Chapter 7  

Dry canopy evaporation

7.1 Introduction

Under dry conditions the evaporation from a forest consists of two parts: transpiration by the vegetation and evaporation from the bare soil underneath the vegetation. Of these two evaporation processes, transpiration is for forested surfaces the main contributor. Under conditions with a relatively moist soil, water loss is largely controlled by the physical boundary layer resistance $r_a$. The magnitude of $r_a$ depends on the roughness characteristics of the canopy and the wind speed. Under conditions when the soil is drying out, the major control of water loss becomes physiological, often represented by a single surface or canopy resistance $r_s$. (e.g. Monteith and Unsworth, 1990).

Forests, however, are complex eco-systems, usually with great variability in space, both horizontally as well as vertically. The most extreme compositions are: on one side a forest with a single tree species and no or nearly no understorey (e.g. beech forest in the mid latitudes), and on the other side a forest with such a diversity in tree species and a lush understorey that there is no free air space left (e.g. tropical rain forest). In the northern mid latitudes where the Netherlands is located, there is almost no natural forest and most forest stands are basically planted single tree species. In these forests the undergrowth composition is influenced by the available radiation which depends on shading by the trees, available nutrients which depends on soil type, litter quality and atmospheric deposition, and hydrological regime. The fact that the undergrowth is seen as a competitor of trees, e.g. bracken (*Pteridium aquilinum*) in the UK (Roberts et al., 1980), dwarf bamboo (*Sasa kurilensis*) in Japan (Ishii et al., 2008), rhododendron (*Rhododendron ponticum*) in Belgium (Nadezhdina et al., 2004) and wild berry (*Prunus serotina*) in the Netherlands (Koop et al., 2000), illustrates the potential impact of the undergrowth on the water balance of a forest.

To overcome periods of droughts it is necessary for forests, i.e. a combination of trees and undergrowth, to reduce the evaporation rate to preserve water. To achieve this reduction in water loss, some tree species drop their leaves, e.g. *poplar* trees, while others close their stomata, e.g. *pine* trees.
It is expected that climate change will come among others with prolonged dry periods without rain (Christensen et al., 2007). For areas like the lower parts of the Netherlands, the connection between the root zone and the groundwater level often determines the composition and hence the quality of the natural vegetation cover. Prolonged disconnection from the groundwater may thus have serious consequences for such eco-systems. In this chapter special attention will be given to the derivation of parametrizations for water stress of forests in The Netherlands.

Transpiration loss of water is not only regulated by the availability of water at the root-soil interface, but also by other bio-physical processes causing stomatal closure.

Cochard et al. (2002) have shown that trees are able to “sense” a coming drought, while the trees are still being supplied with water at rates adequate to meet maximum transpiration requirements. Here we postulate that this process is related to the drying of the top soil layer where most roots are present combined with extractable water being available at deeper layers. It has been shown that vegetation, and especially trees are able to extract water from deeper layers enabling them to survive periods of drought (e.g. Rambal, 1984; Talsma and Gardner, 1986). The “sensing” of drought is most likely a combination of different drivers affecting the leaf water potential, as a dry top soil layer is mostly coinciding with relatively high radiation load $R_{down}$, high air temperature $T_a$ and a large vapour pressure deficit $e_D$. The exact functioning is however still unclear (e.g. Woodruff et al., 2007) and may or may not be caused by feedback mechanisms using enzymes such as ABA (e.g. Franks, 2004; Franks et al., 2007).

The flow of soil water to the roots is much better understood (e.g. Feddes and Raats, 2004). The rate of water uptake depends on rooting density, soil hydraulic conductivity, and the pressure difference in the soil and at the soil-root interface. Non-uniformity of root water uptake from different soil depths as caused by differences in root densities and water availability, greatly complicates the understanding of the feedbacks of water stress on canopy resistance. In general the feedback of soil water on canopy conductance is simulated using a single function based on a single soil water parameter, such as used in Eq. 2.51. However, this soil water parameter is not necessarily a good representation of the complex relationship between stomatal closure and available soil water. To improve on this relationship, we will test a model for the stomatal closure that is able to represent the feedbacks by two distinct soil water sources, i.e. the water content of the top soil and of the soil layer at the depth of the deepest roots.

The flow of water from the soil, through the plant into the atmosphere is determined by a series of resistances: flow of soil water from a point in the soil towards the interface with the roots, - i.e. through the epidermis of the roots, - from the roots to the leaves and finally through the stomata into the stomatal cavities. Under
7.2. Leaf area development of undergrowth at Fleditebos and Loobos site

Conditions of limited water availability, the main contributor to soil water stress is the resistance of the transport of water from the soil to the roots. The magnitude of this resistance depends on the root distribution and the hydraulic characteristics of the soil. Root distribution is variable in space and time and depends among others on plant species, bulk density of the soil and on the water and nutrient availability. Hence, a comprehensive study of effects of soil water stress on stomatal closure would consist of a dynamic root growth model as well as a dynamic unsaturated zone flow model. However, for field studies and for land surface schemes for regional models such an approach is hardly achievable. Hence a simplified approach is proposed.

The first objective of Chapter 7 is to derive parameter sets for a number of different forest types in the relatively small area of the Netherlands as well as to investigate if these sets add any additional information that may be used to describe regional heterogeneity in the transpiration rates of forest. Special attention will be paid to conditions of possible water stress and the effect of the groundwater reservoir.

The second objective of this Chapter is to analyse the separate contributions of the trees and the undergrowth to the total water loss of the forest sites studied.

