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# DO<sub>3</sub>SE modelling of soil moisture to determine ozone flux to European forest trees

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33583

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## Abstract

The DO<sub>3</sub>SE (Deposition of O<sub>3</sub> for Stomatal Exchange) model is an established tool for estimating ozone (O<sub>3</sub>) deposition, stomatal flux and impacts to a variety of vegetation types across Europe. It has been embedded within the EMEP (European Monitoring and Evaluation Programme) photochemical model to provide a policy tool capable of relating the risk of vegetation damage to O<sub>3</sub> precursor emission scenarios for use in policy formulation. A key limitation of regional flux-based risk assessments so far has been the approximation that soil water deficits are not limiting O<sub>3</sub> flux due to the unavailability of evaluated methods for modelling soil water deficits and their influence on stomatal conductance ( $g_{sto}$ ), and ultimately O<sub>3</sub> flux.

This paper describes the development and evaluation of a method to estimate soil moisture status and its influence on  $g_{sto}$  for a variety of forest tree species. The soil moisture module uses the Penman-Monteith energy balance method to drive water cycling through the soil-plant-atmosphere system and empirical data describing  $g_{sto}$  relationships with pre-dawn leaf water status to estimate the biological control of transpiration. We trial four different methods to estimate this biological control of the transpiration stream, which vary from simple methods that relate soil water content or potential directly to  $g_{sto}$  to more complex methods that incorporate hydraulic resistance and plant capacitance that control water flow through the plant system.

These methods are evaluated against field data describing a variety of soil water variables,  $g_{sto}$  and transpiration data for Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), birch (*Betula pendula*), aspen (*Populus tremuloides*), beech (*Fagus sylvatica*) and holm oak (*Quercus ilex*) collected from ten sites across Europe and North America. Modelled estimates of these variables show consistency with observed data when applying the simple empirical methods, with the timing and magnitude of soil drying events being captured well across all sites and reductions in transpiration with the onset of drought being predicted with reasonable accuracy. The more complex methods which incorporate hydraulic resistance and plant capacitance perform less

33585

well, with predicted drying cycles consistently underestimating the rate and magnitude of water lost from the soil.

A sensitivity analysis showed that model performance was strongly dependent upon the local parameterisation of key model drivers such as the maximum stomatal conductance, soil texture, root depth and leaf area index. The results suggest that the simple modelling methods that relate  $g_{sto}$  directly to soil water content and potential provide adequate estimates of soil moisture and influence on  $g_{sto}$  such that they are suitable to be used to assess the potential risk posed by O<sub>3</sub> to forest trees across Europe.

## 1 Introduction

Ground level ozone (O<sub>3</sub>) is an important air pollutant and greenhouse gas that has been found to affect forest trees through visible injury (Schaub et al., 2010; Novak et al., 2005); changes in plant physiology and carbon allocation (Novak et al., 2007); acceleration of leaf senescence (Bussotti et al., 2011); predisposition of trees to attacks by pests and pathogens (Manning and von Tiedemann, 1995); decreasing growth, productivity and fitness of forests (Matyssek and Sandermann, 2003; Karnosky et al., 2007; Matyssek et al., 2010a,b) with possible consequences for altered carbon sequestration potentials of forest ecosystems (Sitch et al., 2007; Bytnerowicz et al., 2007). Current O<sub>3</sub> levels across Europe are considered high enough to constitute a risk for forests across the region with further implications for agro-forestry, renewable resource management and post-Kyoto policies (Matyssek et al., 2008; Mills et al., 2011). The development of metrics to define O<sub>3</sub> exposure in relation to plant response has been an area of intense research effort over the past 30 years in Europe (Ashmore et al., 2004), largely conducted under the auspices of the United Nations Economic Commission for Europe (UNECE) Long-Range Transboundary Air Pollution (LRTAP) Convention which has established an effects-based approach to air quality management (Bull and Hall, 1998). Over recent years, O<sub>3</sub> characterization indices have moved from a concentration- to a flux-based approach defining O<sub>3</sub> dose as the

33586

effective stomatal  $O_3$  flux or uptake accumulated over a defined growth period (Ashmore et al., 2004; Matyssek et al., 2007). For forest trees, flux-based methodologies have been established and recommended for use in risk assessment by the LRTAP Convention (Karlsson et al., 2004, 2007; Tuovinen et al., 2009; LRTAP Convention, 2010; Mills et al., 2011). Currently, these methodologies use empirically derived flux-response relationships (e.g. Karlsson et al., 2004, 2007) to establish critical levels and to estimate damage in terms of tree biomass loss resulting from stomatal  $O_3$  flux. Therefore, the estimation of  $O_3$  flux is one crucial component necessary to assess  $O_3$  risk to forest trees. The estimation of actual damage requires knowledge of the effective  $O_3$  dose, i.e. the fraction of stomatal  $O_3$  flux that the plant is unable to detoxify without loss of vigour (cf. Musselman et al., 2006; Matyssek et al., 2008). The plants detoxification capacity is known to vary with genotype (Karnosky et al., 1998), species (Karlsson et al., 2007), tree age (Wieser et al., 2002) and diurnal (Schupp and Rennenberg, 1988; García-Plazaola et al., 1999; Peltzer and Polle, 2001; Wieser et al., 1995) and seasonal (Luwe, 1996; García-Plazaola and Becerril, 2001) conditions such that current empirical flux-based dose-response relationships may struggle to incorporate the complexities of the damage response (Musselman et al., 2006).

In this paper we focus on the estimation of the stomatal  $O_3$  flux component to enable an assessment of the potential for  $O_3$  damage to forest trees. The model currently used to estimate  $O_3$  fluxes to representative vegetation types (which include crops and semi-natural vegetation as well as forests tree species) across Europe is the  $DO_3SE$  (Deposition of  $O_3$  and Stomatal Exchange)  $O_3$  dry deposition model (Emberson et al., 2001), which is embedded within the EMEP (European Monitoring and Evaluation Programme) photo-chemical model (Simpson et al., 2003a, 2007; Tuovinen et al., 2004).  $DO_3SE$  estimates  $O_3$  flux to vegetated surfaces as a function of  $O_3$  concentration, meteorology and plant-specific characteristics (including phenological, physiological and structural characteristics). At the core of this model is the estimate of stomatal conductance ( $g_{sto}$ ), currently achieved using a multiplicative  $g_{sto}$  algorithm based on that originally established by Jarvis (1976) and modified for  $O_3$  deposition

33587

and risk assessment by Emberson et al. (2000a,b, 2001). This model has been parameterised for four evergreen tree species, i.e. Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), Aleppo pine (*Pinus halepensis*) and holm oak (*Quercus ilex*), and three deciduous species, i.e. birch (*Betula pendula*), beech (*Fagus sylvatica*) and temperate oak (*Quercus robur* and *Q. pretraea*). For some of these species, climate specific parameterisations have also been established to allow for ecotypic variation in  $g_{sto}$  response to climatic variables (LRTAP Convention, 2010). The  $DO_3SE$  model and its variations have been extensively evaluated for different forest species, in different countries, under a variety of seasonal conditions (e.g. Tuovinen et al., 2004; Emberson et al., 2007; Nunn et al., 2005). However, one fundamental obstacle to European-wide application of the flux modelling method has been the difficulty associated with estimating soil water status and its influence on  $g_{sto}$ .

To date, European application of the  $DO_3SE$  model within the EMEP photo-chemical model for  $O_3$  risk assessments has been restricted by the approximation of soil water not limiting  $g_{sto}$  and subsequent  $O_3$  flux (e.g. Simpson et al., 2007), except for some sensitivity studies that have investigated the influence of soil water deficit on  $O_3$  flux (e.g. Simpson et al., 2003b; Nunn et al., 2005). This is perhaps not such an issue for agricultural crops receiving irrigation. However, for forest trees this is a serious limitation to the current modelling methods, particularly in the Mediterranean region, where appropriate flux-based  $O_3$  risk assessments might be compromised by the exclusion of the influence of drought on stomatal  $O_3$  flux (Gerosa et al., 2009). There is also evidence that soil water stress can influence detoxification rates of absorbed  $O_3$  (Matyssek et al., 2006, 2007). High soil moisture deficits will also lead to a reduction in  $O_3$  deposition to vegetated surfaces. This can cause a build up of atmospheric  $O_3$  concentrations through the removal of the vegetation  $O_3$  sink (Solberg et al., 2008; Vieno et al., 2010) with consequences for other receptors, such as increased risk to human health. As such, it is imperative to develop and evaluate methods to estimate the influence of soil water status on stomatal  $O_3$  flux.

33588

Here, we describe the continued development of the DO<sub>3</sub>SE soil moisture module (Emberson et al., 2007), which now incorporates the Penman-Monteith model of transpiration (Monteith, 1965) to drive water cycling through the soil-plant-atmosphere system along with empirical data describing  $g_{\text{sto}}$  relationships with pre-dawn leaf water status to estimate the biological control of transpiration. We trial four different methods to estimate this biological control of the transpiration stream which vary from simple methods that relate soil water content ( $\theta$ ) or potentials directly to  $g_{\text{sto}}$  (denoted as  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models) to more complex methods that incorporate hydraulic resistance (steady-state, SS) and plant capacitance (non-steady-state, NSS) to water flow through the plant system.

