Estimated ozone (O\textsubscript{3}) exposure of the permanent monitoring plots (PMPs) of the CONECOFOR programme often exceeds the critical levels set to identify areas where vegetation can be considered at risk (KARLSSON et al. 2003b; GEROSA et al. 2003 this volume) (Figure 1). However, there is evidence that – especially under xeric environmental condition - concentration-based critical levels are not well related to the effect on vegetation, which is more closely related to the fraction of O\textsubscript{3} that enters the plant (the O\textsubscript{3} flux) (EMBERSON et al. 2000a, b; GRULKE et al. 2003). Unfortunately, in the majority of cases the stomatal fluxes of O\textsubscript{3} (and, thus, the dose of pollutant that reaches the plant) cannot be measured directly. To estimate the fluxes one normally uses models, generically called SVAT models (Soil-Vegetation-Atmosphere-Transfer models) (GRÜNHAGE et al. 2003). These models are usually data intensive and their data requirement needs to be examined in detail, especially when considering that routine monitoring programmes like the CONECOFOR were not designed to address such a topic (see FERRETTI et al. 2003). Recently, two workshops were held under the auspices of the UN/ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) to address the topics of O\textsubscript{3} flux and the Level II approach to critical levels (ANONYMOUS 2002; KARLSSON et al. 2003a). Both workshops acknowledged the value of the flux approach and recommended implementation. Yet, it was also obvious that there are still uncertainties surrounding some aspects of the modelling (GRÜNHAGE et al. 2003) and questions about data requirements that may limit applicability to field situations. For example, BRAUN et al. (2003) argue that, in their experiment, “the calculation of O\textsubscript{3} flux did not represent an advantage over AOT40 in explaining growth response” and this was partly due to the inherent difficulties in flux calculation. This paper will address the question of data requirements and the applicability of the flux approach to the CONECOFOR PMPs.

Modelling O\textsubscript{3} uptake: an overview

Modelling O\textsubscript{3} uptake

It is necessary to distinguish between diagnostic and prognostic models (FINZI et al. 2001). Diagnostic
models are characterized by a top-down approach: stomatal flux is derived directly from flux measurements (total fluxes of O₃ and water) without resorting any assumptions on stomatal behaviour. They are not forecasting models but they provide information to parameterize and calibrate forecasting models. Prognostic models are, on the contrary, forecasting models, based on a bottom-up approach: either the stomatal and total fluxes are predicted by modelling the plant’s physiological behaviour (especially the stomatal behaviour) through a suitable parameterization and by using a relatively little set of meteorological input parameters. Some prognostic models describe the stomatal behaviour in leaves and then scale it up to represent the entire canopy (upscale); others use data relating to a stand and thus describe the stomatal function of the canopy as a whole, the so-called “bulk models”.

Despite differences in the details of parameterization, all these models follow the same potential-resistance electrical analogy in the description of fluxes (Monteith and Unsworth 1990; Garratt 1994). This analogy is formulated based on the integration of the “turbulent diffusion” equation (Eq. 1):

\[ \Phi = -K_c \cdot \frac{\partial \mathcal{C}}{\partial x_i} \]

where \( \mathcal{C} \) is the mean O₃ concentration and \( K_c \) the coefficient of turbulent “diffusion”. This coefficient, unlike what may be suggested by the formal analogy with molecular diffusion, is not constant, rather it varies along the \( x_i \) axis in response to several different factors. In the case of forest ecosystems, where \( x_i \) coincides with the vertical height from the ground, \( K_c \) increases with \( x_i \), the speed of wind, surface roughness and temperature. Furthermore, within the equilibrium sublayer above the canopy, the constant relationship of fluxes to height implies that an increase of \( K_c \) is matched by a reduction of the O₃ gradient. The constancy of fluxes in the surface atmospheric layer, or rather, in the equilibrium sublayer above the canopy, is an assumption that can be experimentally verified in the majority of cases. By definition, in this sublayer the measurement of the vertical flux \( F \) of a scalar entity at a height \( z_m \) above the canopy reflects the exchange at the surface (\( z = 0 \)) or at the top of the canopy.

