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ASSESSMENT AND EVALUATION OF CRITICAL LEVELS FOR O_3 AND NH_3

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Abstract

The effect of O_3 on three different tree species was similar. A threshold of 40 ppb was found for *Pinus* and for *Pseudotsuga*. Over two growing seasons growth was inhibited in *Pinus* and *Fagus* saplings and total assimilation per tree was inhibited over one growing season in *Pseudotsuga* trees. *Pinus* was most sensitive to O_3, but a critical level of 10 ppm.hrs is sufficient to protect the three species from O_3 damage. The effect of NH_3 on growth was ambiguous. Growth was unchanged in *Fagus*, stimulated in *Pseudotsuga* and inhibited in *Pinus*. The effect of NH_3 on tree architecture and stress sensitivity was similar. Tree architecture was changed in both *Fagus* and *Pseudotsuga* and drought and frost sensitivity were increased in *Pinus* and *Pseudotsuga*. At the moment both the critical level for O_3 and for NH_3 are exceeded in The Netherlands in general and in selected areas in particular.

1. INTRODUCTION

The current estimation of the mean nitrogen load in the Netherlands is 35 kg ha^{-1} yr^{-1} of which the largest proportion (16 kg ha^{-1} yr^{-1}) is gaseous ammonia. The regional mean NH_3 concentrations, however, may be very different from the average national concentration, resulting in a much higher exposure level for forest trees in areas with intensive live stock farming [1]. Ozone, another relevant air pollutant, is more evenly distributed over the Netherlands (Tab. 1). The national mean concentration exceeds the phytotoxic level for crops [2], and the economic impact on Dutch crops is large [3]. The effect of O_3 on mature forest trees, on forest ecosystems and on natural ecosystems in general is largely unknown. The available information is mainly acquired from experiments with seedlings and saplings [4].

Two types of air quality standards are currently in use: critical levels and critical loads. Critical levels are based on exposure values, while critical loads are based on deposition values. The use of two different air quality standards is justified, because critical levels focus on individual air pollution components and on non-depositing oxidants such as O_3, whereas critical loads lump either nitrogen or acidifying components together. Moreover critical levels are usually used for short-term exposures (hours - months) and critical loads for long-term exposures (years).

The aim of the present investigation was to assess the impact of NH_3 and O_3 on forest ecosystems at concentrations presently occurring in the Netherlands in relation to the critical level. This was done by comparing the effects on tree saplings exposed to both pollutants in OTC's (Open Top Chambers) with the effects on mature forest trees under ambient field conditions.

2. MATERIAL AND METHODS

2.1 Fumigation experiments in OTC's

Two experiments were performed in OTC's, in which 3-yr-old Beech (*Fagus sylvatica* L.) and Scots pine (*Pinus sylvestris* L.) saplings were fumigated for 15 months, largely covering two growing seasons (from June 1 to September 1). The OTC's have been described earlier [5]. Ammonia and ozone were injected into the air stream prior to the blower via thermal mass-flow controllers (Brooks 5850 TR). Air pollutant concentrations were sequentially monitored with an ozone analyzer (8810, Monitor Labs) and a NH_3 monitor (thermoconverter model 8750 followed by a chemiluminescent NO_x analyzer model 8840, both Monitor Labs) and were computer-controlled. The data were recorded with a HP data acquisition system. A duplicated range of O_3 concentrations (0, 30, 60, 90, 120 and 150 $\mu g\ m^{-3}$) was used in the first experiment and these concentrations were both higher and lower than current ambient concentrations in the Netherlands (Tab. 1).

Table 1
Average concentrations of NH_3 and O_3 ($\mu g\ m^{-3}$) in 1992.

