south disrupts air flow in these directions. Examination of the meteorological data indicates that the fetch is good for wind directions in the ranges 190^{0} to 300^{0} and 70^{0} to 170^{0}.

The main instrumentation consists of:

on the mast and outside

- potentiometer wind vane
- 3 cup anemometers, measuring wind speed at 3 heights
- 2 fine wire thermocouples, measuring the temperature gradient
- pyranometer, measuring solar radiation
- 3 filtered ptfe air inlets, drawing in air at three heights
- Campbell rain gauge
- pcb wetness sensor

in the cabin

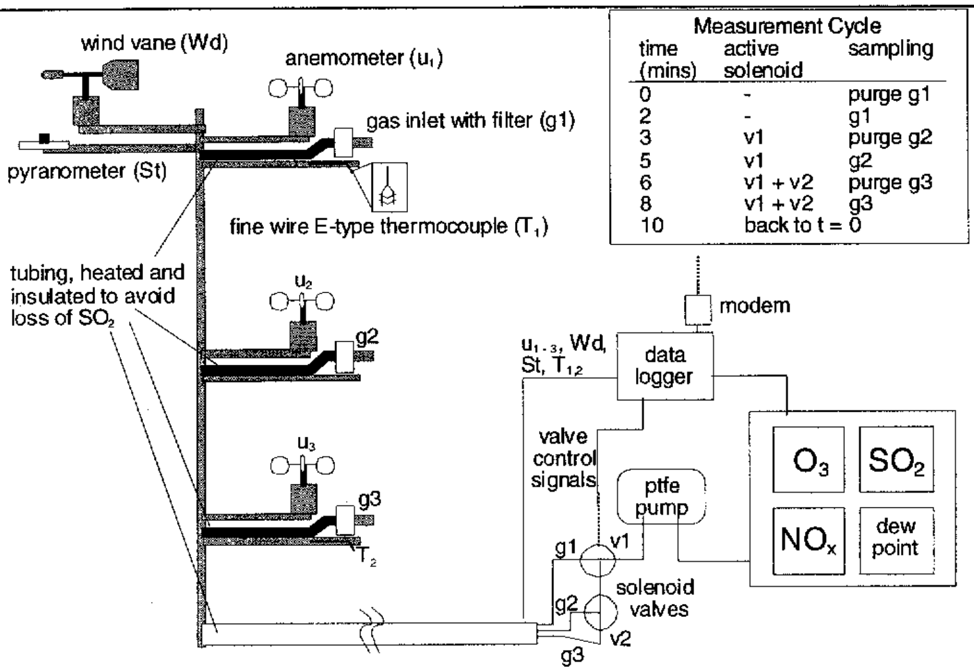
- TECO 49C ozone analyser
- TECO 42 NO/NO_2 analyser
- TECO 43S SO_2 analyser
- 21X Campbell data logger, connected to a modem for remote data access

Measurements are logged every 5 seconds and half hourly averages stored by the data logger are downloaded to ITE via the modem every morning. A preliminary check of the data is made to ensure that the system is functioning before it is stored for later analysis. The full system is illustrated in Figure 2 which also shows the measurement cycle used to obtain the trace gas concentrations at the 3 heights. Regular visits to the site, every 4 to 6 weeks, are made to, check the meteorological instruments, calibrate the gas analysers and fix any problems.

During may to August 1999 instruments were added to allow the calculation of fluxes using the Bowen Ratio method:

- Michel Instruments dewpoint sensor, connected to the gas inlets to measure the gradient in water vapour
- Didcot net radiometer
- Campbell heat flux measuring plates and soil temperature probes

The net radiometer was initially installed on the mast, where it saw the grassy surface around the mast as well as the wheat crop, to avoid damage when the crop was sprayed. During a field trip, from the 6th to 20th June 1999, the instrument was moved into the west field, where it measured the net radiation above the wheat crop only. A preliminary examination of the data shows no systematic difference between the measurements of net radiation from the mast and within the wheat, with westerly winds, and so the whole data set is used in this report.



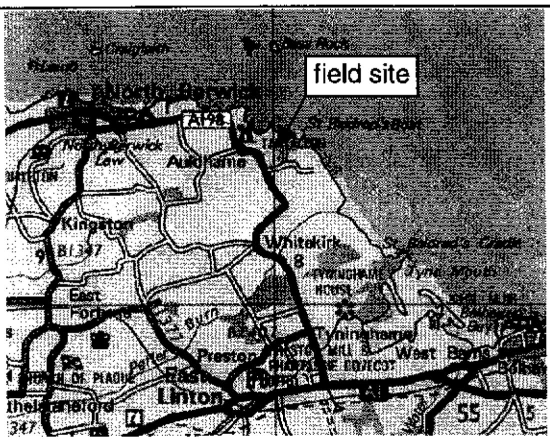
Measurement Cycle

time (mins)	active solenoid	sampling
0	-	purge g1
2	-	g1
3	v1	purge g2
5	v1	g2
6	v1 + v2	purge g3
8	v1 + v2	g3
10	back to t = 0	