Integrating Eq. 1 along the height, from the surface to a reference height \( z_{ref} \) we obtain:

\[ \Phi \cdot \int_0^{z_{ref}} \frac{1}{K_c} \, dz = C(z_{ref}) - C(0) \]

(flux \( \Phi \) appears outside the integration sign because of the hypothesis of the constancy of fluxes in the surface layer). The quantity under the integration sign, which has the physical dimensions of the inverse of a velocity (s/m), is defined total resistance \( R_{tot}(z_{ref}) \), and its reciprocal, a conductance, is the deposition velocity (m/s) introduced by Chamberlain (1953):

\[ R_{tot}(z_{ref}) = \int_0^{z_{ref}} 1/K_c \, dz \]

\[ v_d(z_{ref}) = 1/R_{tot}(z_{ref}) \]

Eq. 2 thus becomes

\[ \Phi = \frac{C(z_{ref}) - C(0)}{R_{tot}(z_{ref})} \]

or

\[ \Phi = v_d(z_{ref}) \cdot [C(z_{ref}) - C(0)] \]

where the analogy with Ohm’s law (I=ΔV/R) is evident: the flux is the analogue of an electric current and the concentration of a potential. It is a very versatile analogy since the total resistance can be expressed as
the outcome of a combination of other resistances mounted in series or in parallel, each representing the different processes influencing the deposition flux. Yet, unlike electrical networks, here the resistances vary during the daytime and the values they express are a reflection of both the turbulent characteristics of the atmosphere and the activity of the vegetation.

**The big-leaf model**

Although models with highly complex arrangement of the various resistances can be formulated, the most used model is the so-called *big leaf* model (Hicks et al. 1987) with a fairly simple subdivision of the $R_{tot}$. This model assumes that, as far as vertical exchanges of matter and energy are concerned, the entire canopy is considered as a single large leaf at a conceptual height $z=d+z_{om}$ above ground. In this model, $d$ is the height of the canopy’s zero plane $(=2/3$ of the height of the individual trees) and $z_{om}$ is the roughness length of the canopy for the transfer of a given scalar entity $x$, like momentum, heat and matter (Figure 2a). The conceptual height changes if one considers the fluxes of momentum, of sensitive (H) and latent heat (LE), and matter: $d+z$ represents the height from the ground at which wind within the canopy (which acts as a sink for momentum) is 0, and in general differs from height $d+z_{om}$, a lower height, from which evaporation and sensible heat fluxes appear to origin (source for H and LE, latent heat) or at which $(d+z_{om})$ the $O_3$ concentration seems to disappear since the pollutant is absorbed by the vegetation (which acts as an $O_3$ sink). Since the turbulent transport processes of heat and matter are so similar, the height $d+z_{om}$ is usually assumed to be identical to height $d+z_{om}$.

The differences observed in the turbulent transport of momentum and matter above permeable canopies suggest the existence of a thin layer, positioned between height $d+z_{om}$ and $d+z$, where transport cannot be turbulent since there is an absence of wind, but must necessarily be diffusive. For this reason it is called *quasi-laminar or viscous sublayer*. Total resistance to vertical $O_3$ transfer consists of three main resistances, arranged serially:

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

where $R_a$ and $R_b$ are two atmospheric resistances and $R_c$ is the resistance of the whole exchange surface (plant-soil system in the big leaf model).

$R_a (d+z_0,z)$ represents aerodynamic resistance encountered by $O_3$ (but equally any scalar entity such as temperature, vapour concentration, $CO_2$ or anything

![Figure 2](image.png)

**Figure 2** – The resistance analogue principle – a) from the canopy to the Big Leaf model; - b) a resistance network, characterized by increasing complexity. The two profiles, i.e. the full and dotted lines, in Figure a) respectively represent the real wind profile above the stand and the theoretical wind profile obtained by logarithmic approximation using the Monin-Obukhov similarity theory. In all figures: $d$ is the height of plane zero, i.e. the top of the canopy; $z_0$ is the length of roughness for momentum; $z_{om}$ is the length of roughness for heat and gaseous exchanges (it is the homologue of $z_{om}$ and $z_{om}$); and $z_m$ is the height at which measurement is performed. Lastly, $H$ indicates the various different resistances to deposition (after Pors 1997).

L’analogia resistiva – a) dalla copertura al Big Leaf model; - b) una rete resistiva a complessità crescente. I due profili a linea piena e tratteggiata in figura a) rappresentano rispettivamente il profilo di vento reale sopra il popolamento vegetale e quello teorico ottenuto come approssimazione logaritmica dalla teoria della similarità di Monin-Obukhov. In tutte le figure d rappresenta l’altezza del piano zero costituito dal top della canapa; $z_0$, la lunghezza di rugosità per il momento; $z_{om}$, la lunghezza di rugosità per il calore e gli scambi gassosi (analogi di $z_{om}$ e $z_{om}$); e $z_m$, l’altezza di misura. Le diverse resistenze alla deposizione sono indicate con $H$ (da Pors 1997).
else) during the turbulent transport from height $z$ to height $d+z_0$ (the sink for momentum), and reflects the thermodynamic and mechanical features of the atmosphere, mainly atmospheric stability and wind.