Evaluation of these new methods incorporated into the DO<sub>3</sub>SE model is performed against observed data collected for a number of different tree species (boreal, temperate and Mediterranean species of deciduous, coniferous and broadleaf evergreen forest types). These datasets provide seasonal observations of key parameters that are selected to indicate the level of soil drought and influence on  $g_{\text{sto}}$  occurring at each site. The soil moisture module is assessed with the aim of providing an indication as to whether this model is “fit for purpose” to estimate, at least in relative terms, the influence that soil moisture deficit may have in regulating stomatal O<sub>3</sub> flux and hence O<sub>3</sub> deposition across Europe. A sensitivity analysis is also performed to establish which aspects of the model (e.g. root depth, maximum  $g_{\text{sto}}$ , leaf area index (LAI), soil texture) are most important as drivers of soil water status to target future parameterisation efforts as well as to understand the reliability with which the model can be applied to different locations and conditions.

33589

## 2 Methods

### 2.1 DO<sub>3</sub> SE model

DO<sub>3</sub>SE is a soil-vegetation-atmosphere-transport (SVAT) model that has been specifically designed to estimate O<sub>3</sub> deposition to European vegetation (Emberson et al., 2001). It is unique in relation to other SVAT models since it has been designed to be embedded within a complex regional scale photo-oxidant model developed by EMEP (Simpson et al., 2003a, 2007) to inform European effects-based air pollution emission reduction policy (Sliggers and Kakebeeke, 2004). This means that the modelling of gas transfer between the atmosphere and biosphere needs to be simple enough to ensure reasonable model run times, yet complex enough to incorporate the key drivers of O<sub>3</sub> flux at the European scale. The application of the model across such a large spatial region also means that the complexity of the model has to be balanced against the availability of spatial data characterising the important physical and environmental conditions that will influence O<sub>3</sub> deposition across Europe (e.g. land cover, species distribution, soil type, root depth and meteorological information).

To calculate total O<sub>3</sub> deposition DO<sub>3</sub>SE uses a standard resistance scheme to estimate the transfer of O<sub>3</sub> from an atmospheric reference height (i.e. the lowest grid level of the EMEP model) to the sites of O<sub>3</sub> deposition at the vegetated surface. Aerodynamic ( $R_a$ ), quasi-laminar boundary layer ( $R_b$ ) and surface ( $R_{\text{sur}}$ ) resistances to O<sub>3</sub> transfer are considered in the scheme.  $R_a$  and  $R_b$  are calculated according to standard methods as described in Simpson et al. (2003a).  $R_{\text{sur}}$  is calculated as a function of stomatal ( $r_{\text{sto}}$ ) and non-stomatal canopy resistances, the latter including external plant surface ( $r_{\text{ext}}$ ), aerodynamic within-canopy ( $R_{\text{inc}}$ ) and ground surface/soil resistances ( $R_{\text{gs}}$ ) for which empirical methods and constants are employed based on published literature; see Simpson et al. (2003a) and Simpson and Emberson (2006) for further details. Stomatal and external resistances to O<sub>3</sub> uptake are defined per leaf/needle area (denoted by a lower case  $r$ ) and for  $R_{\text{sur}}$  scaled according to LAI and surface area

33590













datasets collected meteorological and soil water data at the same site location.

Some variables ( $T, P, u$ ) were recorded at all sites and were suitable to be used directly as model input. For most sites,  $D$  was not recorded but calculated from relative humidity and temperature using standard methods as described in Jones (1992).

5  $\Phi_n$ , required for estimating  $E_{at}$ , was not measured at any site and hence was estimated from total radiation ( $\Phi$ ) or photosynthetically active radiation (PAR) using a standard method (FAO, 1998). Similarly,  $I_{dir}$  and  $I_{diff}$ , required to estimate the PAR available to sunlit and shaded leaves, were derived from  $\Phi$  based on estimated atmospheric transmissivity using the method described by Jones (1992). Soil heat flux  $G$  (Eqs. 3,  
10 4 and 9) was calculated as 10 % of  $\Phi_n$ . For sites where only PAR was recorded (i.e. Davos, Hortenkopf), this was converted to  $\Phi$  before the above steps were performed.

Where meteorological data were missing for periods of a few hours, data gaps were filled using a linear interpolation between adjacent data points. For the Miraflores 2005 dataset, 14 days worth of data were not recorded (14–31 July). In this case, gap-filling  
15 of the dataset was achieved using hourly averages representing the relevant diurnal time for the periods 3–13 July and 1–10 August; it was assumed that no rain fell during this period.

For evaluation purposes, the datasets were also required to comprise frequent seasonal observations of variables describing soil water status. Suitable parameters included:  $\Psi_{soil}$ ,  $\theta$ , all recorded at specified depths, and PAW and  $\Psi_{leaf, pd}$ , which were  
20 assumed to represent the soil water status of the entire root depth. For the former, the model parameter  $d_r$  was set equivalent to the soil depth represented by the measurements; for the latter,  $d_r$  was defined either by local data or according to DO<sub>3</sub>SE default values provided in Table 2. Field data on these soil water status variables were collected in a range of units and comparisons are presented in original units to minimise  
25 errors. Ideally, since the objective of the model is to estimate  $g_{sto}$  for the calculation of stomatal O<sub>3</sub> flux, observations of  $g_{sto}$ , or relevant variables, would also be available for comparison. However, such measurements were only available for a limited number of sites.  $E_t$  data comparisons are provided where possible to give an indication of the

33601

biological control of soil water flux from the system, though it is recognised that such comparisons are not ideal for inferring the influence of soil moisture on stomatal O<sub>3</sub> flux since  $E_t$  is in part driven by the atmospheric water status whilst stomatal O<sub>3</sub> flux is partly dependent upon the ambient O<sub>3</sub> concentration. For those sites where  $E_t$  or  
5  $g_{sto}$  data do exist, totals or daily maxima respectively were compared to equivalently presented modelled values.

In the absence of local data describing soil texture, the model runs were performed with the most appropriate of the four soil textures (Table 3), defined according to site-specific information where this was available or by calibrating modelled with observed  
10 FC under conditions when it would be expected that the soil was fully recharged and precipitation moderate.

Table 2 describes the model parameterisations for each site used in this evaluation. Where possible, local parameterisations of  $g_{max}$  and LAI were used; where these were unavailable, default DO<sub>3</sub>SE model parameterisations were used based upon values given in LRTAP Convention (2010) which provide representative values for tree species in several European regions (Northern, Atlantic Central, Continental Central and Mediterranean).

One set of model runs was carried out for all sites and years for which data were available, each of the four modelling methods were applied. Figures 3 to 11 and S1 to S15 (Supplement) show the results of comparisons between the modelled and measured soil water variables in relation to local precipitation data;  $E_t$  and  $g_{sto}$  are also shown for those sites where comparable data were available.

Statistical analyses of the performance of all four models were carried out by comparing observed and modelled values of soil water (expressed as  $\theta$ ,  $\Psi_{soil}$  or PAW)  
25 using a set of statistical tests consisting of the coefficient of determination ( $R^2$ ), mean bias (MB), root mean square error (RMSE) and Willmott's index of agreement (IA); for definitions see Willmott (1982).

33602



no obvious effect on  $f_{\text{SWP}}$  and hence  $E_t$ . However, soil water conditions in the first 65 cm of the soil became considerably drier in June, resulting in a sharp drop in  $\theta$ ,  $f_{\text{SWP}}$  and, to a lesser extent,  $E_t$  (Figs. 4, S13 and S14). All four models capture the timing of the drought effect and its extent during the summer well, but underestimate and overestimate  $\theta$  in spring and autumn respectively. Also, during the earlier part of the drought period the measured maximum  $E_t$  is higher than that predicted by the model (Figs. 4 and S13). However, both measured and modelled  $E_t$  data show a dip during the driest period at around day 200.

The year 2003 was characterised by a prolonged drought period in Central Europe. This is mirrored by the fairly low  $P$  levels at Kranzberg. Measured data of  $\theta$  show a drop from 0.38 to approximately  $0.25 \text{ m}^3 \text{ m}^{-3}$  during the drought period, which is best mimicked by the NSS model, whereas the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models overestimate and the SS model underestimates the drought effect on  $\theta$ . However, all models capture the period of reduced  $\theta$  well and the match between observed and modelled  $\theta$  is satisfactory at the beginning and end of the growing period. Also, all models apart from the SS model showed a distinct drop in  $f_{\text{SWP}}$  during the drought period in late summer (Figs. 5 and S7). Up until August, modelled and observed  $g_{\text{sto}}$  tended to match each other, although by September, towards the end of the drought period, observed  $g_{\text{sto}}$  showed a clear recovery (Fig. 5), which may have been related to precipitation events during this period. Observations showed that such events only moistened the uppermost 5 cm of the soil profile. Since this is the densely rooted litter layer, wetting may have resulted in increased water availability to the plant that would have been under-represented by the soil water balance model which integrates soil moisture within the uppermost 40 cm of the profile. In addition, since all models relate  $g_{\text{sto}}$  either directly or indirectly to  $\Psi_{\text{soil}}$ , they were unable to capture the observed increase in  $g_{\text{sto}}$  (Figs. 5 and S6). Discrete porometry-based measurements conducted in parallel during that period also showed some recovery in  $g_{\text{sto}}$ , although to a lesser extent than by the approach depicted in Fig. 5 (L6w et al., 2006).