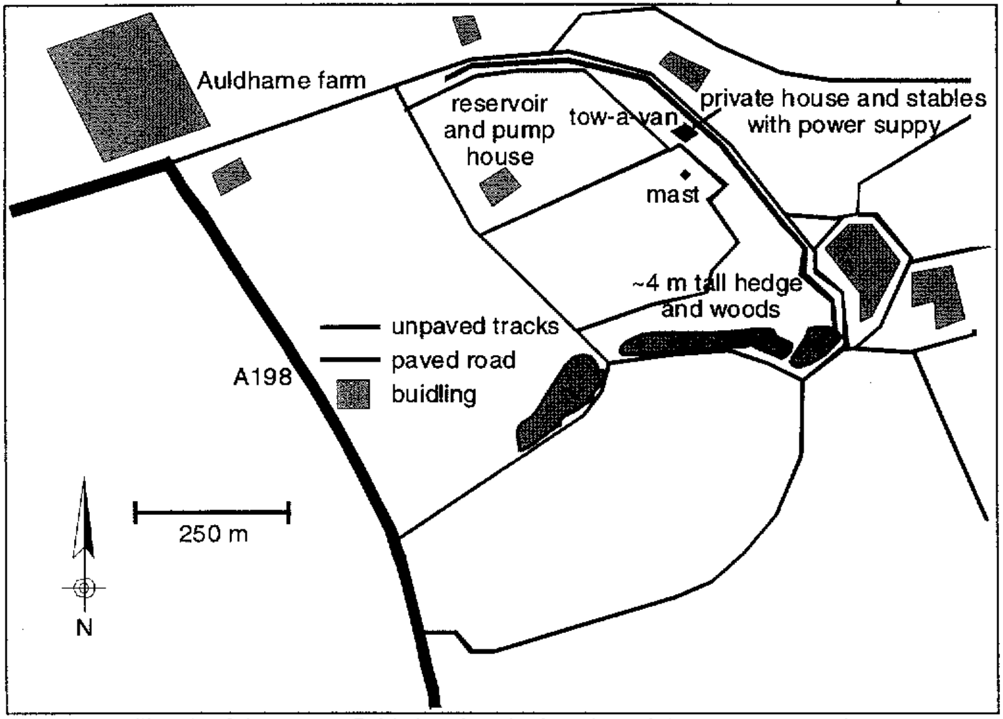
Figure 2. Configuration of the instrument mast and measurement cycle at Sutton Bonnington.

Auldhame Farm

NO_x pollution at the Sutton Bonnington increases the complexity of the analysis of ozone fluxes and so we decided to set up an additional site in a less NO_x influenced area during 1999. At Sutton Bonnington the effects of ozone on commercial potato crops are currently being studied using open-top chambers in the north-east corner of the field (see figure 1b). To link into this research, by providing data on the deposition and uptake of ozone to potatoes, a suitable potato field was found on the relatively unpolluted Scottish coast by the Bass Rock, just east of North Berwick in East Lothian (see figure 3a). The necessity of having access to mains power limited the positioning of the mast and cabin as shown in Figure 8b. Analysis of the meteorological data indicates that measurements from 200^0 to 290^0 should provide suitable data for calculating fluxes at this site. The system is very similar to that at Sutton Bonnington although the only trace gas measured is ozone and shielded thermocouple probes are used to measure air temperature, as shown in Figure 4. As the site is a lot closer to Edinburgh, it was checked and the data collected 2 or 3 times a week.



A. Bartholemews UK Road Map CD v3



B. Sketch of the potato field showing the location of the tow-a-van and mast

Figure 3 . Location of the Auldhame Farm potato field.