	NH_3	O_3
The Netherlands	3.4	60
Wageningen, OTC's	16	72
Veluwe, field	2.5	78

Trees were exposed to O_3 during a 9 h day and to a third of the daytime concentrations during the remaining 15 h. To one of the O_3 ranges, a concentration of 40 $\mu g\ m^{-3}$ NH_3 was added (24 h day^{-1}), which is somewhat higher than the highest mean concentrations experienced in the Netherlands. In the control treatments, the NH_3 concentration was also higher (15 $\mu g\ m^{-3}$) than the national mean due to the fact that Wageningen is located in a region with high NH_3 concentrations (Tab. 1), and the filters used to clean the air have less that 50% capacity for NH_3. In the second experiment, O_3 and NH_3 were applied in factorial design, resulting in a triplicated set of O_3 concentrations (setpoints 0, 90, and 135 $\mu g\ m^{-3}$), supplemented with ambient air, or with NH_3 to 40 $\mu g\ m^{-3}$ and 80 $\mu g\ m^{-3}$ NH_3. The water potential on 1-year-old needles of *Pinus sylvestris* was measured with a pressure bomb [6]. The measurements were performed in six OTC's only, in all three NH_3 treatments combined with filtered air and the highest O_3 concentration and were performed between 08.00 and 13.00 hours in fully watered pots and again after five days without water. The soil water potential was measured daily to ensure that the drought treatment was not prolonged to the point where excessive drought injury to the trees occurred in order to relate the soil water potential to the needle water status. This paper discusses the main results on biomass production and drought sensitivity.

2.2 Correlation studies in the field

All field measurements were performed in a stand of 34-year-old Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco L., provenance Arlington), located at the Veluwe, in the central part of the Netherlands. The Speuld site has a stand density of approximately 800. In 1993, the average tree height was 22.2 m and the average DBH was 25.4 cm [7]. The mean O_3 and NH_3 concentration at Speuld are shown in Tab. 1. A computer controlled field gas exchange system was installed at the site. With this system up to 16 different branch assimilation chambers can be measured continuously. A 22 m high scaffolding was built in the middle of the stand, from which the branch assimilation chambers could be mounted in 8 different trees. The chambers were ventilated with ambient air and contained one year class of needles. Temperature, relative humidity and CO_2 concentration of the air entering the chambers closely resembled that of ambient outside air. A PAR sensor was mounted at the outside of each chamber. Each chamber was sampled twice every hour during 24 hours per day from March 1992 up to December 1993. The light response curve was modelled using the equation of Goudriaan [8] with the measured photosynthetic rate and photoactive radiation levels. The unexplained variance in the data could be reduced by 40% by taking into account changes in vapour pressure deficit (VPD) and the O_3 concentration. In this way, the direct effects of O_3, NH_3 and NO_x and VPD on the photosynthetic rate were statistically estimated. This paper discusses the results on CO_2 assimilation, per month and per year, and on the needle nutrient status.

2.3 Exposure-response relationship for O_3

The levels of exposure to O_3 used here are not expressed as concentrations, but as the *accumulated exposure over a threshold concentration*, abbreviated with AOT [4]. The AOT adds all exposures above a certain threshold concentration over the period of interest, i.e. growing season, but also over several years in which mean concentrations can strongly fluctuate over the seasons. The threshold value is the concentration above which O_3 toxicity becomes evident. The AOT approach proved to be very useful for evaluation of crop loss in which relative yield reductions could be linearly fitted to AOT values. Recently, this approach has also been applied to forest trees, although reliable field data are scarce [4].

3. RESULTS

3.1. Fumigation experiments in OTC's

Fig. 1 shows the effects of O_3 and NH_3 on the total biomass of *P. sylvestris*. The biomass of trees exposed to the lowest 3 levels of O_3 was significantly higher than that in the 3 highest levels. An effect threshold for O_3 is visible between 5 and 15 ppm-hrs. The 3 lowest O_3 concentrations below 40 ppb were logically similar in terms of AOT40, and this was also reflected in the biomass production in those treatments, indicating the validity of the threshold for *P. sylvestris*. The absence of a linear exposure-response relationship is likely due to the fact that high concentrations of O_3 inhibit stomatal conductance [9] and thus the uptake of O_3. The UNECE and the WHO recently recommended an AOT40 of 10 ppm-hrs as a critical level for trees, at which a 10% reduction in biomass production should not be exceeded. The results shown for *P. sylvestris* in Fig. 1 appear to support this critical level. Current concentrations of O_3 in the Netherlands however, exceed this critical level by more than a factor 2, indicating that O_3 is significantly reducing the growth of *P. sylvestris*. Fig. 1 also indicates that at low O_3 concentration, NH_3 tends to inhibit growth, but growth is not further reduced at higher O_3 concentrations.