$R_a$ is the overall resistance encountered by $O_3$ in its diffusion through the quasi-laminar sublayer and thus depends on the molecular diffusivity of $O_3$ in the air, and also to some extent on the intensity of the turbulence above. It is important to stress that, while the value of $R_a$ is the same in each scalar entity, the value of $R_b$ changes according to the scalar entity being considered: for example, if instead of $O_3$ we examine the transport of another gas such as water vapour.

$R_c$ is the surface resistance or canopy resistance to $O_3$ deposition; it includes all those processes connected to the influence of the plant-soil system on the vertical exchanges of $O_3$, and in particular $O_3$ absorption by the vegetation or its destruction on the surfaces. It is strongly influenced by the physiological (e.g. stomatal functioning, water availability) and phenological (architecture, LAI) characteristics of the vegetation and the soil. $R_c$ is 2-3 times greater than the two atmospheric resistances, signalling the important role played by vegetation and surfaces in the deposition process. The lesser relative importance of the two atmospheric resistances (Figure 3) explains why, despite different parameterizations of $R_a$ and $R_b$, all authors end up by determining substantially similar flux values. In theory, $R_c$ can be broken down into any number of parallel sub-resistances, each one representing a different deposition path. In the case of vegetation, a first, natural subdivision is that between stomatal ($R_{ST}$) and non-stomatal ($R_{NS}$) components of the deposition, both relating to the canopy:

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

The stomatal resistance to $O_3$ can also be seen as the sum of a real resistance against the diffusion of the gas operated by the stomata and another resistance to penetration into the mesophyll cells. Experimental evidence, however, suggests that the resistance by the mesophyll cells is very weak and is therefore often neglected (TINGY and TAYLOR 1982; LEUNING et al. 1979a, b; PLOCH et al. 1993). Another path of $O_3$ penetration is through leaf cuticles, occurring in parallel to the stomatal path, which has equally been proved to be of negligible importance (LAISK 1989; KERSTIENS et al. 1992).

The non-stomatal resistance to $O_3$ can also be broken down into several parallel components,
so that different aspects can be considered, such as O$_3$ destruction by outer plant surfaces ($R_{ext}$), soil deposition, or quantity consumed in chemical reactions:

\[ R_c^{-1} = R_{ST}^{-1} + R_{ext}^{-1} + R_{SOIL}^{-1} + R_{CHEM}^{-1} \]

$R_{ext}$ to O$_3$ is generally quite high and depends on the development of the plants (actual LAI): its value is usually around 750-1000 s/m (BALDUCCHI et al. 1987). It has been estimated that, in the case of agricultural crops, this deposition path influences less than 5% of the total O$_3$ flux (MASSMAN 1993).

$R_{SOIL}$ is an integration of 3 other resistance mounted in series: $R_{InCanopy}$ that is influenced by the aerodynamic effects within the canopy, a resistance to the crossing of the soil boundary layer ($R_{Soil}$) and a resistance that describes in an aggregate manner deposition on the soil and on any vegetation present.

Since O$_3$ is not readily soluble in water, a moist soil generally presents a higher resistance to deposition than a dry soil, with an order of difference that has been defined as follows: 1000 s/m in a moist soil and 100 s/m in a dry one, according to WESLEY and HICKS (2000), or 500 and 100 s/m according to ERISMAN et al. (1994), or even 600 and 400 according to BROOK et al. (1999).