Data from 5 sites in the Netherlands will be used. For a detailed description of the characteristics of the sites the reader is referred to Chapter 3. For a description of the continuous measurement system used, see Chapter 4. In the present chapter only some additional information on the undergrowth at the poplar forest of the Fleditebos site and at the pine forest of the Loobos site will be given. At these 2 sites additional eddy correlation measurements were taken below the tree canopy. The measurements of sapflow at the pine stand will be used as an independent check of the performance of the dual source model.

7.2 Leaf area development of undergrowth at Fleditebos and Loobos site

To enable the study of the undergrowth as a separate evaporation source a second flux station has been employed below the canopy at the two sites with a significant undergrowth. At the Fleditebos site the herbal undergrowth is covered by an almost closed canopy cover of poplar trees i.e. $c_{veg} = 0.8$ in summer time and covered by bare trees in winter time i.e. $c_{veg} = 0.2$. At the Loobos site the grass undergrowth is covered by a relatively open canopy of pine trees i.e. $0.55 < c_{veg} < 0.7$.
7.2.1 $L_{AI}$ of the herbal undergrowth of the *poplar* forest

At the *poplar* site the herbal undergrowth started as early as February, with a maximum growth rate in April, leading to a $L_{AI}$ close to $4 \text{ m}^2 \text{ m}^{-2}$. In the second half of May $L_{AI}$ started to decline although the height still increased to reach its maximum of 1.2 m to 1.3 m in July and August. Towards the end of September the height of the undergrowth decreased to 0.4 m and $L_{AI}$ became $\leq 1.0 \text{ m}^2 \text{ m}^{-2}$. In October some regrowth occurred, i.e. average height 0.15 m and $L_{AI}$ 1.5 m$^2$ m$^{-2}$, which lasted until the end of November.

7.2.2 $L_{AI}$ of the grass undergrowth of the *pine* forest

At the *pine* site the grass undergrowth showed a similar seasonal pattern as the herbal undergrowth of the *poplar* forest. However, the maximum $L_{AI}$, i.e. 1.5 m$^2$ m$^{-2}$ of the living grass biomass was reached somewhat later at the end of June and started to decline at the end of July. Regrowth in October was observed with $L_{AI}$ reaching 1.0 m$^2$ m$^{-2}$. It should be noted that in more recent years there was an increase in other species of the undergrowth. A survey done in 2009 showed next to the grass fractional cover of 46% also a fractional cover of 5% by *Vaccinium Myrtillus* and 5% by young *pine* trees. Total $L_{AI}$ of the undergrowth i.e. also including mosses varied in 2009 between 1.1 and 2.3 for winter and summer respectively.

7.3 Root water uptake

7.3.1 Root water uptake parametrization

The parametrization of the root water uptake can be separated into two coupled processes:

1. Effects of water stress on the closure of the stomata,
2. Location of the root water uptake.

The first process determines the total amount of water that will evaporate and is influenced by stress on the stomata as caused by water shortage. The second process determines how root water uptake of this total amount of water is distributed over the different soil layers. It is assumed that allocation of root water uptake is based on minimizing the consumption of energy i.e. most of the water will be taken up in soil layers having the lowest soil water pressure and the highest root density (see Fig. 2.2).
7.3. Root water uptake

For most forests root distribution can be split into two parts: the upper part with a high root density and the lower part with a low root density often existing of tap roots only.

To model the effect of water stress on stomatal closure we take the differences between shallow and deeper soil layers into account. This distinction in soil depth leads to a function for the soil water induced stress being composed of a fast and a slow reacting component. The fast reacting component reflects mainly the vegetation characteristics towards water stress and depends on the soil water content of the upper soil layer. The slow reacting component takes into account the slow depletion of the available water storage as well as the possible additional water available by capillary rise from the groundwater reservoir. The latter is mainly determined by changes in hydraulic conductivity. In the case of a tree canopy with undergrowth, the upper soil layer will include both: roots of trees and undergrowth, while the deeper layer may consist of tree roots only. For time steps less than a day, it is assumed that the upper and the lower soil layer act as two independent parallel sources of soil water.

Taking into account the distinction between the upper and lower soil layer, the soil water stress function becomes (see also Fig. 7.1):

\[ f(\theta) = f(\psi(z_1))f(\psi(z_2)) \]  \hspace{1cm} (7.1)

The function \( f(\psi(z_1)) \) represents primarily the direct and indirect feedback mechanisms of the vegetation to limited water availability in the upper soil layer \( z_1 \).

The function \( f(\psi(z_2)) \) represents available soil water under relatively dry conditions, reflecting the soil water conditions of a relatively thick layer at the bottom of the root zone \( z_2 \). The thickness of the layer allows to take potential vertical root growth under drying conditions into account.

As the exact functioning of stomatal closure is still unclear and complex feedback mechanisms may exist for the stress functions, the following empirical approach will be used for the feedbacks by the soil water stress in the top layer. Here we assume for \( f(\psi(z_1)) \) an exponential function similar to Eq. 2.51.

