Chapter 8

Ozone Fluxes to a Larch Forest Ecosystem at the Timberline in the Italian Alps

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Additional information is available at the end of the chapter

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1. Introduction

Ozone is a phytotoxical pollutant causing negative effects on vegetation at biochemical, physiological, individual and ecosystem level [1]. Alpine forests, could experience high level of ozone concentrations, in particular in the southern part of the Alps. The reason of this phenomena is explained more in detail in the chapter 9, as well as the ozone effects on vegetation.

At the moment, from a regulative point of view, AOT40 (Accumulated Ozone over a Threshold of 40ppb) is the only instrument to evaluate the ozone hazard, even if its scientific soundness is widely discussed [2,3]. In fact, the AOT40 is an exposure index which does not take into account the physiology of the vegetation which is exposed to that ozone concentration. Since the greatest damages to vegetation are produced by the ozone entering through the plant stomata and plants can regulate stomatal opening as a response to the environmental parameters, a new approach based on stomatal ozone fluxes as been proposed by UN/ECE. In fact, the magnitude of the negative effects of ozone on vegetation is related to the real amount of this pollutant taken up through stomata [4], i.e. the dose or stomatal flux, and high environmental ozone concentrations in the air do not necessarily lead to high ozone doses, representing only a potential risk (more correctly an hazard).

The effective ozone dose, based on the flux of ozone into the leaves through the stomatal pores, represents the most appropriate approach for setting future ozone critical levels for forest trees. However, uncertainties in the development and application of flux-based approaches to setting critical levels for forest trees are at present too large to justify their application as a standard risk assessment method at a European scale [5].

The scientific community is hence moving toward an evaluation of the ozone risk based on stomatal ozone fluxes. This can be realized by means of measures or by models. Measurements allow to estimate only local ozone risk but they are necessary to parameterize and validate the models, which, once all the input data are available, allow to estimate ozone risk at regional, national or continental level.

Measurements of ozone fluxes are hence the first fundamental step for a proper evaluation of the ozone risk. The most used technique for the measure of ozone fluxes is called eddy covariance. This technique is based on the atmospheric turbulence and it requires particular instrumentation, which must be able to measure at least ten times per second the three wind components, the air temperature and the ozone and other gases concentrations. This kind of instrumentation must be mounted above the studied ecosystem. Additional meteorological measurements are useful for a better comprehension of the exchange process.

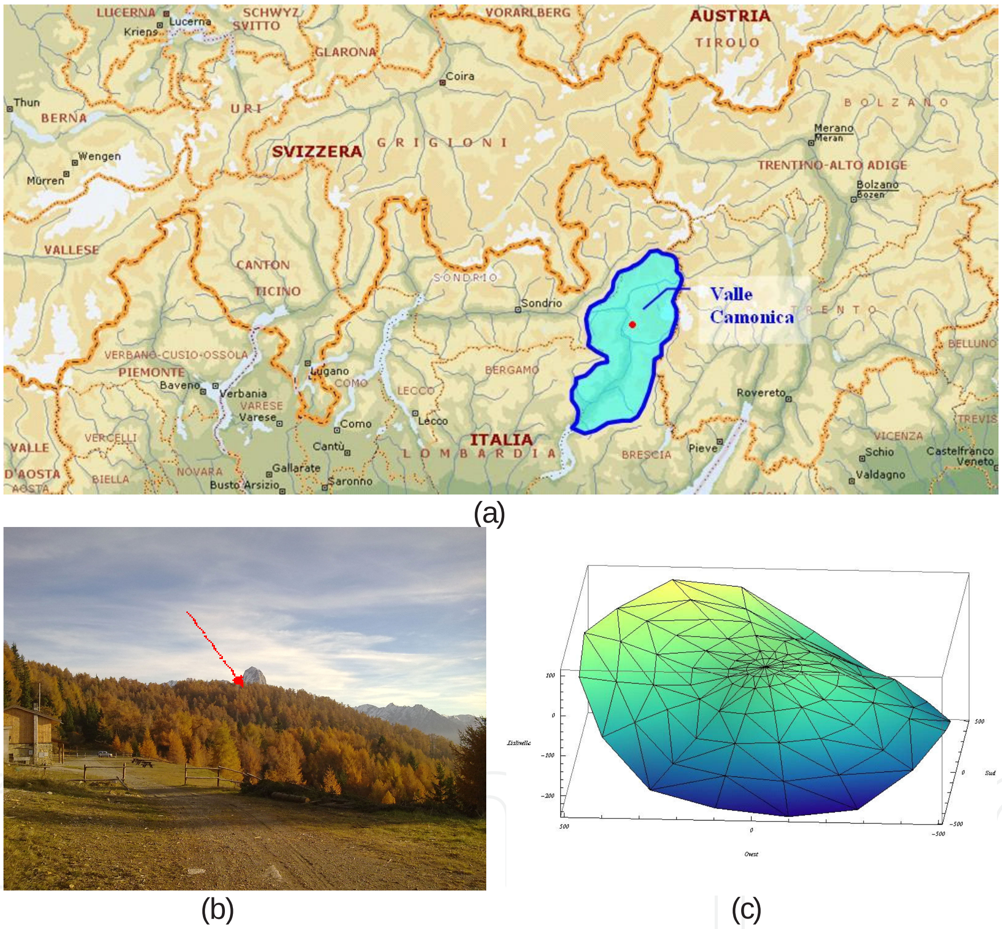

Figure 1. a) Geographical location of the Case Study 4: Valle Camonica, Northern Italy. The red dot indicates the position of the eddy covariance tower.; b) the studied larch forest, the photo was taken from a nearby refuge; c) local orography of the measurement site, the centre of the figure corresponds to tower localization

The eddy covariance technique allow to measure the total ozone deposition to the whole ecosystem, without distinguishing between how much ozone enters through plant stomata (the most harmful pathway) and how much is destroyed on the plant surfaces or on the terrain. In order to estimate the ozone stomatal fluxes, water is used as a tracer. In fact, it is assumed that ozone can enter into plant stomata when they are open during carbon uptake and plant transpiration: for this reason concomitant water fluxes measurements allow for the partition the total ozone fluxes between the stomatal and the non-stomatal component [6].