### Parameterization

Parameterization and the calculation of the individual resistances to O$_3$ deposition derive directly from fluidodynamics equations and from the K-theory (or similarity theory, MONIN and OBHUKOV 1954). Different formulations can be provided for each resistance (for example, integral form and differential form), but they are always formally equivalent (cfr. the sources for the formulations, e.g. MONTEITH and UNSWORTH 1990; GRÜNHAGE et al. 2000; HICKS et al. 1987). Table 1 shows an overview of the most common parameterizations for resistances to O$_3$ depositions. In brief, $R_a$ is calculated integrating

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<table>
<thead>
<tr>
<th>Resistance</th>
<th>Parameterization</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$</td>
<td>$R_a = \int_{d+\infty}^{z_m} \Phi_H(\zeta) \frac{dz}{k u^* z}$</td>
<td>DYER 1974; CIESLUK 1998</td>
</tr>
<tr>
<td></td>
<td>$\Phi_H(\zeta) = \left[1 + 5\zeta^2\right]^{-1/2}$ se $\zeta &lt; 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Phi_H(\zeta) = \left[1 - 16\zeta^2\right]^{-1/2}$ se $\zeta &gt; 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_a = \frac{1}{k u^*} \left[ \ln\left(\frac{z-d}{z_0}\right) - \Psi_H\left(\frac{z-d}{L}\right) + \frac{\Psi_H(0)}{L} \right]$</td>
<td>GRÜNHAGE and HAEDEL 1997</td>
</tr>
<tr>
<td></td>
<td>$\Psi_H(\zeta) = -5\zeta^2$ se $\zeta \geq 0$; $\Psi_H(\zeta) = 2\ln\left[\frac{1}{\Phi_H(\zeta)} - 1\right]$ se $\zeta &lt; 0$</td>
<td></td>
</tr>
<tr>
<td>$R_b$</td>
<td>$R_b = \frac{2}{k u^*} (Sc/Pr)^{2/3}$</td>
<td>All canopies</td>
</tr>
<tr>
<td></td>
<td>$Sc \equiv 1.07$; $Pr \equiv 0.72$</td>
<td></td>
</tr>
<tr>
<td>$R_b$</td>
<td>$R_b = \frac{1.45}{k u^*} Re^{0.24} Sc^{0.8}$</td>
<td>Forage meadows(Pastures)</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$R_b = \frac{1.9}{k u^<em>} (Hu^</em>)^{-2/3}$</td>
<td>Thin pasture</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$R_b = \frac{7.3}{u^*} Re^{0.25} Sc^{0.5} - 5$</td>
<td>Rigid soils and surfaces</td>
</tr>
<tr>
<td>$R_{ext, O_3}$</td>
<td>$R_{ST} = 1.65 \cdot R_{STH_2O}$</td>
<td>continue</td>
</tr>
</tbody>
</table>

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**Table 1**

An overview of the most common parameterization of resistance to ozone deposition. See text for details and symbols. (Continued)
the reciprocal of $K_c$, the turbulent diffusion coefficient for $O_3$, between height $d+z$, and reference height $z_m$; and $K_c$ is obtained by means of the K-theory:

$$K_c = \frac{k u^* z}{\Phi_c(\zeta)}$$

where $k$ is the von Kármán coefficient, $u^*$ is the friction velocity, $z$ the height and $\Phi_c(\zeta)$ is the non-dimensional Monin-Obukhov’s similarity function accounting for the $K_c$ dependance from the atmospheric stability conditions.

There are several different empirical calculations that can be used to establish $R_s$ according to the different type of vegetation examined; the most commonly used is that suggested by Thom (1975) and by Hicks et al. (1987) (Table 1).

In diagnostic models, stomatal resistance to $O_3$, $R_{ST}$, is deduced from water fluxes, i.e. from stomatal resistance to evaporation $R_{ST H2O}$ weighted in relation to different coefficients of molecular diffusion of $O_3$ and vapour in the air.

In prognostic models, $R_{ST H2O}$ is calculated as a response to solar radiation, to temperature and to the balance of water in the atmosphere and in the soil, applying the Jarvis-Stewart physiological approach (Jarvis 1976; Stewart 1988). Stomatal conductance (the reciprocal of the corresponding stomatal resistance: $R_{ST H2O}^{-1}$) is modelled based on a theoretical maximum value, specific for the vegetation being considered, re-scaled according to the product of functions (with values between 0 and 1) that describe the limiting action being exerted on stomatal aperture by the range of environmental factors (Table 1).

In diagnostic models, the canopy’s resistance to evaporation is obtained by the relative term contained in the Penman-Monteith equation (Monteith 1981), based on the energy balance on the surface/crop and in particular on the measurements of atmospheric moisture, temperature and latent heat flux. The formulation and derivation of the Penman-Monteith
equation can be found in good text books on agrometeorology (e.g. Ceccon and Borin 1995), while its solution for $R_{ST,H2O}$ is shown in Table 1. If, as in the case of the original formulation of the Penman-Monteith equation, $R_a$ is neglected and $R_s$ is obtained through measurements of wind velocity ($R_a$ for momentum) and not of heat fluxes, one may overestimate $R_{ST}$ by 25-30% (Callander and Woodhead 1981). For cases such as these, Thom (1975) has suggested a correction mechanism (Table 1).