To simulate the influence of added soil water available to the vegetation by for example capillary of a groundwater reservoir, 2 options will be tested for \( f(\psi(z_2)) \):

The first option \( f(\psi(z_2))_A \) is based on the assumption that at the deeper soil layers the availability of water is mainly driven by the hydraulic characteristics of the soil. It is assumed that soil layers \( z_1 \) and \( z_2 \) function as two parallel sources of soil water. Based on Sinclair (2005) and Sinclair et al. (2005) we derived a simplified equation for \( g_s \):

\[ \frac{g_s}{g_{s,\text{max}}} = 1 - \frac{\psi(z_2)}{\psi_c} \]  \hspace{1cm} (7.2)
Figure 7.1: The soil water stress model \( f(\theta) = f(\psi(z_1)) f(\psi(z_2)) \), with \( f(\psi(z_1)) \) representing the soil water feedbacks of the upper soil layer where 80 - 90% of the roots are found. The left hand side of the figure shows model option A for \( f(\psi(z_2))_A \) representing the feedback of the deepest roots. The right hand side shows model option B for \( f(\psi(z_2))_B \) representing the soil water feedback of the total root zone.

where \( \psi(z_2) \) is the soil water pressure at depth \( z_2 \) and \( \psi_c \) represents the water pressure of the canopy. Sinclair (2005) showed that changes in the hydrostatic pressure of the leaves has no significant impact on the relative transpiration rate. Hence \( \psi_c \) is assumed to be constant at -1.5 MPa. The resulting curve is independent of the soil type.

The second option \( f(\psi(z_2))_B \) is based on the assumption that roots have access to all soil water, i.e. from the surface down to the depth of the deepest roots.

Because in the Netherlands really dry conditions are at the moment relatively scarce, there is a lack of field measurements during prolonged dry periods. To overcome the limited number of data available representing the feedbacks under dry conditions, for the second option \( f(\psi(z_2))_B \), a parametrization based on measurements under more extreme conditions is used. Here an empirical function based on data of 5 different forests in France, i.e. oak, beech, fir, spruce and pine will be used (Granier et al., 2000):

\[
f(\theta_D) = \frac{p_1 + p_2(1 - \theta_D) - \left[ \{p_1 + p_2(1 - \theta_D)\}^2 - 2.8p_1p_2(1 - \theta_D) \right]^{1/2}}{1.4} \quad (7.3)
\]

where \( p_1 = 1.154 \) and \( p_2 = 3.0195 \). The soil water deficit \( \theta_D \) will be based on available soil water in the entire root zone.
Both options do not require site specific parameters. To derive site specific parameters sets only the parameters for \( f(\psi(z_1)) \) have to be optimized.

The soil water pressure \( \psi \) is defined as (see also Eq. 2.8):

\[
\psi = -\frac{\rho_w g}{\alpha} \left[ \left( \frac{1}{S} \right)^{1/m} - 1 \right]^{1/n}
\]

(7.4)

where \( S \) denotes the relative soil water saturation (see Eq. 2.50).

To convert measured \( \theta \) into \( \psi \), parametrizations will be used either determined by analysing soil samples in the laboratory or taken from standard soil databases (e.g. Wösten et al., 1999).

### 7.4 Methods used to derive surface conductance

The response of the transpiration rate to changes in environmental conditions will be analysed based on two separate assumptions:

- The forest is a unique eco-system that behaves as one “big leaf”;
- The undergrowth is an important part of the forest eco-system and needs its own parametrization.

To model the effects of water stress both assumptions need a parametrization depending on the water uptake by roots. The parametrization to simulate water stress as has been described in Chapter 2 is adequate if the objective is to derive a unique set of parameter values for a specific site, i.e. a unique combination of vegetation and soil.

If the objective however, is to derive parameter sets allowing to change vegetation cover at sites, disentangling of the vegetation and soil characteristics is required. This latter objective will not be completely achievable. Not only the vegetation species, but also soil characteristics, such as dry bulk density and nutrient availability have major impacts on the rooting system. Also over longer periods, vegetation itself is one of the drivers in the soil formation processes.

With these shortcomings in mind, an attempt will be made to have a first order separation of the controls on water flow affecting stomatal closure by soil characteristics and vegetation. This separation is especially aimed at vegetation types with deep rooting systems, tapping from water sources such as the unsaturated zone just above a groundwater aquifer, which may be considered being independent of the present daily weather.
7.4.1 “Big leaf” approach

The “big leaf” stomatal conductance $g_s$ has been derived from flux measurements taken above the canopy and by inverting the Penman-Monteith equation (Eq. 2.35):

$$g_s = \frac{1}{r_s} = \frac{\gamma \lambda E}{r_a \Delta_e A + \rho c_p \varepsilon_{D} - r_a (\Delta_e + \gamma) \lambda E} \quad (7.5)$$

The available energy $A$ is derived as the sum of measured $H$ and $\lambda E$.

7.4.2 Dual source model for two vegetation layers

The separate responses of trees and undergrowth have been analysed based on eddy-correlation measurements taken above as well as below the tree canopy at the poplar forest of the Fledite site and the pine forest at the Loobos site. The contribution of the two vegetation layers has been simulated using the sparse canopy model of Shuttleworth and Wallace (1985) and Dolman (1993), as has been described in Section 2.5.5.

7.4.3 Radiative transfer scheme for sparse canopies

In many studies the upper layer vegetation is assumed to be a continuous horizontal layer. For sparse forest, with $c_{veg} < 1$ as often found in managed forests at mid latitudes, this assumption is not necessarily a good one. A number of processes such as soil respiration, undergrowth transpiration and photosynthesis need a proper estimation of the amount of energy available below the tree canopy. Begue et al. (1996) showed that not taking inhomogeneity of discontinuous vegetation into account may result in an overestimation of PAR (Photosynthetic Active Radiation) interception by a factor of 1.5.

Continuous measurement of radiation under a canopy is rather complicated. To at least partly overcome this problem, use has been made of a two layer radiative transfer scheme (Hanan, 2001). This scheme also provides the opportunity to study the sensitivity of total transpiration in relation to the structure of the tree canopy: it makes use of both a macro structure and a micro structure sub-model. The macro structure sub-model describes the geometric distribution of the tree structure. The micro structure sub-model describes the fate of radiation in the tree crown as well as in the lower layer vegetation.