33605

Model runs for Asa, Sweden were carried out for the year 1995 and 2000 (Figs. 6, S1 and S2). While in 2000 soil water conditions were hardly limiting  $g_{\text{sto}}$  of the Norway spruce stand (Fig. S1), in 1995 a distinct drought period in August led to a decrease in  $\Psi_{\text{soil}}$  as depicted both in modelled and measured data (Figs. 6 and S1). The extent of the drought effect is best captured by the  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models, whereas the SS and NSS models clearly overestimate  $\Psi_{\text{soil}}$  and predict the soil to remain far wetter. This difference between models is also mirrored by the  $f_{\text{SWP}}$ : this parameter is strongly reduced during August 1995 only in  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  model predictions.

Similar statements can be made about the Forellenbach results (Figs. 7 and S4), where in the dry year 2003 the PAW steadily decreased to a minimum of approximately 40 mm at the end of August, with an obvious limiting effect on  $g_{\text{sto}}$  starting in late July: the  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models clearly outperformed the SS and NSS models.

Figs. 8 and S5 show the year-to-year variation in  $\theta$  for the central European mixed beech and oak forest at Hortenkopf. Observed and modelled  $\theta$  confirm the relative wetness of 2000, followed by three years of clear drought effects, with 2003 being the driest year. The  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models perform well during all years, capturing the periods and extent of drought, expressed as  $\theta$ , well. The performance of the SS and NSS models are much less satisfactory (Fig. 8). These results are also mirrored by the diurnal course of the  $f_{\text{SWP}}$  as shown in Fig. S5. Episodic rainfall events in between periods of distinct dryness led to an almost full recharge of soil water at several times during the growing seasons 2001 and 2002, but not in 2003 ( $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models, Fig. S5).

Results of model runs for evergreen oak forest sites with Mediterranean climatic conditions (two Spanish, one Californian site) are shown in Figs. 9 to 11 (and Figs. S8, S9, S12, S13 and S16). These sites are more prone to drought conditions with the figures showing limited  $\theta$  during the summer time. The sites Miraflores de la Sierra and Prades are of particular value for this study, since they provide multi-year model input and validation data (though the latter is far from continuous), so model runs spanning more than one growing season could be assessed.

33606

At the Miraflores site (Fig. 9), a total recharge of the soil water was experienced during the winter of 2004/2005 due to some heavy rainfall in autumn and winter (Fig. S9). In 2004, only the  $f_{\text{SWP}}$  model was able to capture the very low  $\Psi_{\text{soil}}$  at the end of the summer, whereas in 2005 all models predicted the drought-induced low  $\Psi_{\text{soil}}$  for most of the summer as also observed at the site. These results are also mirrored in the seasonal course of the  $f_{\text{SWP}}$  as shown in Fig. S9. During both summers, the  $f_{\text{SWP}}$  dropped to its minimum value of 0.2 using the  $f_{\text{SWP}}$  model (Fig. S9), leading to a reduction of  $g_{\text{sto}}$  during drought periods (results presented in Alonso et al., 2008).

In contrast, the Prades holm oak site did not experience a full recharge of soil water during the winters of 2001/2002 and 2002/2003 despite some rainfall during the autumn and winter months (Figs. 10 and S12). However, while the  $\theta$  clearly shows the missing soil water recharge at the end of 2001 and 2002, this effect actually only affects  $g_{\text{sto}}$  – expressed as the multi-annual course of  $f_{\text{SWP}}$  in Fig. S12 – when using the  $f_{\text{PAW}}$  model, i.e. with all three other models the  $g_{\text{sto}}$  is for a long time unaffected by drought at the beginning of the years 2002 and 2003. When comparing the few available measured with modelled  $\theta$  data, it seems that all models slightly underestimate the  $\theta$  during the winter months, but catch well the  $\theta$  during the drought period in 2003 (Fig. 10).

The Strawberry Peak/Crestline evergreen oak site experienced severe drought conditions in 1995 (Figs. 11 and S15). The  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models predict the decline in  $\theta$  quite well until the end of July, but afterwards overestimate  $\theta$ ; the two other models consistently overestimate the  $\theta$  at the site as compared to measured data (Fig. 11). Furthermore, the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models predict that despite an early decline in  $\theta$  from April on, only in mid June dramatic effects of drought on  $f_{\text{SWP}}$  and hence  $g_{\text{sto}}$  are experienced (for the SS and NSS models, this effect appears even later in the year) (Fig. S15).

When comparing the overall performance of all four models with help of the set of statistical parameters given in Table 5, it is apparent that the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models almost always outperform the SS and NSS models, with the SS model showing on average the worst statistical agreement between observed and modelled data as indicated by

33607

low  $R^2$  and IA values on the one hand and comparatively high values of MB and RMSE on the other. The poorer performance of the SS and NSS model is also mirrored by the much smaller number of days when  $f_{\text{SWP}}$  is predicted to fall below 1 for these two models as compared to the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models (Table 6), suggesting a less pronounced effect of dry soil water conditions on  $g_{\text{sto}}$ . To distinguish between the performance of the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models is more difficult, since both models perform well and in a very similar fashion when applied to datasets in which clear drought conditions have been experienced (Table 6).

The results of the sensitivity analysis, performed for the Norunda site, are shown in Table 7. They reveal that a variation in the soil texture and  $g_{\text{max}}$  parameters lead to the biggest change in  $\text{POD}_1$  regardless of the model used, with clay loam as compared to sandy loam and a decreased  $g_{\text{max}}$  resulting in a smaller change in  $\text{POD}_1$  (a reduction of up to 46 %), whereas an increase in  $g_{\text{max}}$  substantially increases (up to 35 %)  $\text{POD}_1$ . In comparison, changes in  $d_r$  and LAI led to much smaller – and, depending on the model, sometimes contradictory – changes in  $\text{POD}_1$ . A reduced consistency in model predictions when using the SS and NSS model as compared to the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models also manifests itself in a larger variation in the number of days predicted with  $f_{\text{SWP}}$  less than 1 for the two former models (Table 7), further confirming the results of the statistical analysis that the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models are more reliable.

## 20 5 Discussion

This study has investigated four different modelling approaches that provide estimates of soil water, expressed as  $\Psi_{\text{soil}}$  or  $\theta$ , and its influence on  $g_{\text{sto}}$  using the  $\text{DO}_3\text{SE}$  model. This approach provides more consistency in estimates of both water vapour and ozone flux between the atmosphere and the plant system. The  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models use an empirical approach to relate soil water status to  $g_{\text{sto}}$ . The difference between these two models is the assumed relationship between soil water status and  $g_{\text{sto}}$ . The  $f_{\text{SWP}}$  model uses empirical relationships derived from data for temperate/boreal and Mediterranean

33608

species (Fig. 2) describing the connection between  $\Psi_{\text{leaf,pd}}$  as a surrogate for  $\Psi_{\text{soil}}$  (Slatyer, 1967) and leaf  $g_{\text{sto}}$ . The  $f_{\text{PAW}}$  model represents a more generic approach by relating soil water status, assessed in terms of PAW, to  $g_{\text{sto}}$ , assuming a limitation on  $g_{\text{sto}}$  once less than 50 % of PAW is available (consistent with findings published by Domec et al. (2009) for forest trees). By contrast, the SS and NSS models also use the empirical relationships of the  $f_{\text{SWP}}$  approach (i.e. they relate  $\Psi_{\text{leaf,pd}}$  to leaf  $g_{\text{sto}}$ ), but in addition allow for hydraulic resistance (SS) and plant capacitance (NSS) to control water flow through the plant system.

Tables 6 and 7 provide summary statistics for the performance of all four models. Considering those sites and years for which soil water deficits occurred (defined as water deficits that resulted in some stomatal limitation for some part of the year as estimated by at least one of the models), the statistics suggest that a ranking of the models with regard to their predictive performance is  $f_{\text{PAW}} = f_{\text{SWP}} > \text{NSS} > \text{SS}$ . The  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  models describe fairly consistently the highest proportion of variance ( $R^2$ - and IA-values of up to 0.94 and 0.97 respectively) and show the smallest absolute difference (fairly consistently low RMSE-values) between modelled and observed data.

The models' performances vary from site to site and year to year. In general, the  $f_{\text{PAW}}$  and  $f_{\text{SWP}}$  models (and with less frequency the NSS and SS models) capture the seasonal course of the observed soil water conditions and the magnitude of drought reasonably well. However there are some cases, especially at the beginning and the end of the growing season, where a more substantial divergence between observed and modelled data occurs. For instance model predictions for the Rhineland, Kranzberg and Forellenbach sites struggle to accurately reflect the rate with which the initial soil drying takes place, often estimating earlier and more prolonged periods of reduced soil water than actually occur.