An alternative diagnostic approach consists in deducing the stomatal resistance to evaporation using an electrical analogy, based on the different levels of moisture between the atmosphere and the crop and on the observed evaporation flux (Table 1). In the stomata the air is considered water saturated, but at a temperature that is different from the external temperature, and which must be estimated through the heat fluxes.

Constant values are usually attributed to resistances $R_{LAI}$, $R_{SOIL}$, $R_{CHEM}$ although it is not always easy to choose between the wide range of values available in the literature.

For other resistances (e.g. $R_{inter}$, $R_{soil}$) other formulations exist, with a higher degree of uncertainty and usually species-specific.

Resistances operated by the vegetation can be related to the entire canopy or to individual leaves: in the latter case, they must be scaled in relation to the LAI of the plant. If the results are to be even more realistic, they should be scaled to the portion of the LAI exposed to light (there are sophisticated energy transfer models that can be used to determine transfer within a canopy according to its architecture: see for example Baldocchi et al. 1987 and Gruszczak et al. 2000). The simplest scaling procedure, which is also the least accurate, yields the value of canopy resistance dividing individual leaf resistance by total LAI or portion of LAI exposed to sunlight.

If one prefers, one can also describe all the formulae illustrated here in terms of conductances, defined as the reciprocals of their respective resistances, i.e. $G = R^{-1}$.

Once the network of resistances has been constructed (Figure 2), by applying Kirchhoff’s law it is possible to determine the $O_3$ concentration at each level and its flux. The flux is constant where resistances are mounted in series, whereas it is divided into different branches when the resistances are in parallel. In the latter case, the $O_3$ flux in each branch is the result of the ratio between $O_3$ concentration at the beginning of the branch and the sum of the resistances downstream from that point. This yields the partition of the total flux and the determination of the quota of $O_3$ that enters the stomata, i.e. the dose of $O_3$ that the plant receives.

**Dual-source and multi-layer variants**

A first variant to big-leaf models is to distinguish between vegetation and soil sources/sinks of energy and matter, and thus examine them separately (Schutte and Wallace 1985; Massman 1992). This first variant can be applied in situations of open canopy, or scattered canopy, where the contributions of soil and vegetation to $O_3$ deposition cannot be all lumped together in a single big leaf. Unlike the big-leaf approach, in the dual-source model the resistances of the laminar sublayer of the canopy ($R_{Canopy}$) do not implicitly include overall air resistance within the canopy ($R_{Canopy,air}$). The derivation of the latter has been discussed, for example, in McNaughton and Van den Hurk (1995).

A second variant consists in subdividing the vegetation into planes and adopting a big-leaf model for each plane, plus a plane for the soil. These models are called multi-layer models (e.g. Meyers et al. 1998) and require an accurate description of the canopy’s architecture as well as sophisticated sub-models to calculate wind profiles and radiation transfer within the canopy.

All models described above are one-dimensional models. Some three-dimensional models, intended primarily to be applied to closed and open forest stands (e.g. Wang and Jarvis 1990), have been developed, but they call for a very large number of input parameters. Descriptions of these models can be found in the literature (Wang and Jarvis 1990). In any case, Grueszczak et al. (2000) conclude that, for the purpose of evaluating the $O_3$ risk of a forest stand, since the time window involved is so wide (the entire growth season), simpler one-dimensional models such as Big-Leaf and Dual-Source appear to be more suitable.

**Modelling $O_3$ uptake: applicability to the CONE-COFOR Permanent Monitoring Plots**

**Diagnostic or prognostic models?**

Diagnostic and prognostic models meet different needs and are therefore suitable for different needs.
Diagnostic models are used basically to analyze energy and matter (gaseous species) flux measurements performed with micrometeorological techniques above the different types of vegetation. The purpose of this type of model is essentially to meet research needs, since it enables researchers to investigate the dynamics of the various parameters involved and to determine the correct values for prognostic models' parameterisation. In particular, these models are necessary for the determination of those functions that can limit stomatal conductance (the $f$ functions of Jarvis-Stewart) that are used in prognostic models (Gerosa et al. 2003; Emerson et al. 2000b). The prognostic models, on the other hand, are more useful in practical application, and can provide evaluations and estimates on broad territorial scales. The objectives of a network of intensive monitoring like CONECOFOR by definition have a greater affinity to research purposes than to generic territorial assessment, and thus the application of a diagnostic model would appear to be more appropriate. It is indeed natural to expect that an intensive monitoring project should yield information that makes subsequent application possible (e.g., provide correct parameter values to develop prognostic models suitable for Southern Europe conditions). Unfortunately, over the period 1996-2000 (i.e., the time window covered by the present I&C report), there were no direct measurements of fluxes, either of $O_3$ or of water and energy in the PMPs and this makes it impossible to apply a diagnostic model. For this reason, the application of a prognostic model should be considered.