The tree canopy is modelled as a discontinuous canopy. The individual tree crowns have a cylindrical form. The gap probability is estimated using the fractional projected canopy cover. The macro structure model also provides the path length needed to calculate the radiation attenuation in the vegetation by the micro structure
7.5. Stomatal conductance using the “big leaf” approach

A negative binomial distribution is used to estimate interception and scattering of radiation by leaves and branches. Leaves and branches each have their own surface and spectral properties. In the lower vegetation layer differences in spectral properties are used to distinguish between green and senescent leaves.

7.4.4 Stomatal conductance parameter optimization

The parameter values (i.e. constants) of the conductance functions (Section 2.5.3) are obtained by optimizing against the measured surface conductance \( g_s \) and by minimizing the sum of squares of model predictions and measurements using a Marquardt-Levenberg algorithm (SigmaPlot v10, Systat Software, Inc). All stomatal conductance functions were optimized simultaneously, resulting in curves maximizing the conductance for the different drivers.

7.5 Stomatal conductance using the “big leaf” approach

To analyse the differences in the behaviour of the stomatal conductance \( g_s \) between sites and years, the parameters for the Jarvis-Stewart model were optimized for each site and each year (Table 7.5). For this analysis the soil water content deficit \( \theta_D \) was derived from \( \theta \) measured in the root zone. The root zone is here defined as the soil layer where 80 to 90% of the roots are present (See Fig. 3.24). To reduce the effect of soil structural differences, \( \theta_D \) has been normalized using the expression:

\[
\theta_D = \frac{1}{\sum_{i=1}^{n} \Delta z_i} \sum_{i=1}^{n} \left( \frac{\theta_{\text{max}} - \theta}{\theta_{\text{max}} - \theta_{\text{min}}} \Delta z_i \right)
\]  

(7.6)

where the difference between \( \theta_{\text{max}} \) and \( \theta_{\text{min}} \) determines the maximum amount of soil water being available for root water uptake during periods of drought. Often \( \theta_{\text{max}} \) and \( \theta_{\text{min}} \) are based on limits for \( \psi \) such as Field Capacity \( \psi_{\text{FC}} \) and Wilting Point \( \psi_{\text{WP}} \). For agricultural crops the expressions \( \psi_{\text{FC}} = -10^{2.0} \) Pa and \( \psi_{\text{WP}} = -10^{4.2} \) Pa are usually taken. For \( |\psi| > |\psi_{\text{WP}}| \) the vegetation will die. The exact value of \( \psi_{\text{FC}} \) may vary depending among others on the groundwater level. The crop type determines at what soil water pressure water stress starts about to occur, e.g. for grass \( \psi = -10^{2.7} \) Pa and for grains \( \psi = -10^{3.0} \) Pa.

For forest these values differ, not only because of physiological differences between trees and crops, but also because of the extensive rooting system of trees. This rooting system compensates for differences in \( \psi \) both in the horizontal as well as in the vertical direction. To calculate \( \theta_D \) for forest, Granier et al. (2007) used \( \psi_{\text{FC}} = -10^{1.5} \) Pa and \( \psi_{\text{WP}} = -10^{3.3} \) Pa.
The table in Appendix E gives an overview of $\theta$ at these different $\psi$ by using the retention curves found at the sites. Fig. 7.2 shows for the 5 sites the amount of available $\theta$ at different $\psi$ by using the retention curves found at the sites. Fig. 7.2 shows for the 5 sites the amount of available $\theta$ at depths close to the surface and at depths at, or close to the maximum rooting depth. The value $\psi = -10^{1.5}$ Pa coincides with the maximum change in slope of $\theta$, from which point onwards an increase in water stress is to be expected.

However, comparing the values of $\theta$ at $\psi = -10^{1.5}$ Pa with the measured $\theta$-values throughout the year shows that these values are extremely high and do rarely occur. In order to obtain a value better representing the amount of soil water available during a dry period under field conditions, $\theta_{\text{max}}$ was determined based on two assumptions. Firstly: $\theta_{\text{max}}$ was based on the lowest values for $\theta$ measured during the months with negligible evaporation, i.e. from November until April. Secondly: these data were only used when the soil was allowed to drain for at least 10 days with $P < 10.0 \text{ mm } 10\text{d}^{-1}$ and $P < 2.0 \text{ mm } 10\text{d}^{-1}$.

These assumptions showed to be similar to the assumption of a fixed $h$ over the different soil layers, i.e. for the sites with sandy soils $\psi = -10^{1.8}$ Pa, and for the Fleditebos site with its clay soil $\psi = -10^{2.1}$ Pa. Only the soil at 1.0 m depth under the oak forest at the Edesebos showed a sharp decline in $\theta$ at a much lower $\psi$, i.e. $\psi = -10^{0.4}$ Pa. This decline could imply that at this site the oaks may experience a stress signal from the roots at this depth at a much earlier stage than from the roots at other depths. Summarizing and following Granier et al. (2000) $\theta_{\text{min}}$ was at all sites defined at $\psi = -10^{3.3}$ Pa.

To prevent evaporation of intercepted water contaminating the optimization of $g_s$, dry records were used only. “Dry” was defined here as records being preceded by a period of at least 48 h without rain. To reduce the number of data with limited accuracy, the following additional data selection criteria were used: $H > 25 \text{ W m}^{-2}$, $\lambda E > 25 \text{ W m}^{-2}$, $T_a > 0 \text{ C}$, $\kappa_r < 98\%$.