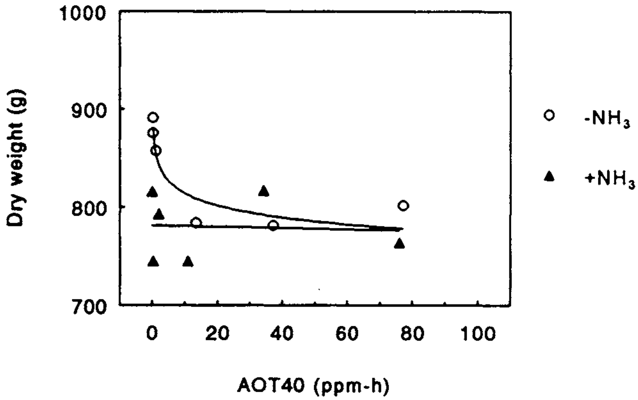

Figure 1. Effect of O_3 and NH_3 on the total biomass production *Pinus sylvestris*. o = O_3 alone; ▲ = O_3+NH_3.

In the same fumigation experiment, *F. sylvatica* was found to be less sensitive to O_3; a 10% reduction in biomass production was found at an AOT40 of 30 ppm-hrs, while NH_3 had no effect on the total biomass. The growth of *F. sylvatica* was differentially affected by NH_3 and O_3 in tree architecture rather than in biomass production (Fig. 2). Although O_3 inhibited tree height, it increased stem diameter, which resulted in relatively sturdier trees. NH_3 did not influence tree height and reduced stem diameter, resulting in relatively smaller trees at higher levels of O_3. Lateral branch growth was also reduced by NH_3 with increasing concentrations of O_3, thus reducing the potential for light interception.

In the second fumigation experiment, special attention was paid to the effect of NH_3 and O_3 on the drought sensitivity of *P. sylvestris*. The data in Fig. 3 show that needles of fully watered *P. sylvestris* saplings have a significantly higher (more negative) water potential when exposed to NH_3 alone than when exposed to NH_3+O_3.