Once the stomatal flux is known it is possible to calculate the ozone dose (which is simply the sum of the stomatal ozone fluxes) and the Phytotoxical Ozone Dose (POD_1, which is the cumulated dose over the threshold of 1 nmol O_3 m^{-2} s^{-1}) [4]. The POD_1 have been introduced in the UN/ECE scientific community because it takes into account the internal capability of the vegetation to detoxify part of the ozone entering through the stomata. Moreover, many experiments have showed that the POD_1 is better correlated with the biomass reduction than the simple ozone dose, allowing thus to estimate the harmful effects of ozone on vegetation.

In this chapter an example of micrometeorological measurements of ozone fluxes over a high elevation larch forest, performed within the framework of the MANFRED project, are presented and discussed. The aims of this field campaign were to quantify the ozone deposition to a forest ecosystem at the timberline in the southern Alps (the more exposed to ozone) and to assess the actual ozone taken up by trees through stomata; a further aim was to gather data for the development of a stomatal uptake model to be employed for the simulation of the ozone deposition to timberline forests in future climatic and ozone pollution scenarios.

Till now ozone uptake by larch at treeline has only been investigated at the twig level [7], so the Eddy Covariance measuring technique has been chosen to get information at whole ecosystem level.

2. Methodology

2.1. Measurements

A micrometeorological tower was run for two years in Paspardo, Valle Camonica, in the Brescia district in Italy (46°2’40”N, 10°23’04”) (Figure 1a). Measurements interested only the summer season of the two years: July-October in 2010 and June-September in 2011. The studied ecosystem was a 10 ha larch forest (*Larix decidua*, Mill) with a mixed grass understorey used as a cattle pasture at 1750 m a.s.l.. Trees were between 100 and 350 years old and their average height was about 26 m. The trees coverage of the population had a LAI equal to 0.9 and a SAI equal to 0.7, while the understorey grass and shrubs had a LAI equal to 1.3 and a SAI equal to 0.2. The ecosystem lays on a westward gentle slope, with an inclination ranging between 3° and 13° (Figure 1b and Figure 1c).

The selected micrometeorological technique was the eddy covariance which requires fast response instrumentation for wind, temperature, water and ozone. For this sake an ultrasonic three axial anemometer-thermometer (USA-1, Metek, D) was installed at 29 m, on the top of the tower, just above the canopy. At the same height an open path krypton-light hygrometer (KH2O, Campbell, USA) was set. Ozone concentrations were sampled from air drawn near the sonic anemometer with two instruments: a fast response one (COFA, Ecometrics, I) and a standard UV photometer (1308, SIR, E) used as a reference since COFA uses cumarine targets whose sensitivity decays in 5 days and have to be changed. At four different levels of the tower additional thermo-hygrometrical (HD9000, Deltaohm,I), radiation (LPAR01, Deltaohm, I) were installed in order to obtain vertical profiles of each parameter. Moreover three reflectometers (CS616, Campbell, USA) and three thermopiles (SHFP, Hukseflux, NL) were deepen into the ground to measure soil water content and soil heat fluxes. In order to assess the energy balance closure a net-radiometer (NR-LITE, Kipp&Zonen, NL) as well as a pyranometer (LI 200 SZ, LI-COR, USA) were installed on the top of the tower. Finally a rain gauge (mod. 52202,Young, USA) was set in a little nearby clearance and a leaf wetness sensor (mod.237, Campbell, USA) was used too. Fast sensor data were sampled 20 times per second and collected by a personal computer through a customized program, saving data in a new file every half an hour. Slow sensor data were sampled by a datalogger (CR10x and AM416, Campbell, USA) every 15 seconds and the 30 minutes averages of each parameter were stored.

Figure 2. a) The flux tower in Paspardo; b) photo of the instrumentation installed on the top of the tower: the ultrasonic anemometer, the fast hygrometer and the inlet of the fast ozone analyzer; c) box at the bottom of the tower, inside the box there was the data acquisition system and the ozone reference analyzer

2.2. Data processing

Vertical fluxes of sensible (H) and latent (LE) heat and ozone (FO_3) were calculated from the 30 minutes data files of the fast instrumentation as the covariance between the vertical component of the wind and the corresponding scalar quantity, following the eddy covariance theory [8]. In particular these fluxes are obtained with the following equations:

$$H = \rho c_p \overline{w'T'} \tag{1}$$

$$LE = \lambda\rho \overline{w'q'} \tag{2}$$

$$FO_3 = \overline{w'O_3'} \tag{3}$$

where ρ is the air density, c_p is the specific heat at constant pressure, w is the vertical component of the wind intensity, T is the air temperature, λ is the latent heat of vaporization, q is the specific humidity and O_3 is ozone concentration; primed variables mean the fluctuations around their 30 minutes averages which are represented as overscript bars [7].