For the poplar forest at the Fleditebos site, the $L_{AI}$ of trees and undergrowth reached their maximum in different months (see Fig. 3.13). These differences in timing of $L_{AI}$ were used to separate the data set of the Fleditebos site in a period in which the undergrowth was dominant and a period in which the trees were considered dominant. Table 7.2 shows the optimized parameter sets for those two periods based on the “Big leaf” approach. The most distinct differences were found in the much higher $g_{s,\text{max}}$ and optimum temperature for the trees. If compared to the parameter set for all years of the poplar forest of Table 7.5, it shows the significant impact of the undergrowth on the magnitude of the overall parameters for this site.

The optimization results in Table 7.5 are presented for each year for the periods when the trees and/or undergrowth are most active, i.e. the period from June until the end of September. In Table 7.3 the maximum $g_s$ is presented based on total $L_{AI}$.
7.5. Stomatal conductance using the “big leaf” approach

Figure 7.2: The soil water content $\theta$ (m$^3$ m$^{-3}$) as a function of soil water pressure $\psi$ (Pa). The top panel depicts the soil properties just below the soil surface (0.07 - 0.15 m), the lower panel depicts the properties of the deepest soil layer (0.54 - 1.0 m) measured. The amount of available soil water $\theta$ between $\psi = -10^{1.5}$ Pa and $\psi = -10^{3.3}$ Pa is illustrated by the horizontal lines (See also Appendix E).
Table 7.1: Optimized maximum surface conductance $g_{s,\text{max}}$ and stomatal conductance functions for each year and each site for the periods that trees and/or undergrowth were active, i.e. end of June until end of September. Also shown are the results of a specific site for all years. The constants $a_R$, $a_T$, $c_e D$, $a_e_D$, $c_{\theta_D}$ and $a_{\theta_D}$ refer to the equations of Section 2.5.3. As a measure of fit, $R^2$ and the Standard Error of Estimate (SEE) are given. In 2001 at the Loobos site no soil water measurements were available because of lightning damage.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>$g_{s,\text{max}}$</th>
<th>$a_R$</th>
<th>$a_T$</th>
<th>$c_{e_D}$</th>
<th>$a_{e_D}$</th>
<th>$c_{\theta_D}$</th>
<th>$a_{\theta_D}$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankenbos</td>
<td>1995</td>
<td>7.3</td>
<td>295.3</td>
<td>21.3</td>
<td>0.703</td>
<td>0.076</td>
<td>0.01</td>
<td>1.70</td>
<td>0.56</td>
<td>0.7</td>
</tr>
<tr>
<td>Larch</td>
<td>1996</td>
<td>8.1</td>
<td>78.5</td>
<td>17.3</td>
<td>0.323</td>
<td>0.096</td>
<td>0.85</td>
<td>0.27</td>
<td>0.51</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>7.2</td>
<td>374.0</td>
<td>20.7</td>
<td>0.460</td>
<td>0.072</td>
<td>0.01</td>
<td>0.10</td>
<td>0.59</td>
<td>0.7</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>7.3</td>
<td>233.7</td>
<td>19.4</td>
<td>0.164</td>
<td>0.075</td>
<td>0.58</td>
<td>0.35</td>
<td>0.50</td>
<td>0.8</td>
</tr>
<tr>
<td>Edesebos</td>
<td>1988</td>
<td>7.5</td>
<td>280.0</td>
<td>16.3</td>
<td>0.233</td>
<td>0.070</td>
<td>0.49</td>
<td>1.68</td>
<td>0.66</td>
<td>0.7</td>
</tr>
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<td>Oak</td>
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<td>8.1</td>
<td>309.7</td>
<td>24.1</td>
<td>1.068</td>
<td>0.090</td>
<td>0.45</td>
<td>3.14</td>
<td>0.62</td>
<td>0.7</td>
</tr>
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<td>All</td>
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<td>290.3</td>
<td>18.9</td>
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<td>0.079</td>
<td>0.40</td>
<td>2.27</td>
<td>0.67</td>
<td>0.7</td>
</tr>
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<td>Fleditebos</td>
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<td>251.1</td>
<td>19.0</td>
<td>0.182</td>
<td>0.076</td>
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<td>0.39</td>
<td>0.52</td>
<td>1.1</td>
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<tr>
<td>Poplar</td>
<td>1996</td>
<td>8.8</td>
<td>165.5</td>
<td>14.9</td>
<td>0.001</td>
<td>0.093</td>
<td>0.57</td>
<td>0.01</td>
<td>0.47</td>
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</tr>
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<td>1997</td>
<td>7.8</td>
<td>57.7</td>
<td>14.7</td>
<td>0.069</td>
<td>0.063</td>
<td>0.57</td>
<td>1.04</td>
<td>0.58</td>
<td>1.2</td>
</tr>
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<td>All</td>
<td></td>
<td>8.3</td>
<td>146.6</td>
<td>16.8</td>
<td>0.034</td>
<td>0.082</td>
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<td>0.22</td>
<td>0.48</td>
<td>1.2</td>
</tr>
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<td>151.7</td>
<td>14.2</td>
<td>0.001</td>
<td>0.086</td>
<td>0.49</td>
<td>1.68</td>
<td>0.49</td>
<td>0.9</td>
</tr>
<tr>
<td>Mixed</td>
<td>1997</td>
<td>8.8</td>
<td>443.7</td>
<td>16.1</td>
<td>0.136</td>
<td>0.093</td>
<td>0.49</td>
<td>1.68</td>
<td>0.60</td>
<td>1.0</td>
</tr>
<tr>
<td>Forest</td>
<td>1998</td>
<td>6.5</td>
<td>0.1</td>
<td>11.5</td>
<td>0.001</td>
<td>0.060</td>
<td>0.49</td>
<td>1.68</td>
<td>0.56</td>
<td>1.2</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>7.7</td>
<td>216.8</td>
<td>16.0</td>
<td>0.045</td>
<td>0.100</td>
<td>0.49</td>
<td>1.68</td>
<td>0.49</td>
<td>1.1</td>
</tr>
<tr>
<td>Loobos</td>
<td>1995</td>
<td>6.6</td>
<td>192.8</td>
<td>14.7</td>
<td>0.001</td>
<td>0.052</td>
<td>0.35</td>
<td>0.64</td>
<td>0.65</td>
<td>0.7</td>
</tr>
<tr>
<td>Pine</td>
<td>1996</td>
<td>11.9</td>
<td>166.1</td>
<td>15.6</td>
<td>0.397</td>
<td>0.127</td>
<td>0.12</td>
<td>0.45</td>
<td>0.61</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>10.0</td>
<td>438.4</td>
<td>16.1</td>
<td>0.293</td>
<td>0.076</td>
<td>0.15</td>
<td>0.26</td>
<td>0.62</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>10.5</td>
<td>479.0</td>
<td>19.8</td>
<td>0.439</td>
<td>0.075</td>
<td>0.16</td>
<td>0.25</td>
<td>0.63</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1999</td>
<td>10.3</td>
<td>323.0</td>
<td>16.2</td>
<td>0.644</td>
<td>0.086</td>
<td>0.27</td>
<td>0.54</td>
<td>0.69</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>11.1</td>
<td>363.3</td>
<td>17.5</td>
<td>0.763</td>
<td>0.100</td>
<td>0.49</td>
<td>1.68</td>
<td>0.65</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>12.9</td>
<td>321.4</td>
<td>24.6</td>
<td>0.107</td>
<td>0.115</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>8.0</td>
<td>126.6</td>
<td>20.1</td>
<td>0.102</td>
<td>0.070</td>
<td>0.01</td>
<td>0.04</td>
<td>0.50</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>9.4</td>
<td>385.8</td>
<td>16.8</td>
<td>0.248</td>
<td>0.088</td>
<td>0.43</td>
<td>0.66</td>
<td>0.50</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>14.2</td>
<td>548.5</td>
<td>19.5</td>
<td>0.101</td>
<td>0.102</td>
<td>0.49</td>
<td>1.68</td>
<td>0.80</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>9.1</td>
<td>217.4</td>
<td>19.0</td>
<td>0.222</td>
<td>0.079</td>
<td>0.60</td>
<td>0.08</td>
<td>0.62</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>10.4</td>
<td>465.3</td>
<td>22.1</td>
<td>0.794</td>
<td>0.078</td>
<td>0.55</td>
<td>0.01</td>
<td>0.74</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>10.2</td>
<td>144.2</td>
<td>17.6</td>
<td>0.231</td>
<td>0.085</td>
<td>0.48</td>
<td>1.00</td>
<td>0.74</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>12.4</td>
<td>511.1</td>
<td>15.3</td>
<td>1.153</td>
<td>0.090</td>
<td>0.56</td>
<td>0.01</td>
<td>0.80</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>14.1</td>
<td>309.6</td>
<td>23.7</td>
<td>0.655</td>
<td>0.114</td>
<td>0.52</td>
<td>1.00</td>
<td>0.73</td>
<td>1.0</td>
</tr>
<tr>
<td>All</td>
<td></td>
<td>9.9</td>
<td>289.3</td>
<td>17.8</td>
<td>0.390</td>
<td>0.090</td>
<td>0.38</td>
<td>0.44</td>
<td>0.62</td>
<td>1.0</td>
</tr>
</tbody>
</table>
7.5. Stomatal conductance using the “big leaf” approach