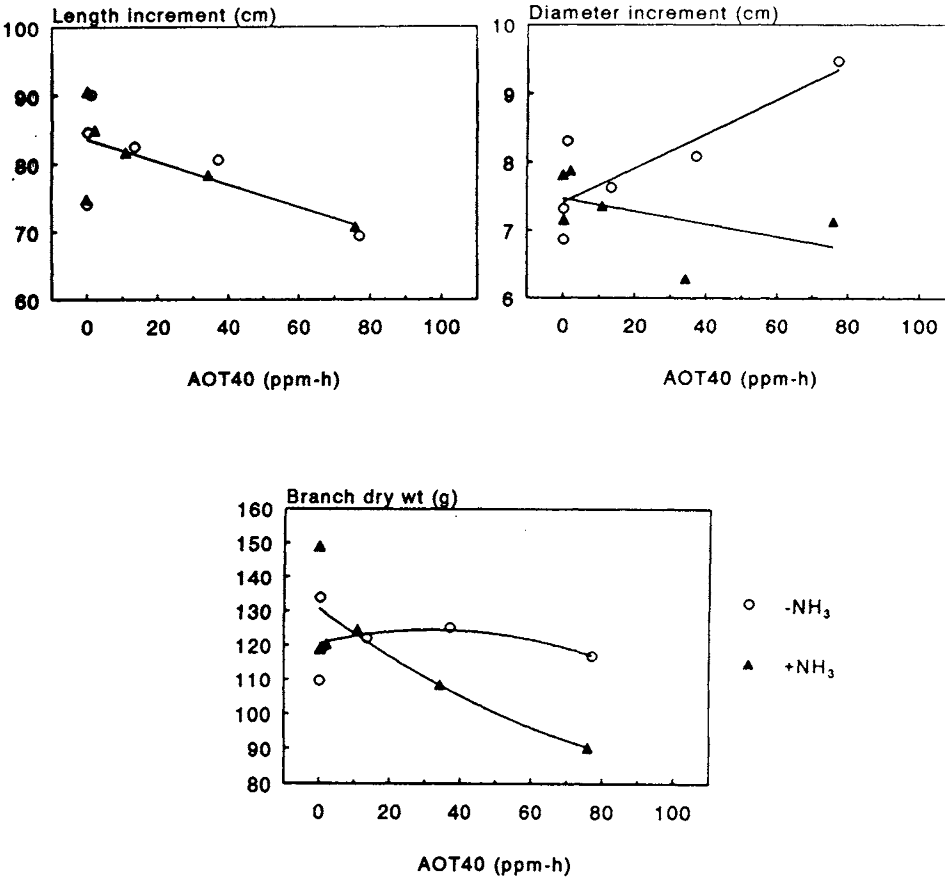

Figure 2. Effect of O_3 and NH_3 on mean length increment, stem diameter increment and branch dry weight of *Fagus sylvatica*. o = O_3 alone; ▲ = O_3+NH_3.

No difference was observed in the needle water potentials between the three treatments of only NH_3. It appears that, irrespective of the NH_3 concentration, O_3 inhibits stomatal conductance and thus transpiration in the absence of water stress, allowing the trees to maintain turgor at a lower (200-400 kPa) needle water potential than when exposed to NH_3 alone. When the trees were droughted for 5 days, the water potential increased linearly with increasing concentrations of NH_3 in the absence of O_3. This indicates that under conditions of drought stress, NH_3 disrupts the stomatal control, resulting in increased transpiration and reduced water use efficiency [10-11]. When O_3 was added to the NH_3 treatments, the effect of increasing NH_3 concentrations was masked, and the water potential in all three O_3+NH_3 treatments remained lower than in treatments with NH_3 alone. This confirms earlier experiments, in which the reduced transpiration of various species exposed to O_3 is attributed to inhibition of stomatal aperture [9]. Thus, even at the concentrations of NH_3 used in this experiment, O_3 appears able to reduce water loss through transpiration and is thus able to reduce drought stress.

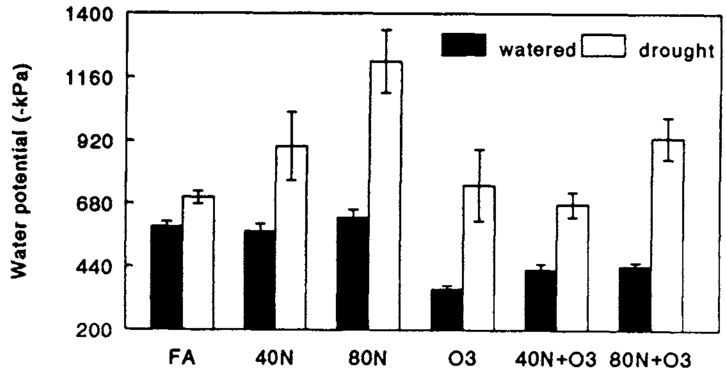

Figure 3. Effect of O_3 and NH_3 on drought stress of *Pinus sylvestris*. Dark bars indicate water potential (means ± SE) of watered trees and white bars that of droughted trees (n=10).

3.2. Correlation studies in the field

The vitality of the Speuld stand was characterized in 1986 according to international EC standards of defoliation and foliar discoloration. The vitality was higher than the nationwide average for *P. menziesii*, which was classified as less healthy for 50% of all trees [12]. The vitality was re-assessed in 1994, and was similar to the nationwide average, indicating that the vitality of the stand had decreased to the level of most other *P. menziesii* stands in The Netherlands, which was classified as less healthy for 80% of all trees [7].

Notwithstanding the poor vitality, biomass production was high. According to yield tables for Dutch *P. menziesii* stands [13], based on data from the pre-intensive livestock age, annual wood volume increment was higher than expected. Speuld can be qualified as an average soil quality site (class III) with an expected mean annual volume increment of around 13.4 m^3 ha^{-1}. The average annual increment over the period 1987-1993 however, was 24.7 m^3 ha^{-1}, which is even higher than the expected volume increment of 17.3 m^3 ha^{-1} on the best quality site class.