The covariances in the above mentioned equations are usually obtained from the rotated covariance matrix, following the methodology proposed by McMillen [9]; the rotations of the covariance matrix remove small tilts of the sonic anemometer from the verticality. In this case, since the forest was located on a gentle slope an *ad hoc* rotation procedure was developed.

The coordinate rotations align the "tower" vertical axis to the perpendicular of the wind streamlines. In this way the mean w component is zeroed and the advective flux component is removed. The angle of the rotation varies in agreement to the slope in the upwind direction (Figure 1c).

Once the total ozone fluxes have been calculated, a flux partition procedure has been employed in order to separate the two main deposition pathways: stomatal uptake by leaves and non-stomatal ozone disruption by both chemical sinks and ozone removal from non-living surfaces.

The partition procedure is based on an electrical analogy which is typical of the SVAT (Soil Vegetation Atmosphere Transfer) models where the flux corresponds to an electrical current flowing through a resistances network. Every resistance describes a part of the whole deposition process whose driving force is represented by the ozone concentration differences between the measuring height z and the substomatal leaf cavity at the standard height $d+z_0$ (d 2/3 of canopy height, $z_0$1/10 of canopy height, for further details see, for instance, [2], where ozone concentration is assumed to be zero [10].

The total resistance, which is obtained directly from measurements as the ratio between the ozone concentration at the measuring height and the total ozone fluxes, is equal to three series resistances:

$$R_{tot}(z) = R_a(d + z_0, z) + R_b + R_c \tag{4}$$

where R_a is the aerodynamic resistance that ozone faces during the turbulent transport from the height z to the height $d+z_0$ (momentum sink), R_b is the resistance faced by ozone while crossing the thin layer of still air surrounding leaves (diffusive transport) and R_c is the integrated resistance of the exchanging surface (leaves, stems, soil).

R_a was calculated following the formulation proposed by Dyer [11] while R_b was calculated using Hicks et al. [12] equation. R_c is finally obtained as a residual from equation (Eq. 4) all the others variables being known.

R_c is hence considered equivalent to two parallel resistances:

$$R_c^{-1} = R_{ST}^{-1} + R_{NS}^{-1} \tag{5}$$

where R_{ST} is the stomatal resistance and R_{NS} is the non-stomatal resistance.

R_{ST} could then be deduced from the Penman-Monteith equation [13] which describes the water loss process between a wet surface and the atmosphere. This equation is based on the energy balance closure at the evaporating surface so, when the net incoming energy (net radiation) as well as all the other energy losses (soil, sensible and latent heat fluxes) are known -as in our case-, R_{ST} is the only unknown term which can be derived by the inversion of the equation.

Finally the stomatal flux is obtained, using the Ohm's:

$$F_{ST} = \frac{R_c}{\left(R_a + R_b + R_c\right) R_{ST}} C_m \tag{6}$$

where C_m is the ozone concentration at the measuring height.

The stomatal dose, D, is simply given by the integral of F_{ST} over the measuring period (from t_a to t_b).

$$D = \int_{t_a}^{t_b} F_{ST}(t)dt \tag{7}$$

The UNE/ECE POD_1 is the dose which exceeds the instantaneous threshold of 1 nmol m^{-2} s^{-1}.

$$POD_1 = \int_{t_a}^{t_b} \left[F_{ST}(t) - 1\right] dt \quad \forall F_{ST} \rangle 1 \ nmol O_3 m^{-2} s^{-1} \tag{8}$$

For comparison purposes, the currently set AOT40 ozone exposure index was calculated too, as it follows:

$$AOT40 \ := \sum_{\substack{[O_3]_i > 40ppb \\ RadGlob > 50W/m^2}} ([O_3]_i - 40) \cdot \Delta t \tag{9}$$

2.3. Estimation of the ozone uptake by Larch trees

The dose calculated in the previous paragraph takes into account the ozone fluxes entering all the stomata of the whole ecosystem, i.e. the stomata of grass and trees. In order to estimate the uptake of the larch needles only, a two layers resistive model was developed (Figure 2). Differently from the SVAT model of the previous paragraph, this model is a prognostic model which tries to predict the stomatal ozone flux from meteorological and atmospheric turbulence data. This model simulates separately the stomatal behaviour of the trees (1st layer) and of the understorey grass (2nd layer) as well as the ozone removal by chemical reactions with terpenes in the trunk space and the ozone deposition to the underlying soil and the external non transpiring surfaces (cuticles, branches, stems). The stomatal processes were modelled using the Jarvisian approach adopted also by UN/ECE *Manual on the Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends*, hereafter simply called Mapping Manual [5]. A maximum stomatal conductance of 125 mmol m^{-2} s^{-1} was chosen for larch, following the findings of Sandford and Jarvis [14] and Wieser et al.[15], while the other parameterizations were taken from the generic continental conifers in the UN/ECE Mapping Manual, since for larch nothing else was available. The second layer was parameterized as the generic grass in UN/ECE Mapping Manual, which prescribes a maximum stomatal conductance of 270 mmol m^{-2} s^{-1}.