A direct comparison of the  $f_{\text{PAW}}$ ,  $f_{\text{SWP}}$ , SS and NSS models (Figs. 3 to 11) shows that the two latter models predicted lower  $E_t$  and less dry soil water conditions (expressed as  $\theta$ ,  $\Psi_{\text{soil}}$  or PAW) as compared to observed data for all sites. This resulted in higher transpiration rates (e.g. Figs. S10 and S13). This finding is not surprising, given that

33609

the SS and NSS models introduce additional resistances to water transfer through the soil-plant-atmosphere continuum. These models were developed to account for the lag effect caused by internal plant resistance to water transfer from the soil-root to leaf-atmosphere interfaces. The water supply from the soil will not always meet the demand resulting from the driving force of a drier atmosphere, resulting in a difference between the soil water status and leaf water status. The NSS model predicts slightly drier (and therefore more realistic, as judged by observed data) soil conditions than the SS model, because the former accounts for a plant capacitance term, representing a buffering effect of water storage in trunk and branches, which causes a lag in  $g_{\text{sto}}$  response.

The application of the SS and NSS models within the DO<sub>3</sub>SE modelling scheme needs further consideration and testing since it may be that the resistance to water transport within the plant can substitute for the  $f_D$  function which is currently a component in the estimate of  $g_{\text{sto}}$ . Similar concepts have been explored for forest trees by Uddling et al. (2005) through the development of models that relate the sensitivity of  $g_{\text{sto}}$  to  $D$  to the accumulated time after sunrise with  $D$  exceeding a defined threshold, hence indirectly accounting for hydraulic resistance effects. Additionally, a sum  $D$  function developed by Pleijel et al. (2007) that is currently used in the DO<sub>3</sub>SE model for crop species (i.e. wheat and potato) is intended to account for a similar reduced water supply to the leaf. Under conditions of continuous and high  $D$  levels (most likely to occur in the late afternoon of exceptionally hot and dry days), the stomata are prevented from re-opening even if  $D$  levels decrease. Again, this limitation of  $g_{\text{sto}}$  in response to increasing  $D$  attempts to mimic severe leaf water loss and the inability of water from the soil to replenish supplies in the leaf. The subsequent reduced loss of water from the system under high  $D$  may in part explain the underestimation found in model estimates of soil drying and subsequent limitations to  $g_{\text{sto}}$ . The capacitance term in the NSS model buffers this hydraulic resistance to water loss so that the plant is able to meet  $D$ -driven transpirational demand until the plant water storage is depleted. As such, more water can be lost from this system compared to the SS system, but the inclusion

33610

of the hydraulic resistance term reduces water loss in comparison to the  $f_{SWP}$  and  $f_{PAW}$  models.

The modelling approaches presented have been used by a number of other studies, with some favouring the  $f_{SWP}$  (e.g. Gao et al., 2002; Emberson et al., 2007) and others  
5 favouring the  $f_{PAW}$  approach (e.g. Gollan et al., 1986; Grünhage and Haenel, 1997; Granier et al., 2000; Van Wijk et al., 2000; Schwalm and Ek, 2004). However, the  $f_{PAW}$  model is often favoured since  $\theta$  is much more commonly measured in ecological studies. Also, the  $f_{SWP}$  model requires that the  $g_{sto}$  response to soil water stress be defined in terms of  $\Psi$  (i.e.  $\Psi_{max}$  and  $\Psi_{min}$ ), which becomes very sensitive to changes in  
10  $\theta$  as the soil dries; hence, the modelled limitation to  $g_{sto}$  may be extremely responsive to small changes in  $\theta$  that are close to the equivalent  $\Psi_{min}$  threshold value.

Other studies that adopted the SS approach of water transfer within plant canopies include Tardieu and Davies (1993), Saliendra et al. (1995), Tardieu and Simonneau (1998) and Anderson et al. (2000), whereas for example Williams et al. (1996), Kuma-  
15 gai (2001) and Lhomme et al. (2001) adopted the NSS approach. The latter all state the importance of the capacitance term and hence favour this approach over the SS approach. Hunt et al. (1991) argue that SS models are sufficient for the prediction of daily totals of water uptake via roots, whereas NSS models are necessary for the assessment of the instantaneous rate of water uptake with regard to diurnal variations in  
20 the use of the water storage capacitance and transpiration rate.

A sensitivity analysis was performed to test the models' sensitivity to key model parameters. The analysis focussed on  $g_{max}$ , LAI, soil texture and  $d_r$ . These four parameters were selected because they were considered particularly important in terms  
25 of determining the availability of soil water to the plant (soil texture and  $d_r$ ) and the rate of water loss from the plant ( $g_{max}$  and LAI). From the range of frequently observed values defined for each of these parameters (Table 7), it is clear that for all four models a variation of  $g_{max}$  by 25 % leads to the largest change in  $POD_1$ , followed by soil texture,  $d_r$  and LAI. As expected, an increase in  $g_{max}$  (increased  $g_{sto}$  and hence higher  $E_t$ ) and  $d_r$  (increase in accessible water and hence enhanced water supply from root

33611

to plant) results in higher  $POD_1$  values, whereas the change from a sandy to clay loam soil texture (less extractable water, hence reduced accessibility to soil water leading to enhanced drought effects) reduces the  $POD_1$ . The effect of LAI on  $POD_1$  is comparatively marginal and inconsistent, which suggests that only pronounced changes in LAI  
5 (as can be found for deciduous trees as the growing season and thus foliage develops) might significantly affect the partition of the canopy into sunlit and shaded fractions with subsequent effects on the light penetration of the canopy and hence  $g_{sto}$ . These findings stress the importance of the accurate parameterisation of these key variables and especially  $g_{max}$ , as noted previously for Jarvis-type models (e.g. B ker et al., 2007).

There are a number of assumptions behind the modelling schemes used here, irrespective of the type of approach. One of the key difficulties in modelling soil water status lies in the characterisation of the soil environment, both in terms of the soil texture and subsequent soil water holding properties, but also in relation to the rooting environment, with the density and structure of roots likely to vary by species, with depth and  
10 according to the severity and evolution of drought conditions. Dynamic approaches to estimates of root depth have been attempted by other models (e.g. Jansson and Karlberg, 2004) and may be an option for future model development. There is also evidence that hydraulic redistribution of water between different parts of the soil may take place (Warren et al., 2007, Domec et al., 2010). However, given the difficulties  
15 in defining maximum root depth under optimum soil water supply, the addition of such dynamic methods may suggest accuracy in the model parameterisation which in reality is extremely hard to achieve.

All methods require knowledge of the soil texture and use soil water release curves to define the characteristics and absolute values of the different texture-related soil water  
25 properties. An argument often cited in favour of the  $f_{PAW}$  models is that they avoid issues related to soil texture since soil water status is expressed as  $\theta$ . However, these models still require that  $FC$  and  $\Psi_{min}$  be defined as absolute values, and these vary by soil texture. Saxton et al. (1986) and Warren et al. (2005) have developed means of estimating soil water releases curves based on sand, silt and clay fractions within the

33612

soil. However, application of these methods at particular sites is still confounded by the fact that such fractions vary both horizontally and with depth over quite short distances (cm to m). In the absence of detailed soil data, the only option is to generalise based on what data are available for a particular site or across a particular geographical region.

5 There are also aspects of water vapour loss from the canopy that may require further consideration. In the past the DO<sub>3</sub>SE model has tended to focus on estimating stomatal O<sub>3</sub> flux and hence  $g_{\text{sto}}$  at the leaf level, and, for forest trees, a leaf that represents a mature leaf of the upper canopy. As such the model has concentrated on estimating conductance for sun leaves. However, a mature forest canopy will comprise both sun and shade leaf morphologies, and sunlit and shaded fractions. The latter will vary over  
10 the course of a day and the former over the course of a growing season, and both by species and prevailing climatic conditions. This can have important implications for canopy water loss since, when considering the entire growing season, upper canopy sun leaves will have significantly higher  $g_{\text{sto}}$  and hence water loss than lower canopy shade leaves. The DO<sub>3</sub>SE model accounts for variable sunlit and shaded leaf fractions through implementation of the canopy light extinction model (Norman, 1982). However, there is currently no allowance made for the existence of different sun and shade leaf morphologies within the canopy. This will lead to an overestimate of water vapour loss and possibly O<sub>3</sub> deposition. Such diurnal and seasonal variations in sun-lit vs. shaded  
15 foliage proportions, and hence in whole-tree transpiration, may be available from analysis of xylem sap flow assessments in tree trunks (Granier et al., 2000; Köstner et al., 2008; Matyssek et al., 2009), allowing for model validation.