Table 2. Biomass partitioning in *Pseudotsuga menziesii* using foliage [7] and root [14] data from Speuld and from [15-16].

	Speuld	low productive, slow grow rate	high productive, fast grow rate
Foliage/ fine root	5.5	0.95-1.1	2.7-3.6
Foliage/ coarse root	0.67	0.21-0.34	0.19-0.31

The dry weight distribution in Speuld in which the N deposition is lower than the Dutch mean, was compared to that of other *P. menziesii* stands. Speuld can be best compared to high productive, fast growing stands of the same age. The foliage/root ratio in Speuld is exceptionally high compared to the other stands (Tab. 2). The high foliage/root ratio results from both lower root biomass and higher needle biomass. The high amount of needle biomass is also reflected in the LAI of the stand which was 10.7 in 1992. The foliage/coarse root ratio is also high (Tab. 2). The branch dry weight however, was lower compared to the other stands.

The nutrient status of the needles changed significantly during the experimental period [8]. The average N concentration increased from 1.7% in 1987 to 2% in 1993. The optimal concentration for biomass production in *P. menziesii* is 1.8%. The K concentration decreased from 0.7% to 0.5%, which is below the deficiency level of 0.6%. The P concentration remained constant, but was also below the deficiency level of 0.14%. The N/P ratio was constantly below/above the deficiency level, while the N/K ratio increased from 2.7 to 3.7. Extrapolating the nutrient trends found over the past 7 years, the ratio of N/K can be expected to reach the deficiency level within 1-2 years. High N/K ratio's, as found in the Speuld stand, are often considered as an indicator for increased stress sensitivity, e.g. frost sensitivity [17]. There seems to be little doubt that the high nitrogen status, the high productivity, the high foliage/root ratio, the high LAI and the increased stress sensitivity are caused by the high N deposition into the stand.

Table 3. Proportional reduction of the monthly CO_2 assimilation due to O_3 and VPD (mean over 2 needle age classes and three crown levels).

	O_3	VPD	O_3	VPD
	1992		1993	
April	3.3	2.4	28.0	14.0
May	12.2	22.9	13.2	8.1
June	4.4	20.1	4.4	6.1
July	5.3	6.3	7.6	2.9
August	4.1	7.0	5.4	NS

Net CO_2 assimilation was measured more or less constantly throughout 1992 and 1993 and was related to changes in meterological parameters and air pollution concentration. No direct effects of NH_3 and/or NO_x on net CO_2 assimilation of *P. menziesii* were found. NH_3 tended to stimulate assimilation, but the differences were not significant. The only obvious relationship of CO_2 assimilation with air pollution was that with O_3 (Tab. 3). The reduction of net CO_2 assimilation by O_3 on a monthly basis can be quite considerable, and was in the same range as the reduction by VPD.

The annual reduction of total CO_2 assimilation per tree was estimated to be in the range of 3-10% in 1992. The annual reduction over 1993 will probably be higher, as the monthly reductions are higher. In order to assess the critical level for O_3 for adult *P. menziesii* trees under ambient conditions, the reduction in biomass production by O_3 has to be known. We assumed that the annual reduction in total CO_2 assimilation is in the same range as the annual reduction in biomass production. Matyssek et al. however, (pers. commun.) found that a 40% reduction in total CO_2 assimilation resulted in a 60% reduction in biomass.