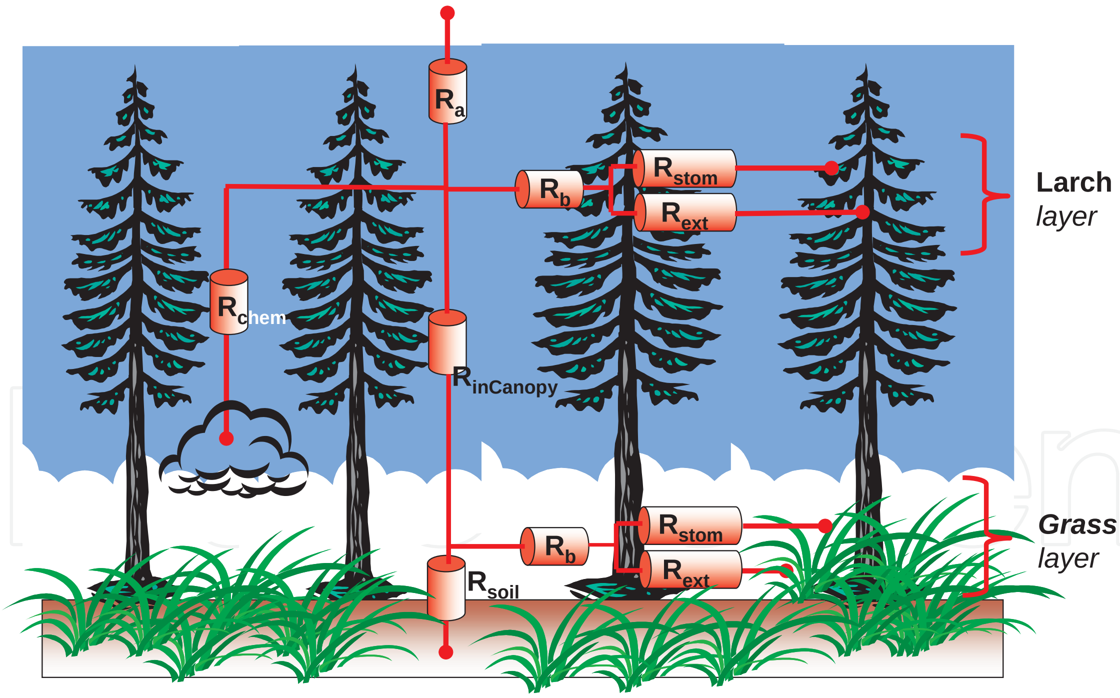

Figure 3. Deposition scheme of the prognostic multi-layer model: going from the top to the bottom the first resistance is the aerodynamic one (R_a). Each vegetation layer (i.e. larch one and grass one) is composed by a sub-laminar resistance (R_b) followed by two parallel resistances: a stomatal one and a non stomatal one. The larch and the grass layer are connected passing by an in-canopy resistance. In parallel to this one there is also the chemical resistance (R_{chem}). Below the lower layer (the grass one) there is the soil resistance (R_{soil}).

3. Results

The meteorological conditions of the two measuring periods are reported in Table 1. Comparing the common trimester (July-September) of the two years (2010 and 2011), it is evident that 2011 summer was hotter and drier than 2010. The average temperature ranged between 9.4 °C and 15.4 °C in 2010 and between 13.6 °C and 18.1°C in 2011. In the same period the rain received by the forest ecosystem was 806 mm in 2010 and 431 mm in 2011.

	Unit	July 2010	August 2010	September 2010	October 2010	June 2011	July 2011	August 2011	September 2011
$T_{Average}$	[°C]	15.4	13.3	9.4	6.2	12.7	13.8	18.1	13.6
T_{Max}	[°C]	20.3	18.2	12.8	10.9	19.5	19.2	23.7	16.5
T_{Min}	[°C]	11.0	8.2	3.6	0.7	8.7	9.4	12.02	3.9
Rainfalls	[mm]	89	291	426	55	90	67	156	208
$RH_{Average}$	[%]	70.4	77.0	78.9	85.7	79.5	74.2	72.9	74.2
RH_{Min}	[%]	43.9	38.5	43.5	66.7	57.7	49.4	47.1	51.8
PAR_{Max}	[µmol m^{-2} s^{-1}]	637	596	469	304	638	616	529	403
$SWC_{Average}$	[%]	23	28	29	30	31	23	25	26

Table 1. Meteorological and soil measurements; $T_{average}$ is the monthly average of the air temperature, T_{Max} is the monthly maximum value of the daily averages of air temperature, T_{Min} is the monthly minimum value of the daily averages of air temperature, Rainfalls are the cumulated rainfalls in the month, $RH_{average}$ is the monthly average of the relative humidity, RH_{min} is the minimum of daily averages of the relative humidity, PAR_{Max} is the monthly maximum of the daily averages of PAR, SWC average is the monthly average of soil water content. Air temperature, air relative humidity and PAR measurements are referred to top canopy measurements.

Most of the energy received by the ecosystem as solar radiation (R_n) was dissipated backward to the atmosphere as sensible heat (H) which reached on average a daily maximum value around 300 W m^{-2} at 3.00 PM local time (GMT +2) (Figure 3). A minor part of the energy was employed to drive the evapo-transpirative processes (LE) with a daily maximum of 150 W m^{-2} and an almost constant minimum of 20 W m^{-2} in the dark hours. The residual energy, a very little part with respect to the other two components, heated the ground (G) with a maximum average daily value of 12 W m^{-2} in the late afternoon. The heat stored in the soil during the daylight hours was completely returned to the ecosystem.