The evaluations presented have shown the capability of both the  $f_{\text{SWP}}$  and  $f_{\text{PAW}}$  approaches used within the DO<sub>3</sub>SE model to perform under a range of climatic conditions  
25 (from Scandinavia, through central Europe to the Mediterranean, and similar climates found in North America) and for a variety of forest species that are representative of those different climates. An important aspect of the models' performance under Mediterranean-type climates is its ability to deal with a lack of complete soil water recharge during the winter months. The results from Prades (Fig. 10), showing a water

33613

loss over three subsequent years without a full recharge during the winter months, suggest that the model is capable of capturing the magnitude of soil recharge and water loss over relatively long periods of time. For the more northerly temperate and boreal forests, phenology becomes especially important since this determines the time during  
5 which the forest trees are actively transpiring. Phenology, here defined as the start and end of the growing season, is calculated according to a latitude model that was derived from remotely sensed (Zhang et al., 2004) and observational data describing the onset and dieback of vegetation and leaf flushes and senescence respectively, as described and used by LRTAP Convention (2010). The importance of phenology can be seen in  
10 terms of controlling the onset and decline of transpiration, with the model seeming able to provide good estimates both of  $E_t$  as well as  $\theta$ .

This discussion has mainly focussed on aspects of water loss via the transpiration stream ( $E_t$ ), since this pathway will also be important for stomatal O<sub>3</sub> flux. However, issues related to water loss from the soil ( $E_s$ ) and evaporation directly from external  
15 plant surfaces ( $E_i$ ) are also important, at least in determining the soil water balance. Modelling of the terms  $E_t$ ,  $E_i$  and  $E_s$  has been consistent through use of the Penman-Monteith approach. Yet, still some assumptions have to be made. For soils we assume a cap on the amount of water lost from this reservoir when soil water is limiting  $g_{\text{sto}}$ , such that we mimic the effect of faster soil drying in the uppermost soil layers. For  
20 future model development it may be desirable to divide the soil into two separate compartments, one that represents these uppermost layers and allows soil water status to be influenced by  $E_s$ , and the other from which gravitationally held water can only be lost via the transpiration stream. In the evaluations  $E_s$  is also tempered by the continuous presence of some LAI or SAI, which will reduce the radiation to the soil, hence limiting  $E_s$ . However, were the model to be suitable for application over bare soil, a new  
25 approach to implementing the cap to water loss via  $E_s$  would be necessary.

Other limiting factors of the model include the omission of various elements of the hydrological cycle, such as snow water and groundwater storage terms. However, for the purposes of the evaluation performed in this paper, which focussed on the

33614



physiologically active plant growth period (when snow is unlikely to be present) and for site conditions which were not known to be affected by water table depth, the omission of these storage terms will have been unlikely to significantly affect the results. Further model development could investigate incorporation of these terms, though groundwater storage may be difficult to deal with in relation to regional scale applications due to limitations in data availability.

In relation to future model development, it is also useful to consider new techniques for model evaluation. Recently, methods have become available for validating modelled  $O_3$  flux to trees with empirical data, derived from assessing the trunk sap flow as a measure of foliage transpiration (Nunn et al., 2007; Köstner et al., 2008; Matyssek et al., 2008). Sapflow gauges can be positioned in tree crowns to distinguish water flow to various parts of the foliage, thereby allowing assessment of the total stomatal  $O_3$  uptake of the canopy. This approach provides direct estimates of stand-level stomatal  $O_3$  flux (determined using allometric tree-stand up-scaling, and provided  $O_3$  concentration is measured within the canopy boundary; cf. Wieser et al., 2008). As such, non-stomatal stand-level  $O_3$  deposition can also be derived when employing the eddy covariance approach in parallel (Nunn et al., 2010). The difference between the whole-stand  $O_3$  deposition provided by eddy covariance methodology and stomatal  $O_3$  deposition as based on the sap flow approach represents the non-stomatal  $O_3$  deposition. Such methods provide the opportunity to compare both  $E_t$  and stomatal  $O_3$  flux using complimentary measurement approaches and therefore could provide a valuable tool in future efforts to evaluate, and further develop, the DO<sub>3</sub>SE soil moisture model.

The modelling performed in this study has assumed no direct effect of  $O_3$  on  $g_{sto}$ . However,  $O_3$ -induced damage to stomatal functioning (Maier-Maercker, 1997; Mills et al., 2009; Wilkinson and Davies, 2009, 2010) might well impact estimates of stomatal  $O_3$  flux. Currently, our understanding of how combinations of stress variables such as increased temperature, drought and  $O_3$  interact to influence  $E_t$  and hence water balance, both on a short-term and long-term basis, are too limited to be incorporated into modelling studies with any degree of confidence. However, observational data

33615

collected for a mixed deciduous forest by McLaughlin et al. (2007a) illustrate the need to consider such interactions in future research efforts. They found an increase in water use under warmer climates with higher  $O_3$  levels. These changes in water balance led to reduced growth of the mature forest trees with potential implications for the hydrology of forest watersheds (McLaughlin et al., 2007b). Such interactions and ecosystem scale responses will be important to consider in future experimental and modelling studies investigating  $O_3$  and drought interactions.

## 6 Conclusions

The present study describes the further development and evaluation of the DO<sub>3</sub>SE soil moisture module previously described in Emberson et al. (2007). This module has been improved through incorporation of the Penman-Monteith approach to estimate  $E_t$ , thereby incorporating energy balance terms in the estimate of soil water status and subsequent effects on  $g_{sto}$  and stomatal  $O_3$  flux. Four different modelling approaches of linking soil water conditions to  $g_{sto}$  were investigated within the DO<sub>3</sub>SE model framework.

The models (especially the  $f_{SWP}$  and  $f_{PAW}$  models) work well at the European scale for various tree species being capable of differentiating between “wet” and “dry” years and of estimating the onset of both soil drying and soil water recharge periods with a good degree of accuracy for a range of different climates typical for Europe and North America.

Both the  $f_{SWP}$  and  $f_{PAW}$  could be recommended for regional scale application. However, given that  $\theta$  tends to be more readily available for evaluation and that the simple assumption of 50 % PAW as a threshold for soil water effects on  $g_{sto}$  is easy to parameterise without losing any obvious predictive ability, we recommend the  $f_{PAW}$  approach for regional scale application. That said, the more physiologically relevant aspects of the  $f_{SWP}$  approach might make this method more suitable for application on a site-specific basis, especially where plant physiological data have been collected which

33616



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33619

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33620

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33621

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33624



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33629

**Table 1.** Symbols, abbreviations and parameter values.

Symbol	Parameter	Units
$a$	Plant absorption flux	$\text{m s}^{-1}$
$b$	Texture dependent soil conductivity parameter	–
$C$	Plant capacitance	1 (B/T), $\text{mm MPa}^{-1}$ 0.17 (M)
$C_c$	Coefficient of transpiration fraction of $E_{\text{at}}$	–
$c_p$	Specific heat of air	$\text{J kg}^{-1} \text{K}^{-1}$
$C_s$	Coefficient of evaporation fraction of $E_{\text{at}}$	–
$d$	Soil measurement depth	m
$D$	Vapour pressure deficit of air	kPa
$d_r$	Root zone depth	m
FC	$\theta$ at field capacity	$\text{m}^3 \text{m}^{-3}$
PAW <sub>min</sub>	$\theta$ at $\Psi_{\text{min}}$	$\text{m}^3 \text{m}^{-3}$
$E_{\text{at}}$	Total evapotranspiration	$\text{m day}^{-1}$
$E_i$	Evaporation from canopy	$\text{m day}^{-1}$
$E_s$	Soil surface evaporation	$\text{m day}^{-1}$
$E_t$	Plant transpiration	$\text{m day}^{-1}$
$G$	Soil surface heat flux	$\text{W m}^{-2}$
$I_{\text{dir}}$	Direct sunlight	$\text{W m}^{-2}$
$I_{\text{diff}}$	Diffuse sunlight	$\text{W m}^{-2}$
$K_s$	Soil hydraulic conductivity	$\text{m s}^{-1}$
$K_{\text{sat}}$	Soil hydraulic conductivity at saturation	$\text{m s}^{-1}$
$k_1$	Root density parameter	$3.5 \times 10^{-12} \text{ m s}^{-1}$
LAI	(Projected) Leaf area index	$\text{m}^2 \text{m}^{-2}$
PAW	Plant available soil water	m
$P_{\text{input}}$	Precipitation reaching the soil surface	m
$P_{\text{total}}$	Total precipitation	m
$q$	Storage/destorage flux	$\text{m s}^{-1}$
$r_{\text{sto}}$	Stomatal resistance (leaf-level)	$\text{m s}^{-1}$
$r_{\text{ext}}$	External plant surface resistance (leaf-level)	$\text{m s}^{-1}$

33630



Table 1. Continued.