**A possible modelling approach: description and data requirements**

A possible solution is to implement an extremely simple model, referring to the entire canopy, that takes into account the aggregate of the two paths of $O_3$ deposition on the vegetation: stomatal and non-stomatal. Total flux of $O_3$ between atmosphere and forest canopy is obtained as the product of the $O_3$ concentration present at the top of the canopy ($[O_3]_{d+z0}$) and the conductance of the canopy itself; or rather the reciprocal of the canopy's $O_3$ resistance (Figure 4). The former expresses the atmospheric features, including primarily photochemical production of $O_3$ and turbulence, which causes $O_3$ to be transported towards the surface, but also $O_3$ deposition on the ecosystem as a whole, which influences the vertical gradient of $O_3$ and ultimately the very concentration of $O_3$ in the atmosphere.

\[ F_{O_3} = [O_3]_{leaf} \cdot G_{O_3} \]

**Figure 4** — Organization of the model, the parameters needed for implementation and the uncertainties. Number and size of question marks represent the degree of uncertainty. See text for the meaning of the symbols.
O₃ present in the canopy. The latter, on the other hand, is an expression of the features of the vegetation and its activity: it includes all those factors (climatic, biological, phenological, geometrical and chemical) that influence both stomatal uptake (gₛₜ) and non-stomatal deposition (gₙₛ). Stomatal conductance determines the fraction of O₃ deposition more strictly linked to biological effects and the modelling of its behaviour; it is thus of crucial importance in any forecast of the O₃ dose absorbed by the vegetation and any risk evaluation performed on such a basis.

Non-stomatal conductance, on the other hand, determines the quantity of O₃ that is intercepted by non-transpiring plant surfaces and by the soil, with which it reacts destroying itself. The importance of this path of elimination of O₃ was emphasized only recently (COE et al. 1995; TUOVINEN et al. 1999; GEROSA et al. 2003a) and any study that does not take it into consideration will inevitably produce a substantial overestimate of O₃ fluxes and of expected risks. The model must therefore consist of three sub-models: an atmospheric one, a physiological one and a non-stomatal one. The atmospheric sub-model will describe O₃ transport to the forest canopy as performed by turbulence and will need the availability at least of the following input parameters: u*, hourly O₃ concentrations measured at the top of the canopy.

The “physiological” sub-model, using a Jarvis-type model (1976), should describe the behaviour of foliar stomatal conductance and, after an appropriate up-scaling, of canopy resistance Rₛ as well (e.g. EMERSON et al. 2000a). In order to do this it will need input data relating to the quantity of solar radiation (PFD), the intensity of the wind, temperature, atmospheric moisture (VPD), water availability in the soil (SMD) or the water potential of the plant (Ψₑₑₑ), phenology. Information on the geometry of the forest cover (LAI, height, roughness zₒ, displacement height d) will all be essential both for upscaling and for the configuration of the atmospheric model.

The “non-stomatal” sub-model, on the other hand, requires data on the concentration of any scavengers of O₃ such as for example NO produced by the activity of microbes in the soil or volatile organic compounds released by the vegetation itself, and resistances to O₃ deposition in the soil and cuticles.

**Problems and uncertainty**

**Availability of meteorological and micrometeorological parameters**

The parameters of atmospheric turbulence and stability, such as friction velocity u*, the Monin Obukhov length L, and the flux of sensible heat H, indispensable if we are to calculate aerodynamic resistance Rₛ and quasi-laminar sublayer resistance Rₜ in the “atmospheric” sub-model, are not measured in any PMP (it would be necessary to dispose of eddy covariance measurements). Only a few plots (see AMORIELLO et al. 2003 this volume) envisage wind velocity and temperature measurements performed at two levels (for example, 2 and 10 m) that may enable us to estimate these parameters by repetition or with empirical procedures such as those suggested by VAN ULDEN and HOLTSLAG (1985). In this case, it is necessary to choose a priori the form of the function

\[ \Phi_H(\zeta) \]

which describes the dependence of atmospheric turbulence on stability; and this further increases the uncertainty of the result of the assessment.