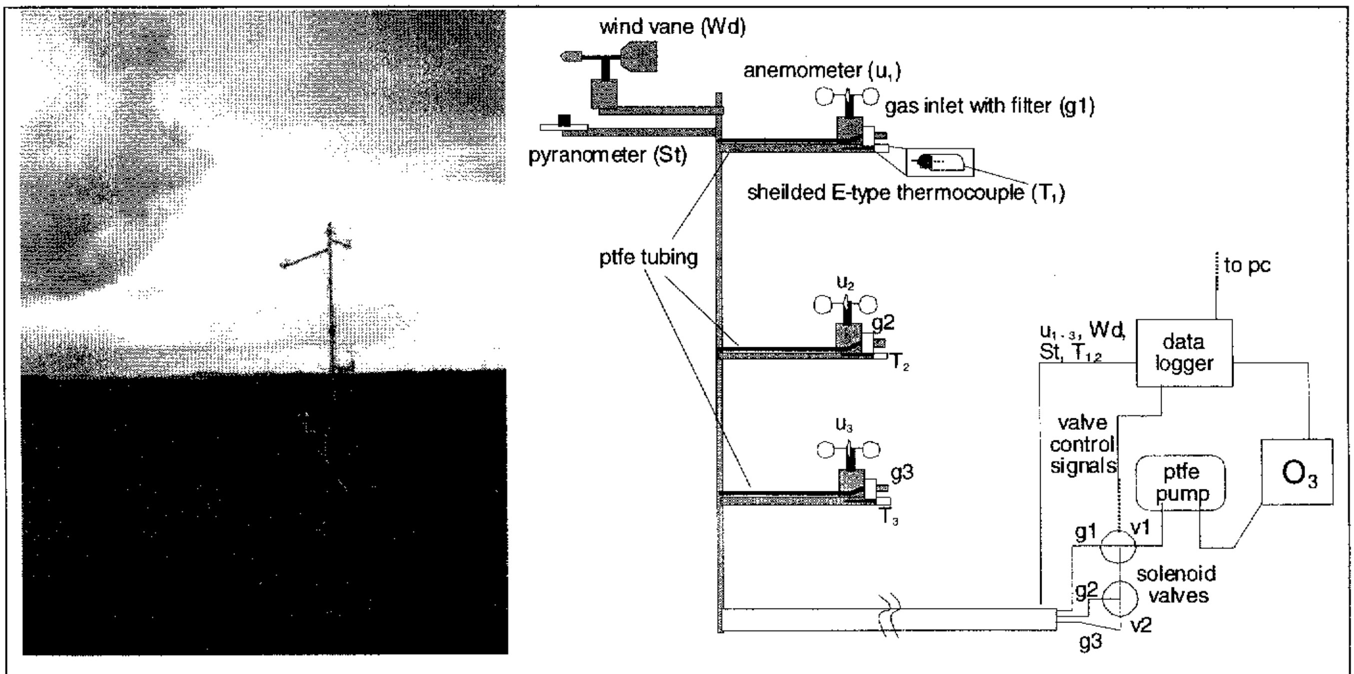


Figure 4. Configuration of the measurement mast in the Auldhame potato field.

Results

Estimates of the total ozone flux to each crop are given here but both data sets require further examination to extract information on the stomatal components of ozone deposition.

Sutton Bonnington - wheat, sugar beet and oats

Ozone measurements at this site started on the 1st of May 1998 and have been made continuously since then, with the exception of a few gaps due to equipment failures or maintenance. Table 2 gives a timetable of operations at the site and table 3 summarises the data capture achieved for the main parameters.

Table 2. Summary of events at the measurement sites.

Date	Sutton Bonnington	Date	Auldhame Farm
	1998		
31/3/98	3rd gas inlet installed on mast		
2/4/98	O_3 and NO_x analysers operational		
	main air intake pump removed for maintenance		
29/4/98	pump returned		
1/5/98	all equipment operational O_3 deposition measurements commence		
26/7/98	NOx analyser faulty		
5/10/98	O_3 analyser removed to examine measurement noise level		
3/12/98	O_3 analyser re-installed		
	1999		
20/2/99	NOx analyser re-installed	6/4/99	all equipment installed and operational except wind direction and solar radiation
22/3/99	NOx analyser faulty	5/7/99	wind direction operational
14/4/99	Dewpoint sensor installed measuring dew point gradient	7/7/99	pyranometer installed
15/4/99	NOx analyser re-installed	21/9/99	potatoes harvested and equipment removed
13/5/99	Heat flux, soil temperature and net radiation sensors installed Bowen ratio measurements commence		
6/6/99 to 20/6/99	field trip net radiometer placed in optimum position		
26/8/99	NOx analyser faulty		
17/8/99	Soil temperature and heat flux sensors removed		
3/9/99	Net radiometer damaged, removed for repair		
7/10/99	NOx analyser re-installed		

Table 3. Monthly %data capture (%DC) within the east and west wind sectors, for measurements at Sutton Bonnington.