Table 7.2: Optimized maximum surface conductance $g_{s,max}$ and stomatal conductance functions for the periods that the poplar trees or the undergrowth were dominantly active at the Fleditebos site. The constants $a_R$, $a_T$, $c_e D$, $a_e D$, $c_\theta D$ and $a_\theta D$, refer to the equations of Section 2.5.3. As a measure of fit, $R^2$ and the Standard Error of Estimate (SEE) are given.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>$g_{s,max}$ mm s$^{-1}$</th>
<th>$a_R$ W m$^{-2}$</th>
<th>$a_T$ °C</th>
<th>$c_e D$ hPa</th>
<th>$a_e D$ hPa$^{-1}$</th>
<th>$c_\theta D$ m$^3$ m$^{-3}$</th>
<th>$a_\theta D$</th>
<th>$R^2$</th>
<th>SEE mm s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
<td>16.5</td>
<td>208.4</td>
<td>12.2</td>
<td>0.322</td>
<td>0.082</td>
<td>0.38</td>
<td>1.46</td>
<td>0.66</td>
<td>1.0</td>
</tr>
<tr>
<td>Undergrowth</td>
<td>7.4</td>
<td>174.2</td>
<td>6.2</td>
<td>0.205</td>
<td>0.145</td>
<td>0.49</td>
<td>1.68</td>
<td>0.09</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 7.3: The maximum surface conductance $g_{s,max}$ and actual conductance $g_s$ for each site, with all reduction functions set to 1 and using the maximum total $L_{AI}$, i.e. combined $L_{AI}$ of trees and undergrowth, of the site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Tree species</th>
<th>$g_{s,max}$ mm s$^{-1}$</th>
<th>$L_{AI,max}$ m$^2$ m$^{-2}$</th>
<th>actual $g_s$ mm s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankenbos</td>
<td>Larch</td>
<td>7.3</td>
<td>1.8</td>
<td>13.1</td>
</tr>
<tr>
<td>Edesebos</td>
<td>Oak</td>
<td>7.7</td>
<td>4.9</td>
<td>37.7</td>
</tr>
<tr>
<td>Fleditebos</td>
<td>Poplar</td>
<td>8.3</td>
<td>6.3</td>
<td>52.3</td>
</tr>
<tr>
<td>Kampina</td>
<td>Mixed forest</td>
<td>7.7</td>
<td>5.0</td>
<td>38.5</td>
</tr>
<tr>
<td>Loobos</td>
<td>Pine</td>
<td>9.9</td>
<td>3.3</td>
<td>32.7</td>
</tr>
</tbody>
</table>

