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Ozone and forests in South-Western Europe – What have we learned?

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Documented evidence for a potential risk to forest due to ozone requires an improvement in monitoring methods.

Abstract

Monitoring of forest condition and ozone (O_3) at 83 sites in France, Italy, Luxenbourg, Spain and Switzerland resulted in a number of findings in relation to the knowledge of O_3 exposure (concentration and cumulative AOT40), feasibility of the assessment of stomatal O_3 flux and relationships between O_3 and crown defoliation of beech and visible symptoms on native vegetation. However, the project provides evidence of issues to be addressed within the current monitoring system (data quality, validation sites and response indicators) and indications as to how the monitoring of O_3 risk in the context of an effect-oriented monitoring program can be improved.

Keywords: Forests; Ozone; Europe

1. Introduction

Ozone (O_3) levels and effects on forests are of considerable concern in Europe, North America as well as in rapidly developing economies (Percy et al., 2003; Emberson et al., 2001). In a recent paper, Karnosky et al. (2003) pointed out some needs in relation to the monitoring of O_3 levels and effects on forests: (i) to increase monitoring in forest areas around the world, (ii) to increase monitoring in urban and rural areas of developing countries, (iii) to increase the use of passive samplers, (iv) to link forest health monitoring to O_3 monitoring, (v) to examine the relationships between forest health and O_3 and (vi) to link forest health monitoring to geographic information systems to allow the use of satellite imagery in forest health classification. The project ‘‘Ozone at the intensive monitoring plots in South-Western European Forests’’ (O_3SWE) (Ferretti et al., 2007a,b, in press) addressed some of these monitoring needs. It was based on the EU and UN/ECE intensive forest monitoring program, which provided the basis for coupling forest health monitoring and O_3 monitoring. Results were extensively reported by Sanz et al. (2007), Gerosa et al. (2007), Schaub et al. (2007) and Ferretti et al. (2007a,b, in press). In this paper, we summarize the main results obtained and the main problems identified in order to suggest possible

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improvements in monitoring (Table 1). This information will be useful for those who intend to start and/or continue O_3 monitoring at their forest plots and will favour future analyses on a broader geographical scale.

1.1. Main results

Within the investigated plots (located in France, Italy, Luxenbourg, Spain and Switzerland), mean seasonal O_3 concentrations were in most cases between 30 and 45 ppb, with significant latitudinal and altitudinal gradients (Sanz et al., 2007). Concentrations were higher in 2001 and weekly peak values exceeded 90 ppb. Estimated AOT40 (the O_3 Accumulated Over Threshold 40 ppb) (Gerosa et al., 2007) show that, on average over the 2000–2002 time period, the critical level of 5 ppmh (Karlsson et al., 2003a,b) was exceeded at 77–100% of the plots. However, Schaub et al. (2007) pointed out that – even at relatively high exposure levels – the O_3 canopy uptake can be strongly reduced in water-limited sites due to the effect of vapour pressure deficit (VPD) and soil moisture deficit (SMD). Multivariate analysis confirmed the intuitive assumption that soil and site factors are important factors related to mean plot defoliation of beech (*Fagus sylvatica* L.), but O_3 resulted a significant predictor (significant at $P = 0.008$) (Ferretti et al., 2007a,b, in press). However, when annual deviations from expected defoliation were considered, a role of O_3 was obvious only at high exposure levels (>35 000 ppbh in terms of AOT40, UN/ECE, 2004), i.e. 7 times higher than current critical levels (set at 5000 ppbh, Karlsson et al., 2003b). Visible foliar symptoms (65 species symptomatic at 74 sites) show limited relationships with O_3 exposures.

1.2. Main problems

A list of the main problems encountered in addressing the various objectives is in Table 1. They include many issues, some of which are strategic and common between all the various objectives. This group include:

- Data quality (data coverage in space and time, data completeness, sampling design, reliability and comparability): It is the key issue as it affects all investigations and all objectives. This is particularly true for O_3 canopy uptake modelling, which is very much demanding in terms of data intensity and completeness.
- Calibration and validation sites: Calibration sites are limited for passive sampling (6) and sites providing a solid data base for the flux model validation were lacking in this project are rare in general.
- Response indicators: Up to now, over the examined period, only crown defoliation and visible symptoms were available as response indicators. They differ in specificity (O_3 visible symptoms are more specific), but their assessment is constrained by a number of factors (sampling and nonsampling error, high variability of species composition between plots, high variability of between- and within-species sensitivity).