%DC	Month	O_3	NO_x	Solar Rad.	Wind speed	Rain-fall	T	Dew point	Net Rad.	Soil heat flux	Soil T	%Wind in sector
East	May-98	97.9	96.6	97.5	100.0	84.3	98.0	-	-	-	-	13.7
East	Jun-98	100.0	100.0	100.0	100.0	100.0	100.0	-	-	-	-	14.4
East	Jul-98	100.0	100.0	100.0	100.0	100.0	100.0	-	-	-	-	6.7
East	Aug-98	100.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	11.6
East	Sep-98	100.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	23.1
East	Oct-98	13.2	0.0	100.0	100.0	100.0	100.0	-	-	-	-	7.1
East	Nov-98	0.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	26.8
East	Dec-98	96.1	0.0	100.0	100.0	100.0	100.0	-	-	-	-	22.6
East	Jan-99	94.6	0.0	100.0	100.0	100.0	100.0	-	-	-	-	15.3
East	Feb-99	100.0	47.7	100.0	100.0	100.0	100.0	-	-	-	-	6.4
East	Mar-99	100.0	68.5	100.0	100.0	100.0	100.0	-	-	-	-	12.4
East	Apr-99	100.0	71.1	100.0	100.0	100.0	100.0	60.7	-	-	-	21.9
East	May-99	100.0	100.0	100.0	100.0	100.0	99.3	95.7	50.7	50.7	50.7	20.3
East	Jun-99	100.0	93.1	100.0	100.0	100.0	100.0	66.8	100.0	100.0	100.0	16.1
East	Jul-99	97.8	97.8	100.0	100.0	100.0	100.0	92.9	100.0	100.0	100.0	18.6
East	Aug-99	99.6	48.7	100.0	100.0	100.0	100.0	89.6	100.0	52.8	52.8	30.8
East	Sep-99	100.0	0.0	100.0	100.0	100.0	98.4	95.1	8.8	-	-	34.7
East	to 26th Oct-99	100.0	94.7	100.0	100.0	100.0	87.1	94.4	-	-	-	32.4
West	May-98	100.0	99.3	100.0	100.0	83.0	100.0	-	-	-	-	32.7
West	Jun-98	95.9	95.9	99.9	100.0	100.0	100.0	-	-	-	-	59.2
West	Jul-98	97.9	76.0	99.3	100.0	100.0	99.5	-	-	-	-	76.8
West	Aug-98	97.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	66.3
West	Sep-98	100.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	39.7
West	Oct-98	0.7	0.0	100.0	100.0	100.0	99.7	-	-	-	-	61.6
West	Nov-98	0.0	0.0	100.0	100.0	100.0	100.0	-	-	-	-	48.1
West	Dec-98	98.5	0.0	100.0	100.0	100.0	100.0	-	-	-	-	58.4
West	Jan-99	86.3	0.0	100.0	100.0	100.0	100.0	-	-	-	-	66.1
West	Feb-99	96.3	29.4	100.0	100.0	100.0	100.0	-	-	-	-	79.9
West	Mar-99	97.7	59.9	100.0	100.0	100.0	100.0	-	-	-	-	58.3
West	Apr-99	98.6	22.5	100.0	100.0	100.0	100.0	16.3	-	-	-	45.1
West	May-99	99.5	99.5	100.0	99.5	100.0	98.0	95.0	58.9	58.9	58.9	42.2
West	Jun-99	98.6	91.9	100.0	100.0	100.0	99.9	74.6	99.2	100.0	100.0	52.8
West	Jul-99	97.8	97.8	100.0	100.0	100.0	100.0	93.0	100.0	100.0	100.0	49.8
West	Aug-99	96.6	19.5	100.0	100.0	100.0	100.0	90.2	100.0	42.3	42.3	37.2
West	Sep-99	100.0	0.0	100.0	100.0	100.0	97.4	94.3	7.0	-	-	46.6
West	to 26th Oct-99	82.5	56.3	100.0	100.0	100.0	100.0		78.4	-	-	48.9

The Climate at Sutton Bonnington

Figure 5 plots the frequency distribution of wind direction, indicating that most of the time the wind is coming from SW to W and includes the sector of good aerodynamic fetch. Figure 6 summarises the weather at the site during 1998 and 1999 with plots of a. monthly total rainfall, b. average wind speed, c. average temperature at each height and d. maximum solar radiation. Total rainfall during the growing season of May to July 1998 and 1999 are the same at 1.6 m, although during 1998 most of the rain fell during June whereas in 1999 it was spread throughout the 3 months. The wind speed data show the typical seasonal cycle observed in the UK, with increased wind speeds during the winter months. A gradient in wind speed can be clearly seen, with speed decreasing towards the surface. The temperature measurements also show a typical seasonal cycle of high summer and low winter values. During 1998 the temperature gradually increased from around 12 °C in May to 15 °C in July with a peak of 16 °C in August whereas during 1999 the temperature rapidly increased from 12 to 13 °C in May and June to over 17 °C in July. The temperatures during August and September 1999 remained higher than those in 1998. The average half-hourly maximum solar radiation reflects the trends in temperatures, with steady values of ~850 Wm^{-2} in May to July 1998 and an increase from ~850 Wm^{-2} in May to ~950 Wm^{-2} in June 1999.

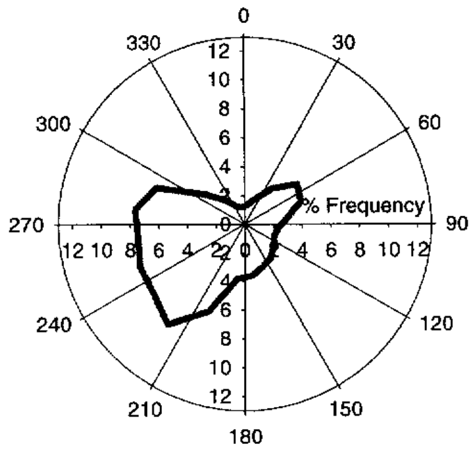


Figure 5. Wind rose of the % frequency of wind directions during the field measurements at Sutton Bonnington (3/3/98 to 26/8/99).