Figure 4 shows a detailed example of the energy fluxes (Figure 4a) as well as of the ozone concentrations and fluxes (Figure 4.b) measured at the top of the tower. Each point in Figure 4 is a semi-hourly averaged sample from 36000 rapid measurements collected 20 times per second.

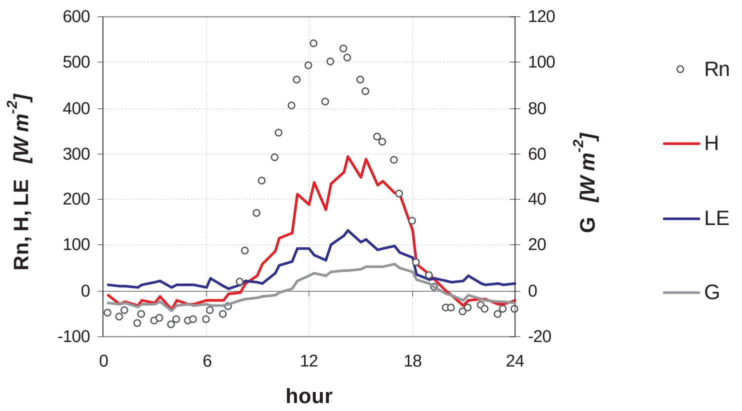

Figure 4. Energy fluxes at the Paspardo flux tower between July and September 2010. Mean daily courses of Net radiation (Rn), sensible heat flux (H), latent heat (water) flux (LE), soil heat flux (G). The scale of G curve has been enhanced five times for a better reading.

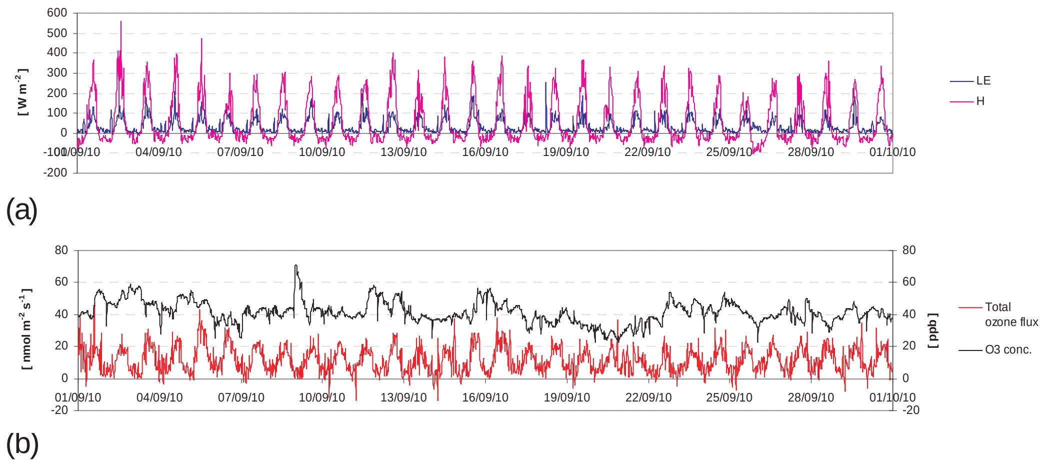

Figure 5. Example of semi-hourly measurements of a) sensible (H) and latent heat (LE) fluxes, and b) ozone concentrations (right axis) and total ozone fluxes (left axis) in a selected month (September 2010) at the Paspardo flux tower.

The ozone fluxes showed in Figure 4b are the net ozone amount received by the ecosystem from the atmosphere. In the convention adopted here a positive ozone flux value means a flux directed from atmosphere toward the ecosystem, while a negative value means the opposite direction. The studied ecosystem behaved as a net ozone sink with very rare episodes of ozone effluxes in the night-time. Despite ozone concentrations varied during the presented month ranging from 23 to 71 ppb the behaviour of the total ozone fluxes was almost the same. This fact highlights that the ozone deposition is not only driven by the atmospheric chemistry but also by the atmospheric turbulence and the plant physiology, which in turn responds to the soil water content.

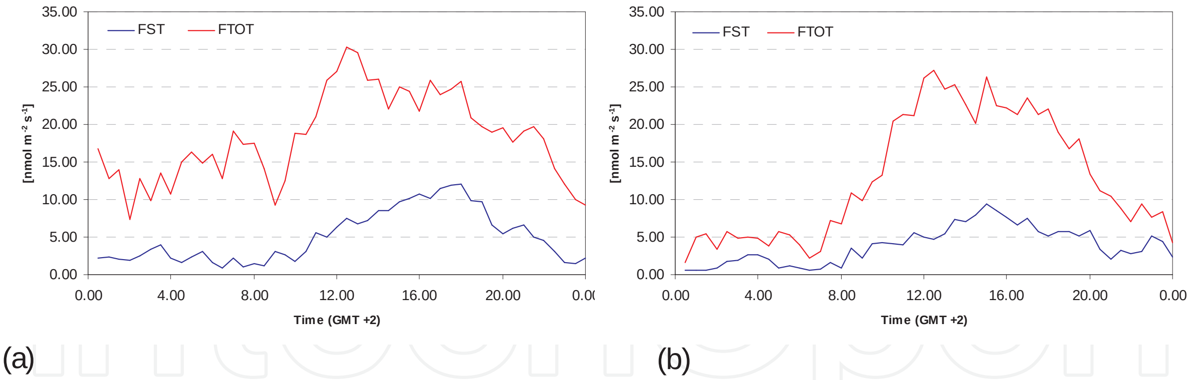

Figure 6. Ozone flux partition a) in 2010 and b) in 2011.