i.e. including $L_{AI}$ of the undergrowth. The highest $g_s$ during the year is found at the forest with the highest total $L_{AI}$, i.e. at the poplar forest of the Fledite site $g_s = 52.3$ mm s$^{-1}$. The oak forest of the Edesebos and the mixed forest of Kampina have almost identical $g_{s,max}$ and $L_{AI}$ resulting in similar $g_s$, i.e. $g_s = 37.7$ mm s$^{-1}$ and $g_s = 38.5$ mm s$^{-1}$ for the oak and mixed forest respectively. Although at the pine forest of the Loobos site the $L_{AI}$ is relatively low, this is compensated by the highest $g_{s,max}$ resulting in an almost identical $g_s = 32.7$ mm s$^{-1}$ as the oak and the mixed forest. The larch forest at the Bankenbos site with almost no undergrowth has the lowest $g_{s,max}$ and $L_{AI}$, resulting in the lowest $g_s = 13.1$ mm s$^{-1}$ of all 5 sites.

Fig. 7.3 shows the behaviour of the stress functions for the different sites, based on the parameter sets of all years of investigation as listed in Table 7.5.

As a reaction to the radiation load the poplar forest shows an almost on-off behaviour of the stomatal opening. The pine forest and to a lesser extent the oak forest demonstrate a much greater dependency on radiation.

The larch and oak forests show the highest optimal air temperature $T_a$, differing 3.4 °C with the lowest optimal $T_a$ of the mixed forest. With the daytime $T_a$ during the growing season being well above 10 °C, $T_a$ will mainly have a negative feedback.
The fractional surface conductance $g_s/g_{s,max}$ as a function of radiation $R_{down}$, air temperature $T$, vapour pressure deficit $e_D$ and soil water deficit $\theta_D$ for all sites optimised for all years as listed in Table 7.5.

The strength of this feedback at the higher $T_a$ range increases from larch, oak, pine, poplar to mixed forest.

As vapour pressure deficit $e_D$ is strongly related to $T_a$, the same order in the decrease in strength in the negative feedback signal of increasing $e_D$ to $g_s$ is observed for the different forest types. The mixed forest and the pine forest are especially for $e_D < 15$ hPa most sensitive to an increase in $e_D$. The least sensitive to an increase $e_D$ are the oak and larch forests.

For the pine forest $g_s$ is influenced over the whole range by $\theta_D$. The other forests start to be influenced at $\theta_D \gtrsim 0.3$ (m$^3$ m$^{-3}$). The oak and mixed forest follow the
Table 7.4: \(t\)-test values, testing the Null hypothesis that the independent variable does not contribute to predicting the surface conductance \(g_s\) for each site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Tree species</th>
<th>(g_{s,max})</th>
<th>(\alpha_R)</th>
<th>(\alpha_T)</th>
<th>(c_{\theta_D})</th>
<th>(\alpha_{\theta_D})</th>
<th>(c_{\theta_D})</th>
<th>(\alpha_{\theta_D})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankenbos</td>
<td>Larch</td>
<td>0.86</td>
<td>8.89</td>
<td>28.30</td>
<td>0.01</td>
<td>21.03</td>
<td>9.41</td>
<td>5.03</td>
</tr>
<tr>
<td>Edesebos</td>
<td>Oak</td>
<td>0.86</td>
<td>12.22</td>
<td>24.09</td>
<td>0.04</td>
<td>19.27</td>
<td>22.22</td>
<td>6.77</td>
</tr>
<tr>
<td>Fleditebos</td>
<td>Poplar</td>
<td>0.00</td>
<td>8.90</td>
<td>28.74</td>
<td>0.00</td>
<td>20.05</td>
<td>1.99</td>
<td>3.09</td>
</tr>
<tr>
<td>Kampina</td>
<td>Mixed forest</td>
<td>0.74</td>
<td>7.91</td>
<td>30.92</td>
<td>0.00</td>
<td>25.31</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Loobos</td>
<td>Pine</td>
<td>0.00</td>
<td>14.04</td>
<td>44.59</td>
<td>0.00</td>
<td>34.02</td>
<td>1.10</td>
<td>9.44</td>
</tr>
</tbody>
</table>

7.5. Stomatal conductance using the “big leaf” approach

7.5.1 Effect of parameter reduction on uncertainty

Reducing the number of parameters in a model will generally make the model more robust. To analyse the variance explained in \(g_s\) by each individual parameter of Eq. 2.46 a \(t\)-test was used. We tested the Null hypothesis that the coefficient of the independent variable is zero, i.e. the independent variable does not contribute to predicting the dependent variable \(g_s\).

The low \(t\)-values for \(g_{s,max}\) and \(c_{\theta_D}\) indicate that these variables did not contribute much in explaining the variance of \(g_s\) (see Table 7.4). Therefore, replacing both of these parameters by fixed values will most likely not reduce the explained variance significantly. In addition at the mixed forest of the Kampina site \(\theta\) did not explain any of the variance in \(g_s\). And at the poplar and the pine forest the parameter \(c_{\theta_D}\) did not contribute much to explain the variance of \(g_s\).