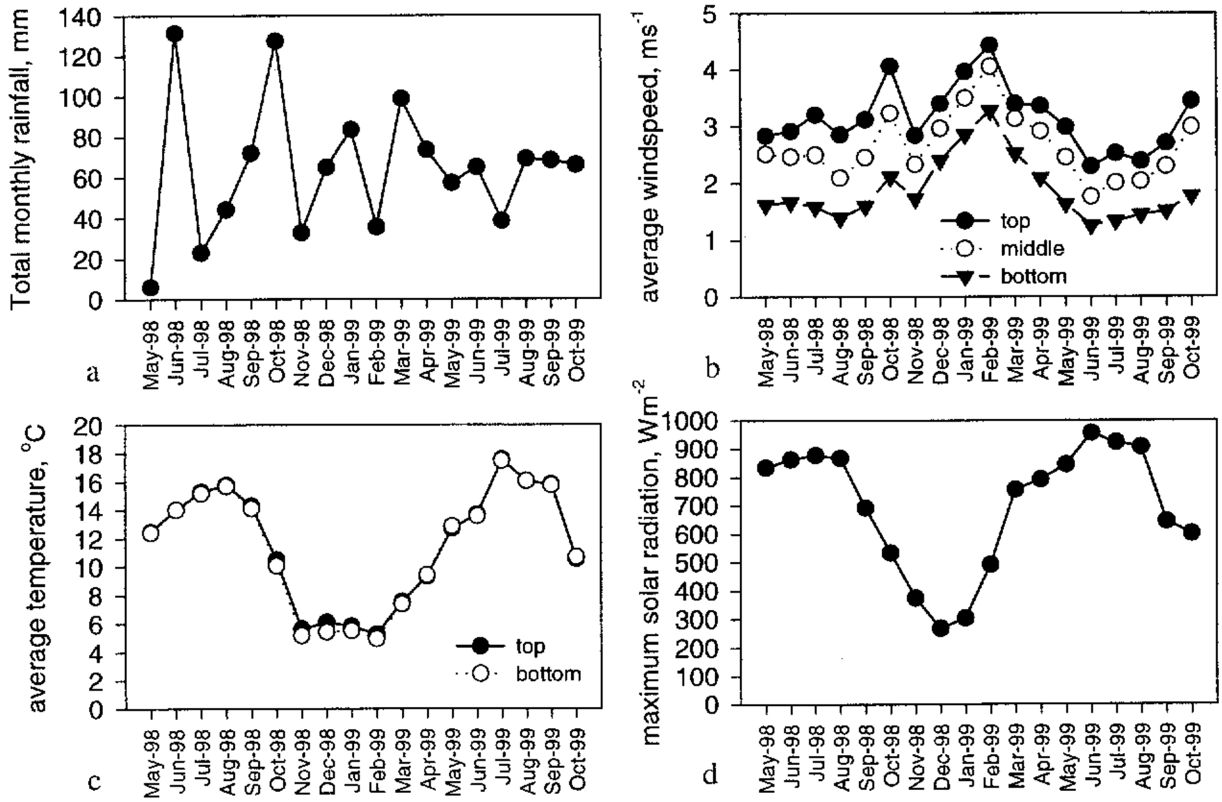
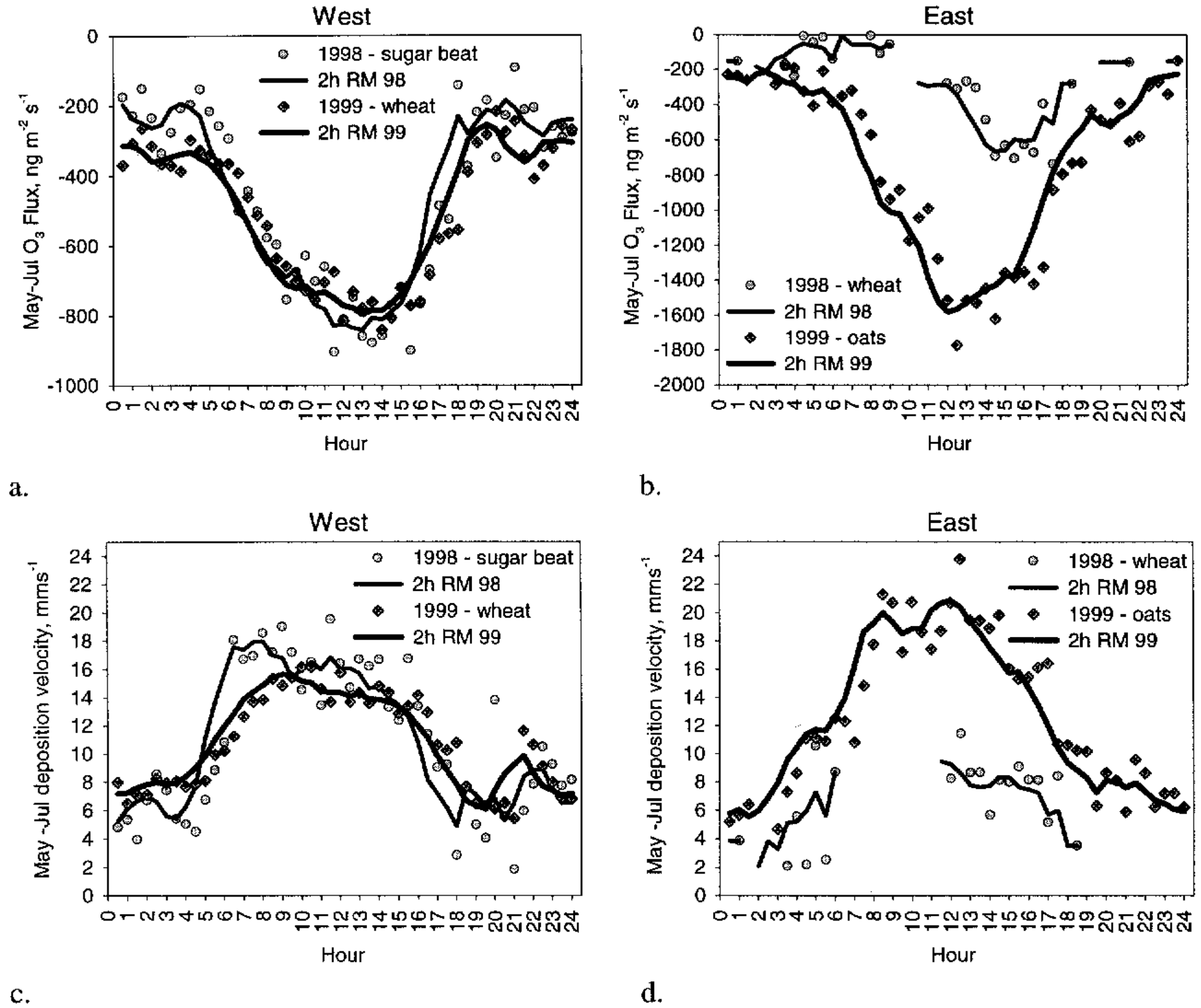