4. EVALUATION AND CONCLUSIONS

Despite the fact that different tree species were used, the reaction of saplings and adult trees under field conditions to high NH_3 concentrations showed both similarities and discrepancies. Most of the work done on effects of NH_3 on plants to date indicate that NH_3 stimulates growth, but the results presented in this paper show that NH_3 may also inhibit growth in the presence of low concentrations of O_3 in *Pinus*. In *Fagus* however, NH_3 had no effect on growth, but changed tree architecture by decreasing tree height and branch biomass. Under field conditions the high N input resulted in both increased growth and in a changed architecture. Dry weight distribution in *Pseudotsuga* was affected, as foliar biomass was higher and fine root and branch biomass was lower. Another similarity was the increased sensitivity. NH_3 was found to increase drought sensitivity in *Pinus* saplings, and both drought and frost sensitivity in adult *Pseudotsuga* trees under ambient conditions. NH_3 is the major part of the total N deposition in the Netherlands. The aim to reduce emissions until critical loads are not exceeded, will surely reduce NH_3 levels below the critical level for NH_3. The critical level proposed for NH_3 is 8 and 270 $\mu g\ m^{-3}$ respectively, for an annual and a 24 hrs mean [18]. The annual mean is currently being exceeded in half of the Dutch areal [1]. On sites removed from the direct influence of point sources, the 24 h critical level is probably not being exceeded, not even in the Netherlands. Exceedances are frequent only on a local scale, in the first 300 meters from a point source. If environmental policy will be based on damage estimates in relation to emission and dispersion, knowledge of effect thresholds of NH_3 is insufficient. Although NO_x is only a small part of the total N deposition, its abatement would be very profitable because it would reduce the O_3 concentration as well.

High O_3 concentrations resulted in decreased growth in all tree species. However, a 10% reduction in biomass production was reached at different AOT40 values (Fig. 4). It seems that the critical level for forest trees of 10 ppm.hrs is able to protect our trees from damage by O_3. From the range of AOT40 values between '87-'93 it is evident that these values are exceeded in general and in the forested area of the Veluwe in particular. Timber producers may not bother about a 10% reduction in biomass by O_3 if the fertilizing effect of atmospheric N deposition compensates for the losses by O_3. However, this does not hold for the Dutch situation. First of all growth stimulation by N is of a temporary nature. An initial growth stimulation by N is accompanied by increasing ratio's of N to cations and following luxurious N consumption will eventually lead to a decreased growth due to severe cation deficiencies [19]. The progressing nutrient status of Speuld suggests that it will not take decades to reach this situation. Furthermore, a number of forested areas in The Netherlands appears to have reached the stage of growth reduction already [19].

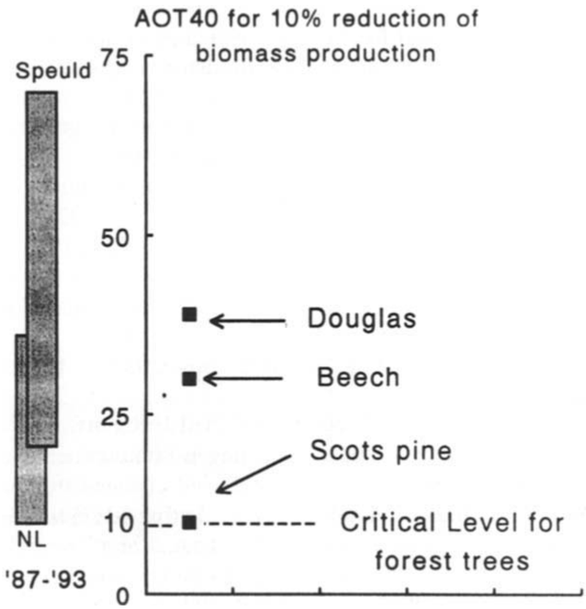

Figure 4. AOT40 values for forest trees. The columns on the left indicate the range of O_3 concentrations measured during 1987-1993 in Speuld (25m height) and as a national average (3m). The arrows indicate the AOT40 values for *Pinus sylvestris*, *Fagus sylvatica* saplings and for mature *Pseudotsuga menziesii*, presented in this paper in relation to the critical level proposed for forest trees.

Secondly, forests are more than trees alone. The impact of air pollution on trees (and crops) should not be seen as indicative of the unknown effects on other parts of the forest ecosystem. Effects on herbs and grasses in the undergrowth and on biodiversity of plants and animals are likely to be more pronounced [20]. The results presented in this paper suggest that all three tree species used in the experiments are adversely affected by current O_3 concentrations in The Netherlands. The possibilities to quantify this damage has increased strongly in recent years, but much has yet to be done.

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