The importance of the plant physiology is further confirmed by the results of the flux partition (Figure 5), where it is evident that a significant part of the ozone deposition was removed by the stomatal activity. This process accounted for a maximum flux of about 10 nmol m^{-2} s^{-1} which was nearly 50 % of the ozone deposition in the afternoon of both years, even if this daily stomatal peak was located in the late afternoon in 2010 and earlier in 2011. During the night a residual stomatal uptake around 2 nmol m^{-2} s^{-1} was observed, revealing an incomplete stomatal closure as already reported by Matyssek and Innes [16].

On average the daily peak of the total ozone deposition (30 nmol m^{-2} s^{-1} in 2010 and 27 nmol m^{-2} s^{-1} in 2011) was measured at noon when turbulence is usually high. At the same time, the non-stomatal deposition, i.e. the ozone disruption on the external non-living surfaces, was maximum as can be inferred by the difference between the two curves in Figure 5 which is just the non-stomatal deposition.

The diurnal behaviour of stomatal and total fluxes, of course, showed a clear dependence on the seasons as it can be observed in Figure 6, which presents as an example the average daily course of every month in the 2010 measuring period. The total flux (Figure 6b) increased until August, when it reached its maximum values, and then decreased until October when it became four times lower. On the contrary, the stomatal flux maximum was observed in July and, in the following months, it decreased gradually reaching values three times lower in October.

The stomatal fraction of the total ozone deposition, during the central hours of the day, was 40%, 24%, 23% and 37% respectively in July, August, September and October. The non-stomatal deposition hence was always the main ozone sink for this measuring site.

Ozone concentrations (Figure 6a) reached their maximum values in August and after that slowly decreased. It is worth noticing the reversed bell shape of the ozone concentration daily courses which is typical of high elevation sites [17]. The concentration minimum occurred when the total ozone deposition was maximum. This fact highlights the sink role of the forest in the ozone removal from the atmosphere, a role which decreased as the end of the growing season was approaching.

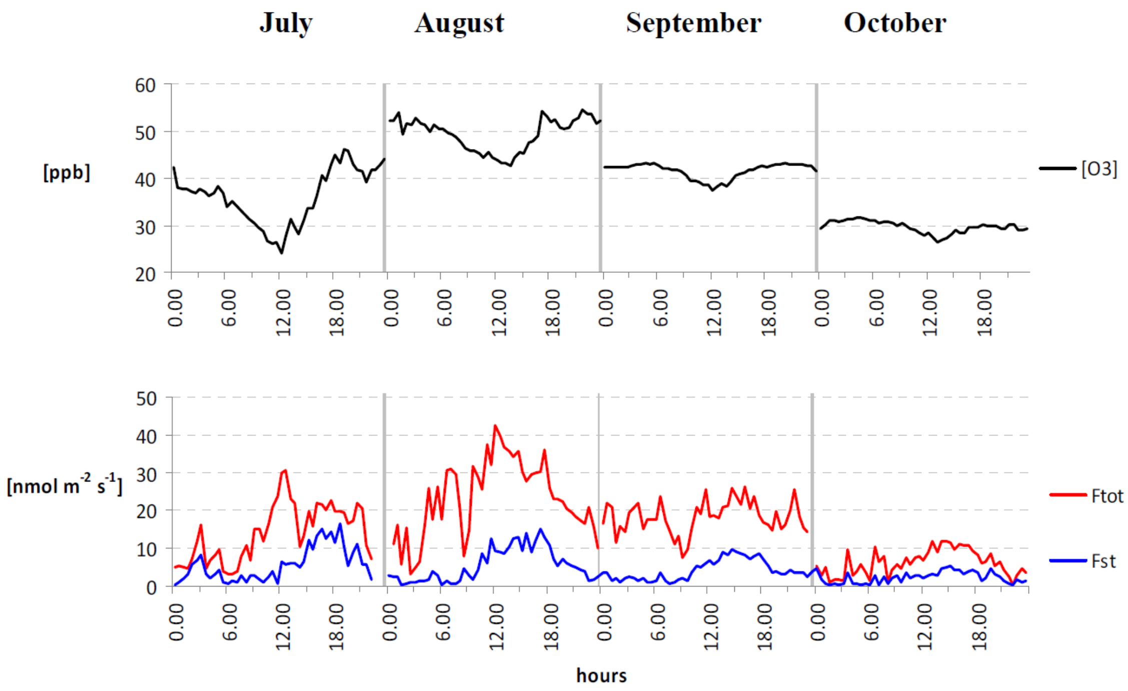

Figure 7. Mean daily courses of ozone concentration (a) and ozone fluxes (b), both total and stomatal fluxes, registered in the four months July-October 2010 at the Paspardo flux tower.