Figure 6. Plots of monthly mean a. total rainfall, b. wind speed, c. temperature and d. maximum solar radiation, measured at Sutton Bonnington.

Summary of O_3 deposition results from Sutton Bonnington

The analysis of data from Sutton Bonnington is on-going and a summary of the results obtained up to the end of October 1999 is given here. Figure 7, below, shows plots of the May to July average ozone flux and deposition velocity measured over the west and east fields during 1998 and 1999. The sugar beet and wheat in the west field during 1998 and 1999 respectively have show similar patterns of ozone deposition although night-time fluxes may be slightly enhanced over the wheat. The measurements from the east field are more scattered due to the low frequency of winds from that sector. The wheat in the east field during 1998 has an ozone flux of similar magnitude to the west in 1999 although the deposition velocities appear to be slightly lower. The 1999 easterly data indicates a large ozone flux and high deposition velocities to the oats.



a. b. c. d.

Figure 7. Average diurnal cycles on ozone flux and deposition velocity, over each crop during May to July 1998 and 1999. Half-hourly averages are plotted with symbols and the lines show the 2 hour running mean.

Figure 8 shows plots of the monthly mean ozone flux and deposition velocity from the west field partitioned into day and night-time values.

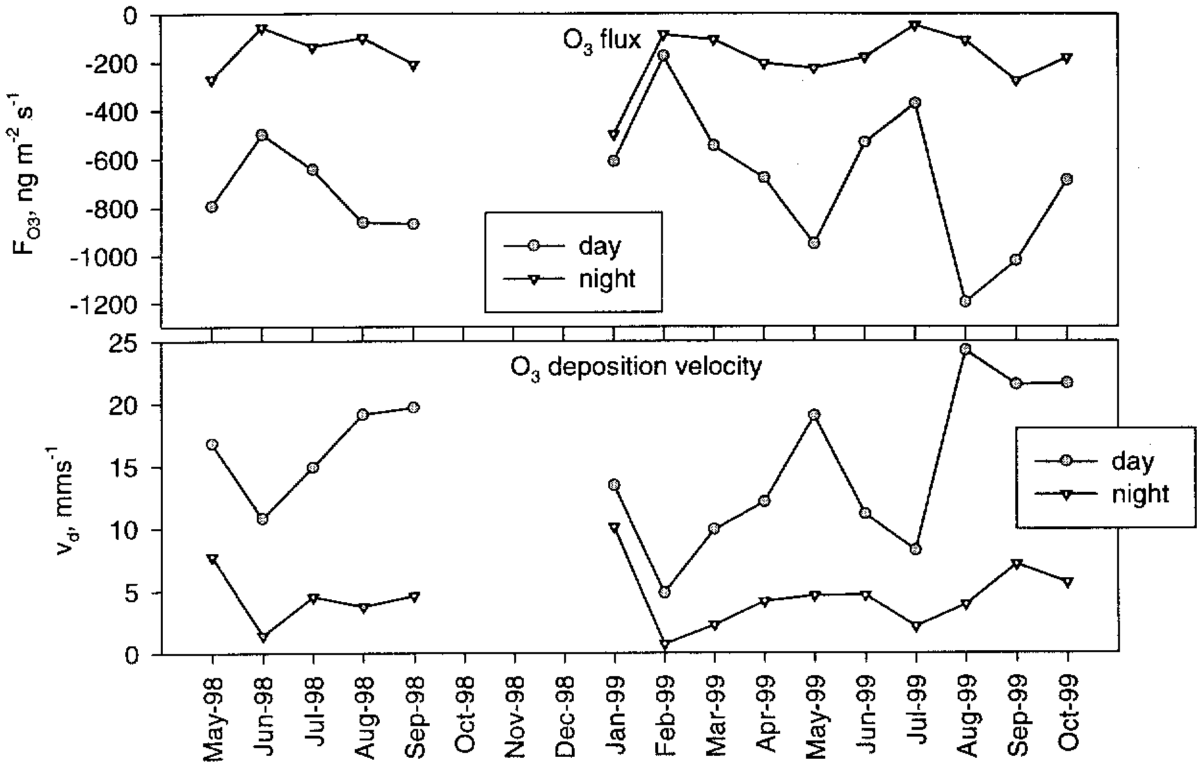