1.3. Suggestions for possible improvement

Suggestions for an improved monitoring include (Table 1):

- Ensure a full coverage of O_3 measurements throughout April–September, and if possible extend the measurement

Table 1
Main results, main problems and suggestions for improvements in relation to the objectives of the O_3SWE project

Objective	Main results	Main problems	Suggestions
1. O_3 concentration in forests (Sanz et al., 2007)	Data for 83 remote sites show seasonal mean 30–45 ppb and evidence of significant latitudinal and altitudinal trends ($P < 0.0001$)	Data completeness	Ensure coverage of April–September period
		Unequal exposure periods	Adopt 1-week sampling regime
		Few calibration sites; lack of correlation ($P > 0.05$) in 21.7% of cases of parallel measurements with automatic monitors	Existing air quality networks to supplement calibration sites
2. AOT40 estimates (Gerosa et al., 2007)	AOT prediction significant ($P < 0.0001$; standard error, $P = 0.05$: 3.27 ppmh). Data for 81 remote sites show 77–100% of sites >5 ppmh and significant latitudinal and altitudinal trend ($P < 0.01$)	As above plus	As above plus
		Upscale concentration at canopy level	Derive and test correction factors
		Improve hourly estimates	Better parameterization of the model
3. O_3 uptake (Schaub et al., 2007)	Flux approach proved feasible, although data intensive. Data for 6 sites show mean monthly flux 1–2.7 nmol O_3 m^2 PLA and inconsistency with exposure data due to driving influence of VPD and SMD	As above plus	As above plus
		Data availability and completeness	Increase completeness of meteo measurements
		Lack of flux validation sites	Identify sites and/or datasets for model parameterization and out-put validation.
4. O_3 effects (Ferretti et al., 2007a,b, in press)	AOT40 significant at $P = 0.008$ in a model predicting defoliation of beech plots. Visible symptoms on 65 species and 73 sites with no relationship with exposure	Nature of the response indicators	Consider growth, modelling approach and improve statistical analysis
		Ozone exposure	Reduce uncertainty (see above)
		Data completeness and reliability	Improve data coverage, completeness, reliability and comparability
		Multicollinearity	Improve statistical methods

period throughout the year in particular for the Mediterranean evergreen forests (e.g. *Quercus ilex*).

- Avoid monthly exposure periods for passive sampling. One-week exposure periods should be emphasised as a future target, at least for southern Europe, and this will permit a more sound modelling approach. A possible drawback is the increase of costs and personnel needs: however, it should be considered that many intensive monitoring plots are visited regularly for deposition sampling and routine checks. Thus, the increase of costs will be less than expected.
- Increase the number of calibration sites in order to provide more robust calibration datasets; carry out a cross-calibration exercise for passive sampling to assess and document the data quality and to identify and address critical QA/QC issues.
- Improve the reliability of individual hourly estimates by a better parameterization of the model function and/or adopting a different modelling approach, when possible (e.g. Krupa et al., 2003). This latter option, however, requires meteorological data, which are not always available in the forest monitoring plots.
- Concentration data need to be scaled up to the canopy height, at least by using empirical functions and/or coefficients.
- Coordinate the recording of meteorological parameters with the recording of O_3 concentrations to enable more solid datasets as input for flux modelling and effect evaluation.
- Promote a more sound experimental design in future monitoring and observational studies. This implies a full consideration of the statistical requirements to detect effects (sampling design), sound response indicators that must be consistent with those used in experiments (see below) and data of known quality (Percy and Ferretti, 2004; Manning, 2005).
- Objective and sound response indicators are needed. Response indicators such as growth needs to be considered in the future: this will allow an objective estimate for the overall tree/ecosystem response and will help to keep consistency with the currently applied critical levels, which are based on biomass reduction. It is necessary to stress the need for annual growth data, it is essential and it can be achieved by tree-ring analysis. Visible symptoms are of values, but their assessment needs to be improved in terms of statistical design, species to be considered and observer and method performance. Some of these improvements have been already addressed.
- Re-consider the suitability of an unique exposure critical level to estimate the potential for a risk to forest due to O_3 in Europe. For the time being, a unique critical level of 5000 ppbh has been set in order to protect sensitive species under sensitive conditions (UN/ECE, 2004). This limit has been questioned since some time (De Santis, 1999) and proven unrealistic and unattainable over most of the plots investigated by the O_3SWE project (Gerosa et al., 2007; see also Ferretti et al., 2007a,b, in press).
- Identify a network of validation sites for flux modelling. In this respect, the sites involved in the CO_2 flux research networks (e.g. Valentini et al., 2000) can be of help.

2. Conclusions

Ozone passive sampling at 83 forest monitoring sites in France, Italy, Luxenbourg, Spain and Switzerland resulted in a number of findings in relation to the knowledge of O_3 exposure (concentration and cumulative AOT40), feasibility of the assessment of stomatal O_3 flux and relationships between O_3 and crown defoliation of beech and visible symptoms on native vegetation. In addition, the work leads to the identification of a number of issues related to the monitoring set-up, methodology, data completeness and availability, data reliability and comparability. A number of suggestions for the improvement of the monitoring activities have been proposed towards a more effect-oriented program. However, these suggestions need to be incorporated in a consistent, coordinated effort for data collection and management. Consistent and harmonized routine procedures and clear definition of monitoring endpoints are essential to ensure a more effective long-term forest monitoring and more straightforward evaluation of the O_3 risk assessment for European forest ecosystems.

References

De Santis, F., 1999. New directions: will a new European vegetation standard be fair to all European countries? Atmospheric Environment 33, 3873–3874.