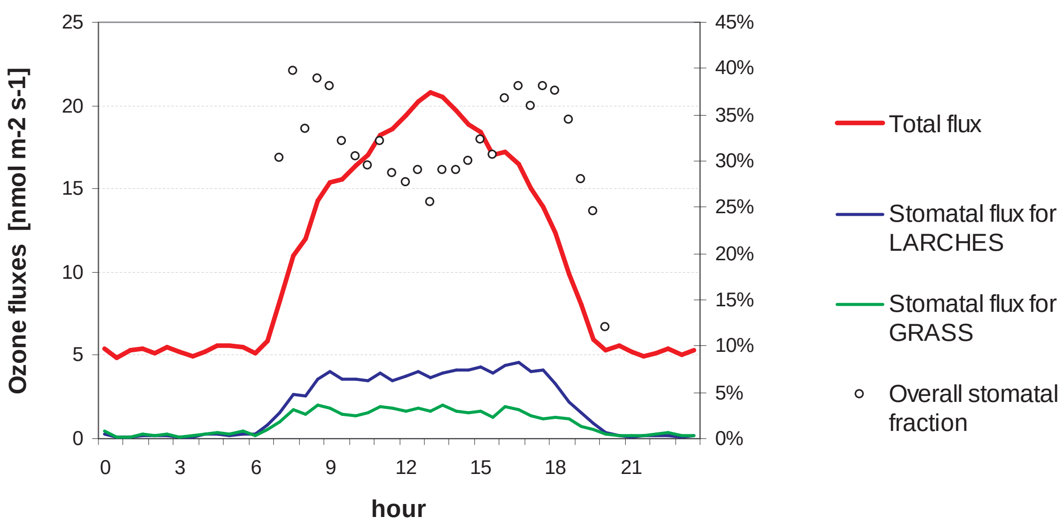

Figure 8. Model sub-partition of stomatal flux into a larch component and a grass component (2010 data)

In order to assess the ozone risk for the larch only, it was necessary to separate the stomatal flux taken up by the whole ecosystem into a stomatal component for the larch forest and a stomatal component for the understorey grass. The results of the sub-partition modelling exercise on 2010 data are showed in Figure 7. The model results were in satisfactory agreement with the measured fluxes, taking into account the correction by Moelder et al. [18] for the measurements taken in the roughness sub-layer, as in our case.

In the central hours of the day, the ozone fraction taken up by the larch needles through stomata was around 70% of the bulk stomatal flux calculated for the whole ecosystem. The remaining part (around 30%) was due to the understorey grass uptake. On average, the larch stomatal flux was about 25% of the total ozone deposition to the whole ecosystem.

Taking into account the uptake of both larch and grass, their overall stomatal uptake was on average 32% of the total flux, thus confirming the results of the flux partition obtained from the measurements. It is worth noticing that most of the ozone was destroyed by non-stomatal processes (68%) which include deposition on soil, leaf cuticles and stems.

Using the outputs of this model in order to estimate the phytotoxical ozone dose received by the larch trees during the whole measuring period, a POD1 value of 17.9 mmol m^{-2} was found, which is more than twice the critical flux level set by UN/ECE to protect Norway spruce, the species which was chosen as representative for all conifers.

By applying the flux-effect relationship proposed by UN/ECE for Norway spruce, a biomass reduction around 4 % can be predicted.

This reduction should be intended as the missing plant growth in the measuring period. Even if this value seems low, it is not negligible considering a pluriennial time scale. In fact it could be responsible of a slowing of the forest development as well as a minor plant capability to cope with other biotic and abiotic stressors.

It is important to highlight that the UN/ECE flux effect relationship had been developed on epigean biomass data only. However some studies showed a more significant effect of ozone uptake on root development [19, 20]. On a long time scale this effect could lead to a general impairment of the plant capability to stabilize mountain slopes and to prevent hydro-geological instability.

In any case it should be important to remark that the quantification of the effects is based on Norway spruce, the only species for which data are currently available in literature. The effects on larch could be lower or even worse but this is the best that could be done with the present knowledge. Ozone will obviously affect even the understorey vegetation and the other ecosystem components. So the estimated negative effects are likely higher than those predicted for larch only.

From a regulative point of view, the larch forest experienced an ozone exposure of 5.1 ppm h in the measuring period. This value was calculated as AOT40, the exposure index currently in use, following the EU and Italian legislation. Using the relationship between epigean biomass reduction and AOT40 for Norway spruce [5], in this case a biomass reduction of 0.8 % can be expected, a value that is 5 times lower than the corresponding biomass reduction estimated with the POD1 approach. This great difference underlines once more the criticism addressed toward AOT40, which does not take into account the real interaction between ozone and the plant, but only mimes it by the exclusion of the night-time measurements.

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In this case, although this situation is typical of the mountain sites and particularly of the most elevated ones, the relatively low AOT40 value is the consequence of the ozone concentrations minima experienced in the midday hours of the daily concentration profile (Figure 6a). On the contrary the highest concentrations were always measured at night, when the AOT40 index is not calculated. It is worth noticing that the highest stomatal fluxes are experienced just when the ozone concentrations are lower, thus causing this risk assessment discrepancy. For this reason, besides the fact that the plant physiological processes are taken into account, the flux-based approach is considered more scientifically sound and advanced.