Figure 8. Monthly mean ozone deposition flux and velocity measured from the westerly wind sector at Sutton Bonnington, partitioned between day-time and night-time values (day-time solar radiation ≥50 Wm^{-2}).

Auldhame Farm - Potatoes

The site at Auldhame farm was set up at the beginning of June 1999, however the first few weeks data were lost due to problems with the power supply and data retrieval. Regular measurements of ozone concentration, wind speed and temperature started on the 2nd of July 1999 and the solar radiation sensor and wind vane became operational on the 7th and 5th respectively. Table 2 gives a timetable of operations at the site and table 4 summarises the data capture achieved for the main parameters.. Figure 9 shows a wind rose of wind direction frequency, indicating that the prevailing wind direction, throughout the measurement period, is south westerly and includes the good fetch.

Table 4. Monthly %data capture (%DC) for measurements at Auldhame Farm.

Period		O$_3$	Solar Rad.	Wind speed	T	Wind direc.
%DC all data	**from 4th Jun- 99**	36.5	0.0	36.8	36.7	99.7*
	Jul-99	52.2	41.9	52.3	52.3	99.3*
	Aug-99	32.9	36.4	36.4	36.4	100
	to 21st Sep-99	50.7	55.7	55.7	55.7	100
%DC in good sector	**from 4th Jun- 99**	55.4	0.0	56.0	56.0	65.8*
	Jul-99	99.2	80.1	99.4	99.4	52.3*
	Aug-99	91.5	100	100	100	36.4
	to 21st Sep-99	90.8	99.8	99.8	99.8	55.7

*100% June and 14% (50% in sector) July contains UKMO wind direction data from Blackford Hill, Edinburgh (obtained from the BADC).

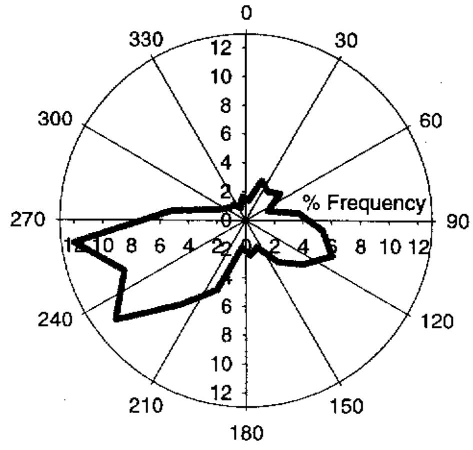
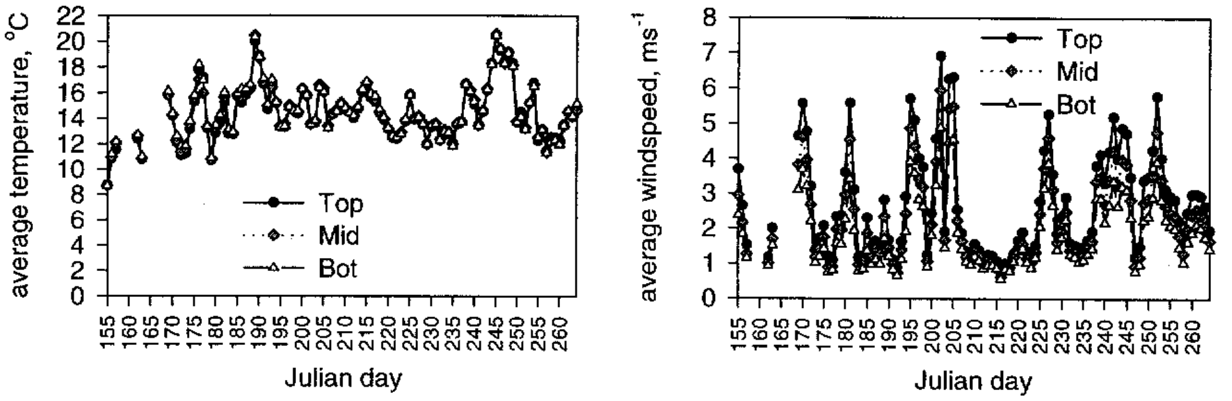