Emberson, L.D., Ashmore, M.R., Murray, F., Kuylenstierna, J.C.I., Percy, K.E., Izuata, T., Zheng, Y., Shmizu, H., Sheu, H., Liu, C.P., Agrawal, M., Wahid, M., Abdel-Latif, N.M., van Thienoven, M.N., de Bauer, L.I., Domingos, M., 2001. Impacts of air pollutants on vegetation in developing countries. Water, Air, and Soil Pollution 130, 107–118.

Ferretti, M., Bussotti, F., Calatayud, V., Sanz, M.-J., Schaub, M., Kräuchi, N., Petriccione, B., Sanchez-Peña, G., Ulrich, E., 2007a. Ozone and forests in South-Western Europe: an introduction. Environmental Pollution 145 (3), 617–619.

Ferretti, M., Bussotti, F., Calderisi, M., 2007b. Ozone exposure, defoliation of beech *Fagus sylvatica* L and visible foliar symptoms on native plants in selected plots of South-Western Europe. Environmental Pollution 145 (3), 644–651.

Ferretti, M., Fagnano, M., Amoriello, T., Badiani, M., Ballarin-Denti, A., Buffoni, A., Bussotti, F., Castagna, A., Cieslik, S., Costantini, A., De Marco, A., Gerosa G., Lorenzini, G., Manes, F., Merola, G., Nali, C., Paletti, E., Petriccione, B., Racalbuto, S., Rana, G., Ranieri, A., Tagliaferro, A., Vialetto, G., Vitale, M. Measuring, modelling and testing ozone exposure, flux and effects on vegetation in southern European conditions – what does not work. Environmental Pollution, in press-c. doi:10.1016/j.envpol.2006.05.012.

Gerosa, G., Ferretti, M., Bussotti, F., Rocchini, D., 2007. Estimates of ozone AOT40 from passive sampling in forest sites in South-Western Europe. Environmental Pollution 145 (3), 629–635.

Karlsson, P.E., Selldén, G., Pleijel, H. (Eds.), 2003a. Establishing Ozone Critical Level II. IVL Swedish Environmental Research Institute, Gothenburg, Sweden. UN/ECE Workshop Report, IVL Report B 1523.

Karlsson, P.E., Uddling, J., Braun, S., Broadmeadow, M., Elvira, S., Gimeno, B.S., Le Thiec, D., Oksanen, E., Vandermeiren, K., Wilkinson, M., Emberson, L., 2003b. New critical levels for ozone impact on trees based on AOT40 and leaf cumulated uptake of ozone. In: Karlsson, P.E., Selldén, G., Pleijel, H. (Eds.), Establishing Ozone Critical

Level II. IVL Swedish Environmental Research Institute, Gothenburg, Sweden. UN/ECE Workshop Report, IVL Report B 1523.

Karnosky, D.F., Percy, K.E., Chappelka, A.H., Krupa, S.V., 2003. Air pollution and global change impacts on forest ecosystems: monitoring and research needs. In: Karnosky, D.F., Percy, K.E., Chappelka, A.H., Simpson, C., Pikkarainen, J. (Eds.), Air Pollution and Global Change and Forests in the New Millennium. In: Krupa, S.V. (Ed.), Developments in Environmental Science, vol. 3. Elsevier Science Ltd., Oxford (UK), pp. 447–459.

Krupa, S.V., Nosal, M., Ferdinand, J.A., Stevenson, R.E., Skelly, J.M., 2003. A multivariate statistical model integrating passive sampler and meteorology data to predict the frequency distributions of hourly ambient ozone (O_3) concentrations. Environmental Pollution 124, 173–178.

Manning, W.J., 2005. Establishing a cause and effect relationship for ambient ozone exposure and tree growth in the forests: progress and an experimental approach. Environmental Pollution 137, 443–454.

Percy, K., Ferretti, M., 2004. Air pollution and forest health: towards new monitoring concepts. Environmental Pollution 130, 113–126.

Percy, K.E., Legge, A.H., Krupa, S.W., 2003. Tropospheric ozone: a continuing threat to global forests? In: Karnosky, D.F., Percy, K.E., Chappelka, A.H., Simpson, C., Pikkarainen, J. (Eds.), Air Pollution and Global Change and Forests in the New Millennium. In: Krupa, S.V. (Ed.), Developments in Environmental Science, vol. 3. Elsevier Science Ltd., Oxford (UK), pp. 85–118.

Sanz, M.J., Calatayud, V., Sanchez-Peña, G., 2007. Measures of ozone concentrations using passive sampling in forests of South-Western Europe. Environmental Pollution 145 (3), 620–628.

Schaub, M., Emberson, L., Bueker, P., Kräuchi, N., 2007. Preliminary results of modeled ozone uptake for *Fagus sylvatica*L. trees at selected EU/UN-ECE intensive monitoring plots. Environmental Pollution 145 (3), 636–643.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.-D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, Ch., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalsky, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guomudsson, J., Thorgeirsson, H., Ibrom, K., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of European forest carbon balance. Nature 404, 861–865.