$R_a$	Aerodynamic resistance		$\text{m s}^{-1}$
$R_b$	Boundary layer resistance		$\text{m s}^{-1}$
$R_{\text{btH}_2\text{O}}$	Boundary layer resistance to water vapour exchange		$\text{m s}^{-1}$
$R_c$	Storage hydraulic resistance	0.4 (B/T), 2 (M)	$\text{MPa h mm}^{-1}$
$R_{\text{gs}}$	Soil resistance to ozone		$\text{m s}^{-1}$
$R_{\text{stotH}_2\text{O}}$	Stomatal resistance to water vapour exchange		$\text{m s}^{-1}$
$R_{\text{inc}}$	In canopy resistance		$\text{m s}^{-1}$
$R_p$	Plant hydraulic resistance	5.3 (B/T), 7 (M)	$\text{MPa h mm}^{-1}$
$R_{\text{sp}}$	Soil-plant hydraulic resistance		$\text{MPa h mm}^{-1}$
$R_{\text{sr}}$	Soil-root hydraulic resistance		$\text{MPa h mm}^{-1}$
$R_{\text{soil}}$	Soil resistance to water vapour		$\text{m s}^{-1}$
SAI	Surface area index		$\text{m}^2 \text{m}^{-2}$
$S_c$	Canopy storage capacity		m
$S_n$	Soil water storage		m
$S_{n-1}$	Soil water storage of previous day		m
$\beta$	Root fraction parameter	0.97	
T	Air temperature		$^{\circ}\text{C}$
$\Delta$	Slope of the relationship between saturation vapour pressure and temperature		$\text{MPa K}^{-1}$
$\gamma$	Psychrometric constant		$\text{MPa K}^{-1}$
$\lambda$	Latent heat of vaporisation		$\text{J kg}^{-1}$
$\rho_a$	Air density		$\text{kg m}^{-3}$
$\theta$	Volumetric soil water content		$\text{m}^3 \text{m}^{-3}$
$\theta_{\text{sat}}$	Volumetric soil water content at saturation		$\text{m}^3 \text{m}^{-3}$
$\Phi_n$	Net radiation at top of canopy		$\text{W m}^{-2}$

33631

Table 1. Continued.

$\Phi_{\text{ns}}$	Net radiation at soil surface	$\text{W m}^{-2}$
$\Psi_e$	Soil water potential at air entry	MPa
$\Psi_{\text{leaf}}$	Leaf water potential	MPa
$\Psi_{\text{leaf,pd}}$	Pre-dawn leaf water potential	
$\Psi_{\text{min}}$	Soil water potential below which plant water uptake ceases	MPa
$\Psi_r$	Reservoir potential	MPa
$\Psi_{\text{sat}}$	Soil water potential at saturation	MPa
$\Psi_{\text{soil}}$	Soil water potential	MPa

N.B. B/T = boreal/temperate forest trees; M = Mediterranean forest trees.

33632



**Table 4.** Forest datasets used to test soil water status estimates of the  $\text{DO}_3\text{SE}$  model. References as in Table 2.

Site name	Country	Location	Elevation (m a.s.l.)	Species	Wind speed height (m)	Soil texture	Soil water metric	Soil water measurement depth (m)	$g_{\text{sto}}$ data	Measurement period
Asa	Sweden	57°09' N 14°45' E	285	Norway spruce	5	Silt loam	$\Psi_{\text{soil}}$ (MPa)	0.4	–	1995, 2000
Davos	Switzerland	46°48' N 09°51' E	1640	Norway spruce	30	Silt loam	$\Psi_{\text{soil}}$ (MPa)	0.1	–	2004
Forellenbach	Germany	48°56' N 13°25' E	825	Beech	51	Sandy loam	PAW (mm)	1.2	–	2003
Hortenkopf	Germany	49°16' N 07°49' E	550	Beech and oak	10	Sandy loam	$\theta$ (%)	0.4	–	2000–2003
Kranzberger Forst	Germany	48°25' N 11°25' E	485	Beech	33	Silt/Clay loam	$\theta$ (%)	0.3	Porometer	2003
Miraflores de la Sierra	Spain	40°48' N 03°48' W	1095	Holm oak	10	Sandy/silt loam	$\Psi_{\text{pobal}}$ (MPa)	–	LI-COR 6400	2004, 2005
Norunda	Sweden	60°05' N 17°29' E	45	Norway spruce, Scots pine	37	Sandy loam	$\theta$ (%)	0.5	Sap flow	1999
Prades	Spain	41°12' N 00°55' E	930	Holm oak	5	Clay loam	$\theta$ (%)	0.1, 0.4	–	2001–2003
Rhinelander	USA	45°36' N 89°30' W	500	Aspen; mixed Aspen-Birch	10	Sandy loam	$\theta$ (%)	Between 0.05 and 1.3	Sap flow	2006
Strawberry Peak/Crestline	USA	34°30' N 117°18' W	1800	Evergreen oak ( <i>Quercus spp.</i> )	15	Loam	$\theta$ (%)	0.5	–	1995

Measurement height: OF = Open Field; C = within Canopy

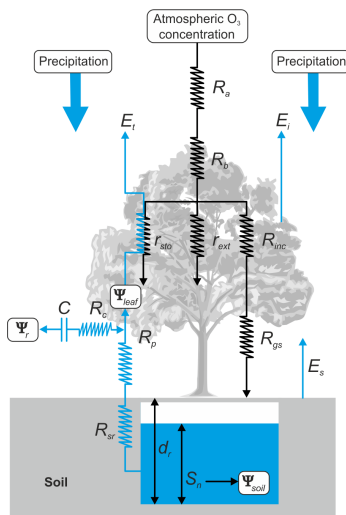
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**Table 5.** Statistical agreement (coefficient of determination ( $R^2$ ), mean bias (MB; normalised value in parenthesis), root mean square error (RMSE; normalised value in parenthesis) and Willmott's index of agreement (IA)) of measured and modelled soil water using four methods that relate soil water to  $g_{\text{sto}}$ . Results for Miraflores are not shown due to scarcity of measured data points. Metric units:  $\Psi_{\text{soil}}$  [MPa], PAW [mm],  $\theta$ [%].

Site	Year	Soil water Metric	$f_{\text{opt}}$				$f_{\text{low}}$				SS				NSS			
			$R^2$	MB (NMB)	RMSE (NRMSE)	IA	$R^2$	MB (NMB)	RMSE (NRMSE)	IA	$R^2$	MB (NMB)	RMSE (NRMSE)	IA	$R^2$	MB (NMB)	RMSE (NRMSE)	IA
Asa	1995 2000	$\Psi_{\text{soil}}$	0.48	-0.02 (14.02)	0.53 (-236.25)	0.89	0.47	0.05 (-24.41)	0.53 (-145.63)	0.79	0.57	0.20 (-90.32)	0.36 (-161.98)	0.44	0.51	0.19 (-83.15)	0.23 (-148.37)	0.50
			0.02	0.02 (-54.89)	0.02 (-62.87)	0.19	0.02	0.02 (-54.89)	0.02 (-62.87)	0.19	0.04	0.02 (-64.86)	0.02 (-65.74)	0.18	0.03	0.02 (-61.43)	0.02 (-63.04)	0.19
Davos	2004	$\Psi_{\text{soil}}$	0.01	0.01 (-42.73)	0.01 (-56.79)	0.44	0.00	0.01 (-45.07)	0.01 (-58.54)	0.43	0.00	0.01 (-48.10)	0.01 (-60.67)	0.42	0.00	0.01 (-44.07)	0.01 (-57.87)	0.43
Forellenbach	2003	PAW	0.91	21.00 (29.98)	25.43 (36.32)	0.88	0.90	14.49 (20.69)	24.28 (34.67)	0.90	0.08	109.50 (156.34)	113.53 (162.09)	0.31	0.61	78.29 (111.78)	80.62 (115.11)	0.44
Hortenkopf	2000 2001 2002 2003	$\theta$	0.78	0.01 (7.40)	0.02 (8.15)	0.84	0.78	0.01 (7.40)	0.02 (9.15)	0.84	0.40	0.03 (15.59)	0.03 (17.98)	0.49	0.54	0.03 (14.19)	0.03 (16.19)	0.53
			0.81	-0.02 (-16.67)	0.03 (23.21)	0.90	0.81	0.01 (4.46)	0.02 (17.00)	0.94	0.55	0.09 (74.42)	0.10 (80.67)	0.42	0.88	0.07 (57.97)	0.07 (60.98)	0.56
			0.60	-0.03 (-24.91)	0.03 (27.88)	0.81	0.12	0.00 (-0.73)	0.02 (20.73)	0.59	0.00	0.09 (84.57)	0.09 (90.61)	0.25	0.04	0.05 (45.96)	0.05 (51.67)	0.39
Kranzberger Forst	2003	$\theta$	0.94	-0.01 (-5.55)	0.02 (18.25)	0.97	0.94	0.00 (3.42)	0.01 (13.21)	0.98	0.73	0.07 (60.88)	0.08 (67.36)	0.58	0.83	0.03 (30.67)	0.04 (35.72)	0.84
			0.84	-0.02 (-7.18)	0.04 (12.01)	0.82	0.85	-0.02 (-8.19)	0.04 (12.41)	0.91	0.43	0.03 (6.84)	0.05 (16.53)	0.73	0.73	0.00 (0.68)	0.03 (9.97)	0.82
Norunda	1999	$\theta$	0.89	-0.02 (-12.67)	0.03 (23.52)	0.98	0.89	-0.01 (-5.97)	0.03 (16.83)	0.97	0.87	0.05 (29.84)	0.06 (38.03)	0.85	0.94	0.01 (4.78)	0.02 (14.84)	0.98
			0.77	-0.03 (-13.57)	0.05 (19.24)	0.88	0.82	-0.03 (-9.82)	0.04 (15.12)	0.82	0.84	-0.02 (-6.78)	0.03 (12.49)	0.84	0.81	-0.02 (-9.73)	0.04 (15.34)	0.82
Rhinelander	2003	$\theta$	0.72	0.00 (0.56)	0.03 (19.41)	0.91	0.53	-0.01 (-9.53)	0.03 (28.80)	0.83	0.27	0.01 (4.68)	0.04 (21.56)	0.68	0.41	0.00 (-0.76)	0.04 (28.07)	0.78
Strawberry Peak/Crestline	1995	$\theta$	0.78	0.03 (18.70)	0.04 (25.74)	0.96	0.80	0.03 (19.40)	0.04 (25.84)	0.86	0.89	0.06 (41.61)	0.06 (44.09)	0.70	0.90	0.05 (36.34)	0.05 (38.73)	0.75