Figure 9. Wind rose of the % frequency of wind directions during the field measurements at Auldhame Farm.



a.

b.

Figure 10. Daily mean temperature and wind speed measured at Auldhame Farm.

Figure 10 above shows the daily mean temperature and wind speed measurements from Auldhame Farm. The average temperature during the period was 14.5 °C with around ±0.5 °C difference between the top and the bottom measurement height. The daily mean wind speeds at each height clearly show a positive gradient with a difference of 0.5 to 2 ms^{-1} between the top and the bottom.

Summary of O_3 deposition results from Auldhame Farm

The gradient in ozone concentration measured over the potatoes was often small during the day-time, with a difference of only about 0.2 ppb between the top and bottom heights. During the night when a stable boundary commonly develops larger differences of over 5 ppb were measured. The ozone analyser used has a precision of ±1 ppb and so when the concentration differences are small the uncertainty in the measured gradient becomes large. To compensate for the uncertainty in some of the measurements and smooth out noise, the data was block averaged into 4 hour periods over June to July and August to September, as shown in Figure 11. The diurnal cycle in ozone deposition can be seen with enhanced flux and increased deposition velocity from 830 to 2000. There is a clear difference between the June-July period and August-September. During June and July the potatoes were in the main period of active surface growth and so the ozone deposition is enhanced whereas during August to September the canopy began to die back, reducing the amount of deposition.

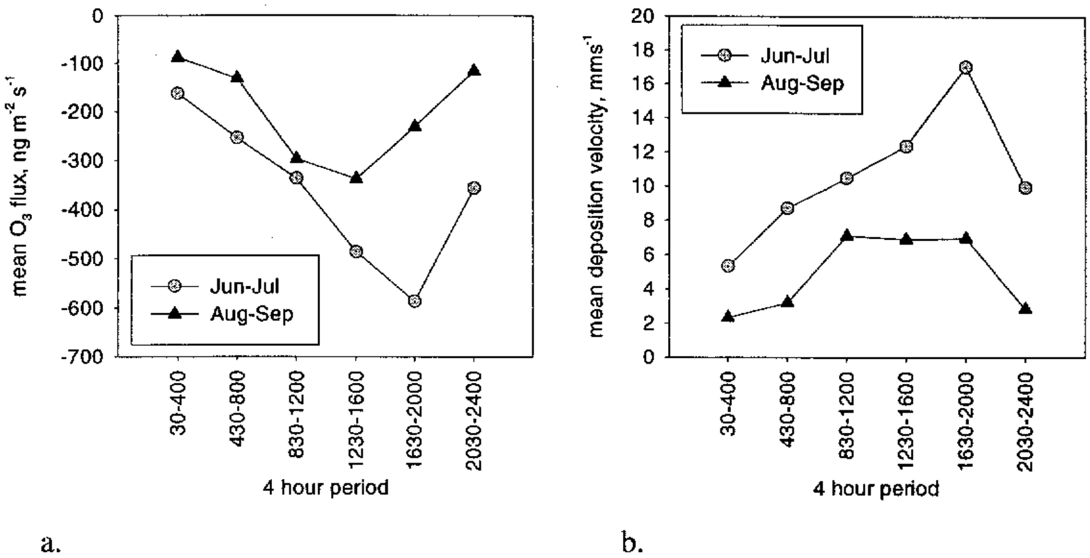


Figure 11. Average ozone flux and deposition velocity measured over potatoes at Auldhame Farm.

Conclusions

- Substantial seasonal data sets, of total ozone flux, are available for sugar beet (1305 hours), wheat (1615 hours), oats (403 hours) and potato (2290 hours) crops.
- The data for wheat and sugar beet, show that the non-stomatal uptake of ozone represents > 50% of the total flux over the growing season, but the precision of estimates for the daily measurements is limited.
- Ozone deposition fluxes to potatoes provide estimates of the total seasonal flux to the crop.
- Analysis of the data for all crops is in progress to: quantify the stomatal and non-stomatal components of the total flux; show whether the variables associated with large evaporative demand and water stress are associated with the magnitude of the stomatal ozone flux.

Acknowledgements

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