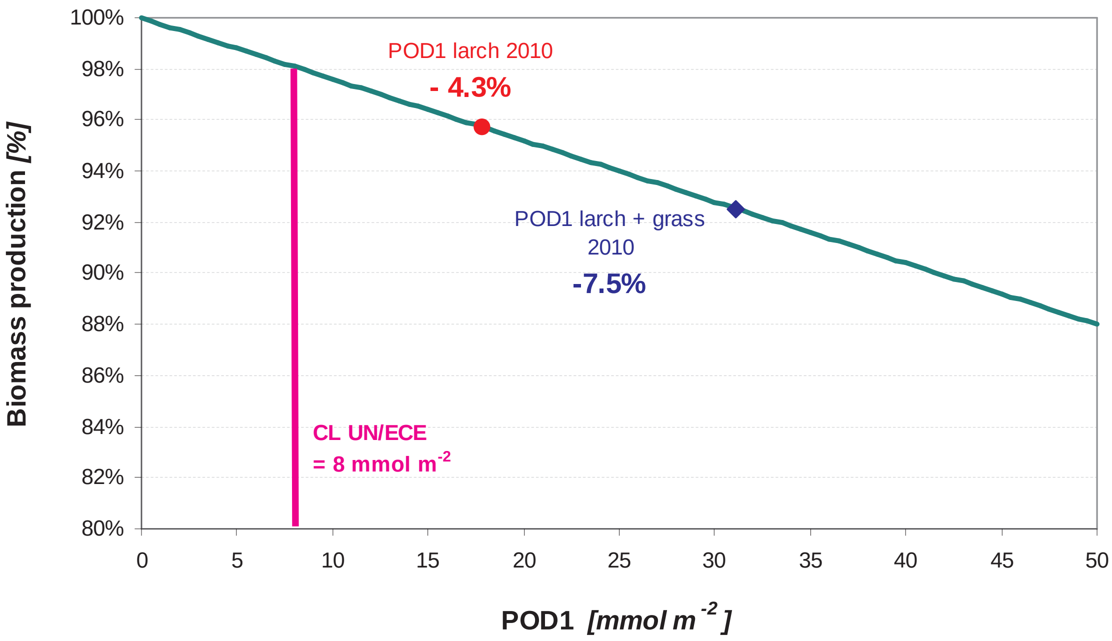

Figure 9. Estimated reduction of biomass production in Larch due to the ozone negative effects. See text for explanation.

The flux-based approach allows further considerations on the forest ecosystem services and in particular on the forest capability to remove the air pollutants, an aspect which is difficult to quantify, and it is not often treated.

In order to assess this aspect it necessary to consider also that part of ozone deposition which is called non-stomatal flux. This process is responsible for the removal of 38 kg O_3 ha^{-1}(Figure 9), which are destroyed without harming the vegetation, while the total amount of ozone removed by the forest ecosystem is equal to 53 kilograms of ozone per hectare in three months, an amount that is remarkable. In fact, considering an air volume with a basis of 1 ha and a thickness of three meters, containing ozone at a concentration of 90 ppb (i.e. nearly 180 µg m^{-3}, the attention threshold for the Italian regulation) the amount of ozone is only 5 grams.

This significant ecosystem service has a counterpart of forest growth reduction of about 4%.

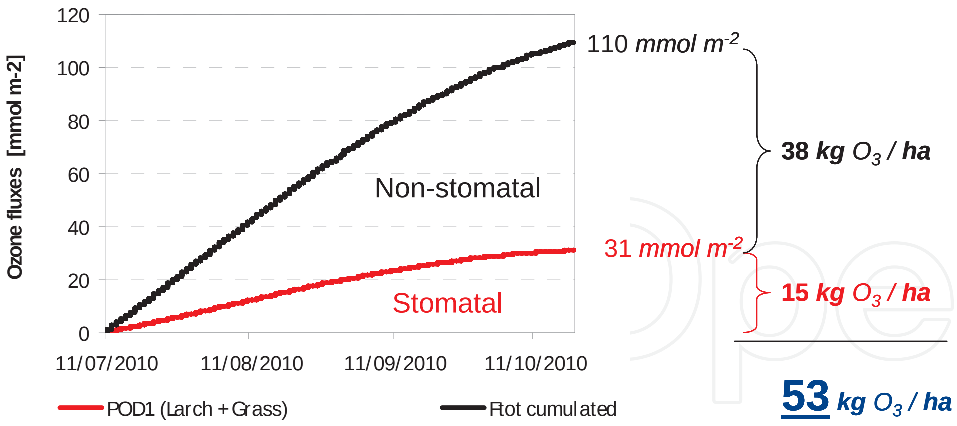

Figure 10. Evolution of stomatal and total fluxes during the measuring period in 2010.

4. Conclusions

The MANFRED project allowed to run a micrometeorological tower to measure directly ozone fluxes over a larch forest ecosystem for the first time in the Alpine region, with the eddy covariance technique.

Results showed that ozone removed by the forest was significant (53 kg ha^{-1}), but the quantity absorbed by leaves was the minority (between 23 to 40%), the most being non-stomatal.

A double layer (4-sinks) SVAT model was developed to study the sub-partition of the stomatal fluxes between the larch trees and the understorey grass, as well as to give an insight to the non-stomatal processes. The model is now suitable for simulations of ozone uptake in climate change scenarios.

Larch needles uptake 25% of the total ozone flux, around 70% of the bulk stomatal flux. The remaining 30% of the bulk stomatal flux was absorbed by the understorey grass.

Even taking into account the detoxifying capability of the plants (instantaneous flux threshold) the phytotoxically active ozone dose (POD1) appears above the critical level for fluxes provisionally set by the UN/ECE to 8 mmol m^{-2} for Norway spruce, the species chosen as a reference for conifers. At such ozone flux levels, the calculated POD1 for larch suggests a possible trees growth reduction of 4 – 5% in a growing season. This missing growth is counterbalanced by the offer of an ecosystem service, that is the removal of 53 kg ha^{-1} of ozone from the atmosphere.

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