At the CONECOFOR PMPs, meteorological parameters are usually measured in a clearing and not above the canopy, as would be preferable for a correct assessment of the fluxes. This influences the turbulence parameters considerably, since it is well-known that the roughness of an herbaceous cover is markedly different from the roughness of a forest canopy (think for example of the logarithmic profile of wind). Measurements in the clearing also rules out the condition of horizontal homogeneity necessary to apply the similarity theory and to the establishment of flux constancy on which it is based.

**Availability of hourly ozone concentration measurements from the top of the canopy**

O₃ data requirements have been discussed by FERRETTI and GEROSA (2003). Problems arise in relation to the time resolution and location of measurements. At the CONECOFOR PMPs, O₃ concentration is measured by passive sampling (BUFFONI and TITA 2003 this volume). This means that only mean weekly concentration data are available. This temporal scale is too broad to enable us to estimate the fluxes of O₃, since we know that O₃ concentrations undergo a marked daily variation. In order to estimate O₃ fluxes we would need at least hourly concentration measurements. It may be solved...
by adopting the same technique used in estimating AOT40 (GEROSA et al. 2003 this volume). However, in this case, the uncertainties in the application of the Loibl function (GEROSA et al. 2003 this volume), would be much greater than for the estimation of AOT40 on a seasonal basis. The same measurements with passive samplers also imply another uncertainty because of their positioning which is not always ideal: outside the plot, sometimes quite far away or at different altitudes, and only in one case above the forest canopy (BUFFONI and TITA 2003 this volume). This last aspect is of crucial importance since \( O_3 \) concentration displays a sensitive positive gradient above all kinds of vegetation cover. Passive samplers were placed at a standard height of 2m above ground. For the majority of agricultural crops this may be sufficient, but for forests it is necessary to estimate the \( O_3 \) concentrations above the canopy which, in the case of CONECOFOR PMPs ranges from 9.9 to 29.1 m (mean height) (ALIANIELLO et al. 2003 this volume).

The problem of estimating \( O_3 \) concentration at the height of the canopy, based on concentrations measured at a greater height, has already been addressed by several authors (e.g. GRUNHAGE et al. 2001; TUOVINEN 2000; PLEIJEL 1998). But the procedure cannot be applied to the reverse situation, i.e. when you need to estimate the concentration at a height greater than the height at which the measurements were performed, since it is necessary to know the value of resistances to deposition and in particular of the surface resistance \( R_c \) which, as is well known, depends on the type of vegetation and on its physiological activity. The value of these resistances determines the profile of the \( O_3 \) concentrations above a given vegetation cover. As a result, the concentration gradients above a meadow or above a clearing may differ considerably from those above a forest canopy. It is therefore preferable to dispose of actual measurements of \( O_3 \) concentration above the canopy.

When, however, these data are not available, an approximate estimate of the \( O_3 \) concentration at the top of the canopy \( (z_{\text{top}}) \) can be obtained from the wind and temperature measurements performed a few metres away \( (z_m) \), above a clearing, based on the calculation of the coefficient of turbulent diffusion of \( K_H \), heat and passing through the finite differences of the flux-profile equation (MONTEITH and UNSWORTH 1990):

\[
K_H^* = \frac{k u_* z_m}{\Phi_H(\zeta)}
\]

\[
[O_3]_{\text{top}} = [O_3]_{zm} + (z_{\text{top}} - z_m) \cdot \frac{H}{K_H^*}
\]

where \( H \) is the flux of sensible heat (which is in itself another crucial parameter that needs to be estimated), \( k \) is the von Kármán constant and \( \Phi_H(\zeta) \) is the Monin-Obukhov similarity function, with \( \zeta = (z/L) \), the analytical formulation of which can be taken from Dyer (1974).

An empirical approach to estimate \( O_3 \) concentration at the top of the canopy can be based on circumstantial evidence and could consist in the use of empirical correction coefficients applied to the \( O_3 \) concentration at the ground level. For example, the ratio between the concentration measured at canopy height and measurement height was reported to vary between 1.10 and 1.29 (BROADMEADOW, pers. comm.; GEROSA et al. 2001; KRAUSE et al. 2002), according to the height, the LAI, the canopy roughness and the wind velocity at the site being considered.