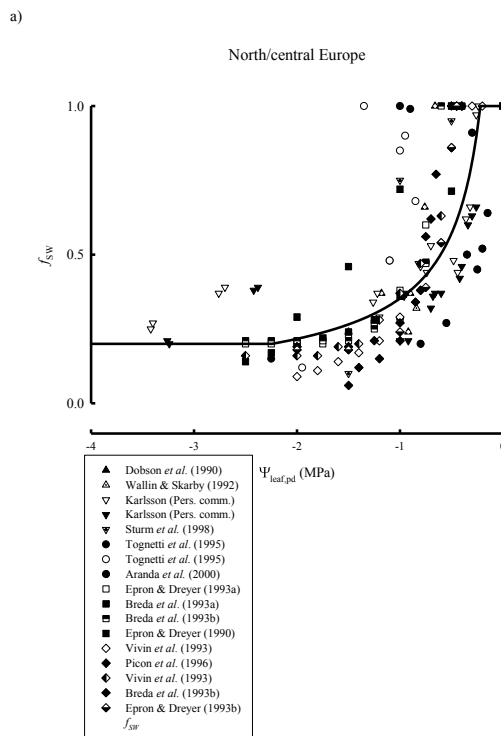
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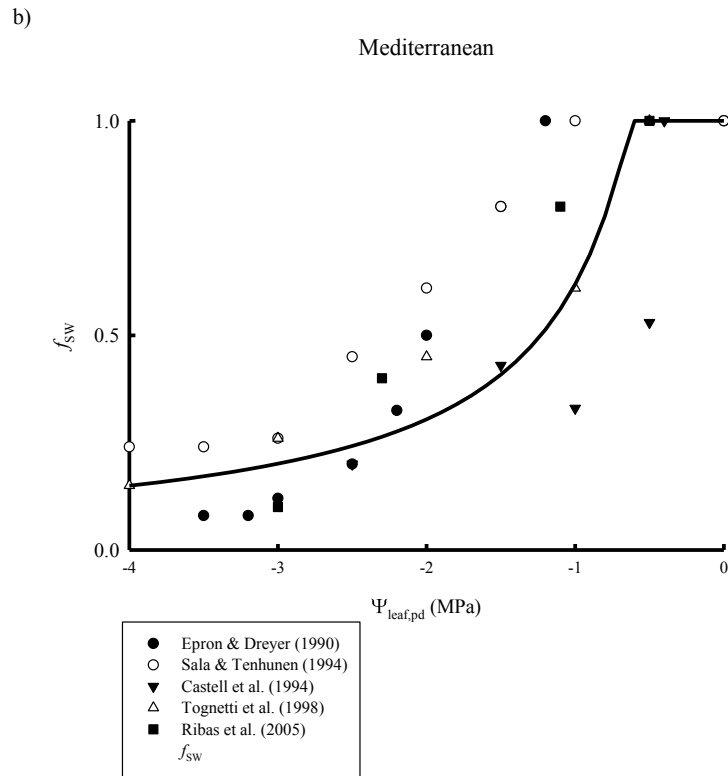
**Fig. 1.** Schematic of resistance to  $O_3$  deposition (black) and water vapour exchange (blue) in relation to the  $DO_3SE$  model resistance scheme. The coupling between soil water loss and transpiration is achieved through the influence of soil drying on  $g_{sto}$  resulting in reduced transpiration. Denotation: see Table 1. Note that all possible resistances are shown in the schematic though different models will use different combinations of these resistances; the  $Rsr$  and  $Rp$  terms are specific to the SS model and the  $Rsr$ ,  $Rp$ ,  $Rc$  and  $C$  terms are specific to the NSS model. The  $f_{SWP}$  and  $f_{PAW}$  models do not use these particular terms. Further details are provided in the text.

33639



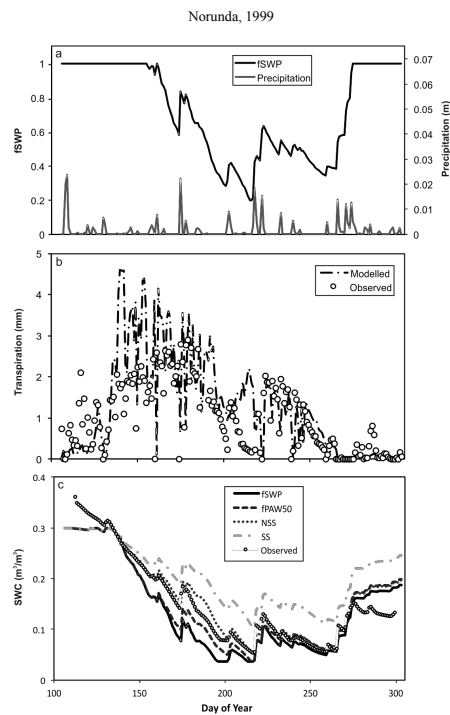
**Fig. 2a.**  $f_{sw}$  relationships in comparison with observed data describing relative  $g$  with pre-dawn leaf water potential for (a) coniferous (Norway spruce and Scots pine) and deciduous (beech) trees in north and central Europe with  $\Psi_{max} = -0.6$  MPa;  $\Psi_{min} = -1.5$  MPa; PWP =  $-4.0$  MPa.

33640



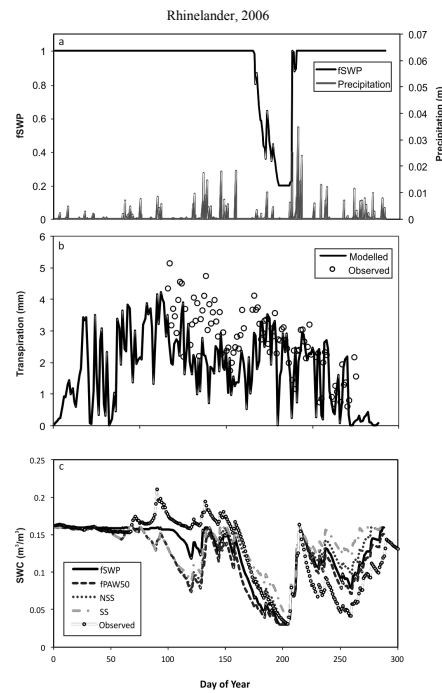
**Fig. 2b.**  $f_{SW}$  relationships in comparison with observed data describing relative  $g$  with pre-dawn leaf water potential for **(b)** Mediterranean trees (holm oak) with  $\Psi_{max} = -0.9$  MPa;  $\Psi_{min} = -3.6$  MPa; PWP =  $-4.0$  MPa.