**Availability of a reliable parameterization of stomatal conductance**

A reliable parameterization of stomatal conductance is perhaps the most problematic aspect. First of all, any parameterization is highly species-specific and is therefore not very effective at describing mixed stands. In any case, even the spectrum of the main species growing in the CONECOFOR plots (Norway spruce, 4 PMPs; beech, 7 PMPs; Turkey oak, 5 PMPs; European oak, 1 PMP; sessile oaks and hornbeam, 1 PMP; holm oak, 2 PMPs) requires the use of several parameterizations. Unfortunately, the parameters of \( g_{\text{max}} \) (or \( R_{\text{min}} \)) drawn from the literature are not always representative of the ecotypes and the environmental conditions of the CONECOFOR plots.

The determination of the limiting functions (Jarvis-Stewart's f functions) calls for the availability of continuous measurements of both conductances and of the environmental parameters considered. Among the latter, soil water content, a factor that can exert a markedly limiting function especially in the Mediterranean environment, is the one that would be most necessary, alongside the measurement of the plant's water potential. When attempts are made to make up for this lack of information by using estimates coming from the application of simple “bucket” sub-models to the different soil types and data on rainfall, temperature and wind, the result is merely to introduce further uncertainties into the overall model. Generally, the uncertainties associated with parameterization of stomatal conductance are fairly high. For example,
an attempt to model $g_{ST}$ was carried out for Norway spruce trees growing between 1000 and 2000 m asl in the Alps, a situation similar to Norway spruce PMPs of the CONECOFOR programme (see FERRETTI et al. 2003 this volume). The model (based on the Jarvis multiplicative model) was based on air temperature, time of the day, vapour pressure deficit and soil water content expressed as % of soil water holding capacity. Figure 5 reports the comparison between measured (1849 measurements carried out by different devices: PPSystem and ADC LCi) and modelled $g_{ST}$. The portion of the variance explained is 47% and the considerable scatter of Figure 5 is a clear demonstration of the high degree of uncertainty surrounding estimates of $g_{ST}$.

We further need to consider that this refers only to foliar stomatal conductance. Further uncertainties will be encountered when up-scaling to the whole canopy. Here, even the validation is problematic as we shall need to have flux measurements above the canopy, which require the use of sophisticated techniques such as eddy covariance. Upscaling from the individual leaf to the entire canopy thus remains an open problem.

Further problems are linked to phenology (leaf/needle unfolding, laminar distension, seasonal evolution of LAI, optimal function and ageing), which will need to be incorporated into the model, and other aspects related to the diversity of individual leaves, to adaptation or resistance to other stress factors, primarily to water shortage.

**Parameterization of non-stomatal deposition and stand geometries**

Parameterization of non-stomatal deposition is still unclear in the case of forest stands, while some information is available in the case of agricultural crops (GEROSA et al. 2003a, b). It has been suggested that it may play an important role in forests as well, especially in environments that exert a limiting function on stomatal aperture, such as Mediterranean environments. Thus, a priority in research in this field is to obtain measurements that can help us understand the nature of these processes. On the other hand, some information about canopy geometry (e.g. LAI) is already available for the CONECOFOR plots.

**Conclusions**

Modelling stomatal uptake of $O_3$ is a complex matter. There are a large number of uncertainties - and of considerable importance - involving different measurements of input parameters as well as model parameterizations. Further, many approximations would be necessary and their propagation (additive or multiplicative propagation?) is unknown. For all these reasons, for the time being, it has been decided to stop attempt at applying a model for the estimation of $O_3$ fluxes at the CONECOFOR plots, since the results of such a model would not offer acceptable reliability and would not be verifiable at all.

In the near future, a process aiming at elaborating such a model would need first of all to strengthen intensive monitoring efforts, equipping at least some of the Level II plots with eddy covariance flux measurement and continuum analyzers recording hourly $O_3$ concentrations above the canopy. The recent incorporation in the network of the site BOL1 and the possible cooperation with other sites of the EUROFLUX project (see for example the site Collelongo, located close to the CONECOFOR site ABR1) will provide the chance for a step ahead. Furthermore, it would be important to extend and improve the focus of meteorological measurements. In this perspective, the data collected could contribute not only to a more accurate parameterization of flux models to be applied in CONECOFOR plots, but also be useful to the international scientific community (see GRÜNHAGE et
to validate large-scale models. This will help the study of those still unclarified aspects relating to the deposition of pollutants on vegetation in natural environments.

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