33641



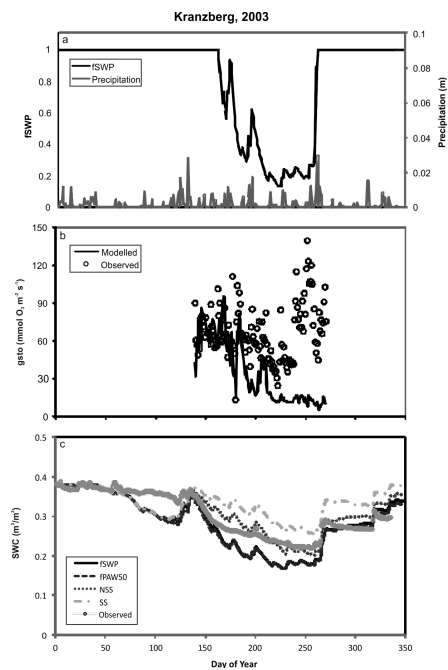
**Fig. 3.** **(a)** Modelled  $f_{SWP}$  and measured precipitation for a mixed Norway spruce and Scots pine stand at Norunda in 1999 using the  $f_{PAW}$  method; **(b)** Observed and modelled transpiration for the same year, stand and soil water calculation method; **(c)** Observed and modelled soil water content (SWC) using all four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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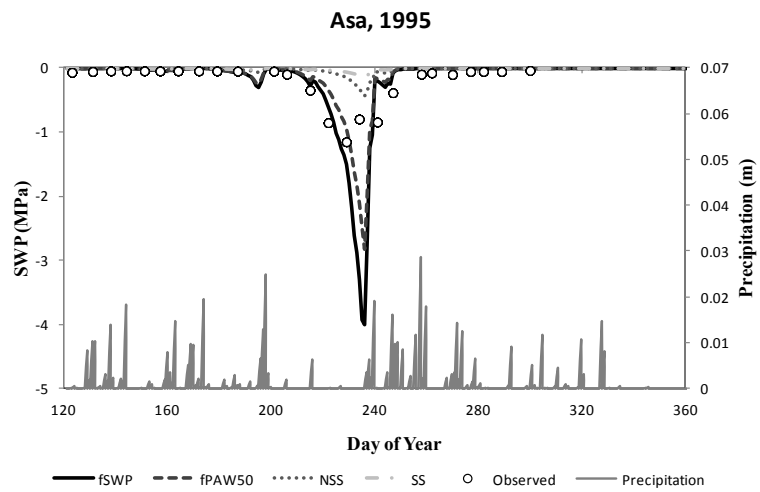
**Fig. 4.** (a) Modelled  $f_{SWP}$  and measured precipitation for a mixed aspen-birch stand at Rhinelander in 2006 using the  $f_{SWP}$  model; (b) Observed and modelled transpiration for the same year, stand and soil water calculation method; (c) Observed and modelled soil water content (SWC) using all four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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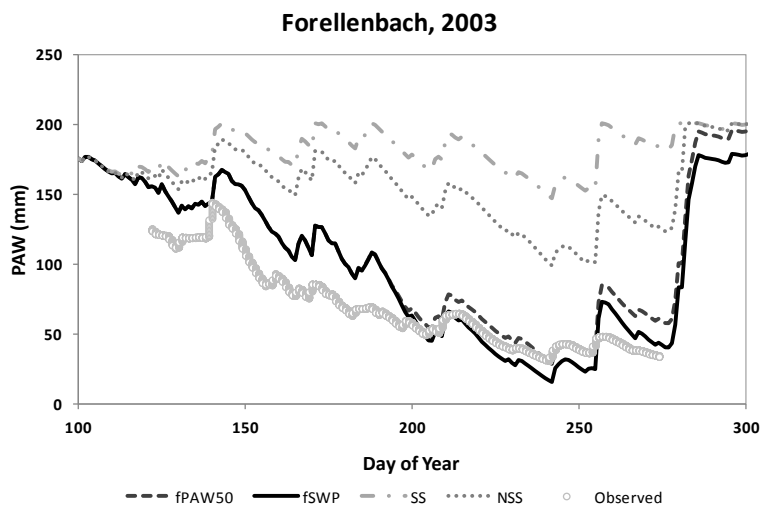
**Fig. 5.** (a) Precipitation and modelled  $f_{SWP}$  for a beech stand at Kranzberger Forst in 2003 using the  $f_{SWP}$  model (see methods section for details); (b) Observed and modelled leaf-level  $g_{sto}$  for the same year, stand and soil water calculation method; (c) Observed and modelled soil water content (SWC) using all four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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**Fig. 6.** Comparison of observed and modelled soil water potential (SWP) in 1995 for a Norway spruce stand at Asa using four methods that relate soil water to  $g_{sto}$  (see methods section for details).

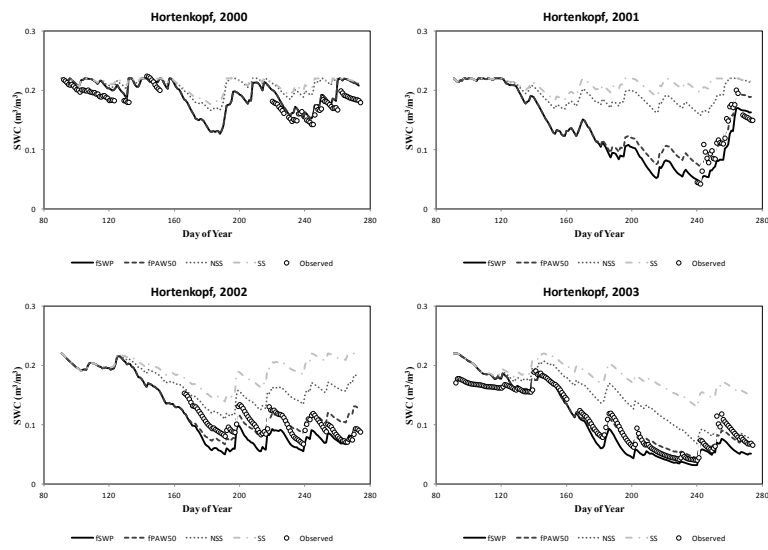
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**Fig. 7.** Comparison of observed and modelled plant available water (PAW) in 2003 for a beech stand at Forellenbach using four methods that relate soil water to  $g_{sto}$  (see methods section for details).

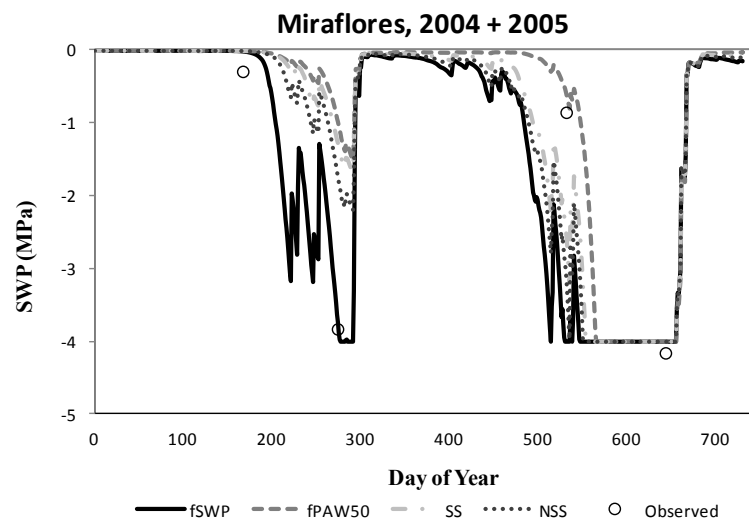
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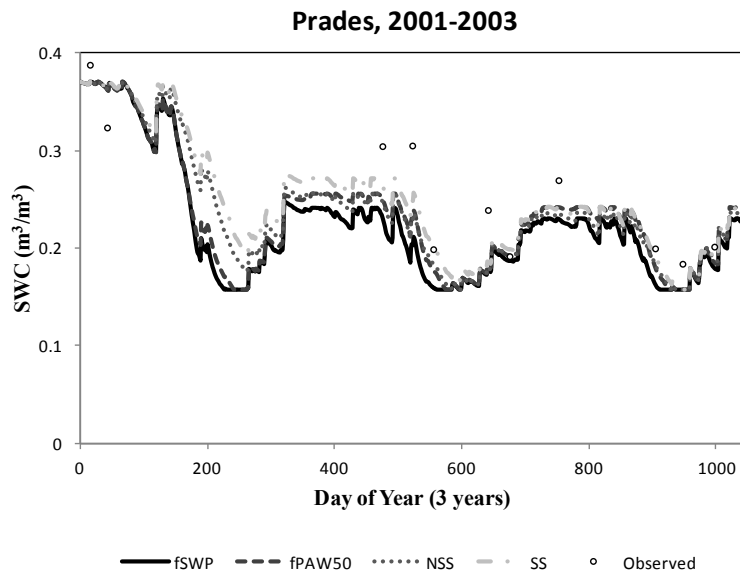
**Fig. 8.** Comparison of observed and modelled soil water content (SWC) in 2000, 2001, 2002 and 2003 for a mixed beech and temperate oak stand at Hortenkopf using four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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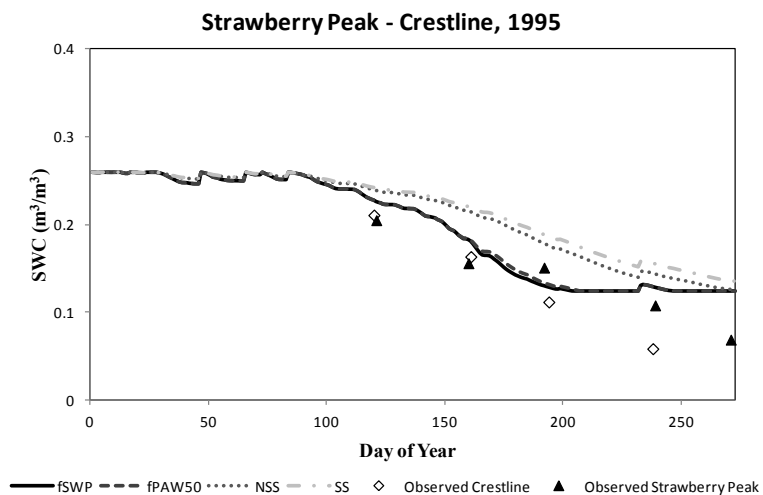
**Fig. 9.** Comparison of modelled soil water potential (SWP) and observed pre-dawn leaf water potential in 2004 and 2005 for a holm oak stand at Miraflores de la Sierra using four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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**Fig. 10.** Comparison of modelled and observed soil water content (SWC) from 2001 to 2003 for a holm oak stand at Prades using 4 methods that relate soil water to  $g_{sto}$  (see methods section for details).

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**Fig. 11.** Comparison of observed and modelled soil water content (SWC) in 1995 for a ever-green oak stand at Strawberry Peak/Crestline using four methods that relate soil water to  $g_{sto}$  (see methods section for details).

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