To check how important the different functions are to simulate \(g_s\), each function, one by one was set to 1. The complete data series of each site was used (see Table 7.5). The resulting \(R^2\) shows that except for the oak forest, \(f(T_D)\) contributed most to explain the variance of \(g_s\). Not including \(f(T_u)\) to simulate \(g_s\) even increased \(R^2\). This increase in explained variance is mainly because of the relatively high values for \(g_s\) at \(T_u\) below the optimum temperature \(\alpha_T\). Adding the lower temperature limit \(T_l\) as an independent variable improved \(R^2\) for 2 sites. However, the resulting value for \(T_l\) became unrealistically low, i.e. \(> -200^\circ C\) for the poplar forest of the Fleditebos site. Such values for \(T_l\) imply that in the data sets studied, there is no evidence for relationship \(g_s/g_{s,max} = f(\theta_D)\), which has also been found by different authors at other sites (e.g. Fig. 5 of Granier et al. (2000). The fact that at the poplar, pine and larch forests \(g_s\) does not drop to low values at high \(\theta_D\) may have 2 reasons. The first reason being the data set not covering the whole parameter space, i.e. not including dry periods. The second reason could be the fact that the used \(\theta_D\) was based on the soil layer where 80-90% of the roots were present. Soil layers deeper down could also have functioned as a source of soil water regulating \(g_s\).
Table 7.5: The correlation coefficient $R^2$ of the surface conductance $g_s$ for each site. $R^2$ is listed using the relationships for all dependent variables and $R^2$ is listed excluding each relationship one by one by setting $f(x) = 1$. Also listed is $R^2$ using all relationships but adding the minimum temperature $T_i$ as an independent variable.

<table>
<thead>
<tr>
<th>Site</th>
<th>Tree species</th>
<th>All</th>
<th>$f(R_{down}^2) = 1$</th>
<th>$f(T_a) = 1$</th>
<th>$f(\epsilon_D) = 1$</th>
<th>$f(\theta_D) = 1$</th>
<th>$T_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bankenbos</td>
<td>Larch</td>
<td>0.50</td>
<td>0.41</td>
<td><strong>0.59</strong></td>
<td>0.26</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>Edesebos</td>
<td>Oak</td>
<td>0.67</td>
<td>0.27</td>
<td><strong>0.69</strong></td>
<td>0.56</td>
<td>0.60</td>
<td>0.57</td>
</tr>
<tr>
<td>Fleditebos</td>
<td>Poplar</td>
<td>0.48</td>
<td>0.42</td>
<td><strong>0.52</strong></td>
<td>0.36</td>
<td>0.47</td>
<td>0.51</td>
</tr>
<tr>
<td>Kampina</td>
<td>Mixed forest</td>
<td>0.48</td>
<td>0.43</td>
<td><strong>0.53</strong></td>
<td>0.26</td>
<td>0.48</td>
<td>-</td>
</tr>
<tr>
<td>Loobos</td>
<td>Pine</td>
<td>0.62</td>
<td>0.47</td>
<td><strong>0.64</strong></td>
<td>0.44</td>
<td>0.60</td>
<td>0.63</td>
</tr>
</tbody>
</table>

A decrease of $g_s$ with lower $T_a$.

Comparison of the variance explained by the different variables showed that for all sites the temperature dependency did not improve the results significantly. For the larch forest at the Bankenbos site when removing the temperature dependency, $R^2$ of the optimization results improved by approximately 15%. Removal of the soil water stress function reduced the variance explained by approximately 4%. For the pine site, Loobos, there was no major change in the results by removing either the temperature or the soil water function for 1996. For 1997 $R^2$ improved to 0.66 and for 2003 $R^2$ improved to 0.54 after setting $g_s$ as $f(T_a) = 1$.

### 7.5.2 Stress from different soil water sources in the unsaturated zone

In Section 7.5 $f(\theta_D)$ was analysed based on $\theta_D$ of the soil profile with > 90% of the roots present (see Fig. 3.24 3.24). The fact that at most sites and years under dry conditions there was nearly no decrease in $g_s$, may have been caused by water being available at deeper soil layers. At other sites, for example the larch forest of the Bankenbos site, the limited parameter space could well be the reason for the limited range of the $\theta_D$ stress function, i.e. the length of the data set is limited and $\theta_D$ ranges from 0 to 0.7.

For the pine forest at the Loobos site and depending on which soil layer has been used to determine $\theta_D$ (Fig. 7.4), the parameter space is well covered with $\theta_D$ ranging from 0 to 0.8 or 1.0 $m^3 m^{-3}$.

Comparing $\theta_D$ of the different depths and layers as depicted in Fig. 7.4 shows the strong dampening influence of $\theta$ measured at the deeper layers, i.e. at 2.00 m depth. Choosing a deeper soil layer to model water stress also implies that the stress is expected to develop later in time. The peak after DOY 30 is caused by a short period with temperatures well below zero and has not been taken into account.
7.5. Stomatal conductance using the “big leaf” approach

Figure 7.4: Soil water deficit $\theta_D$ measured at specific depths of 0.10 m and 2.0 m for the pine trees at the Loobos site. Also shown are $\theta_D$ for the top soil layer 0 - 0.25 m of the soil and $\theta_D$ for the entire soil profile 0 - 2.87 m, i.e. down to the maximum rooting depth. Data are for the year 1996.

To analyse for the Loobos site with its deep sinker roots of the pine trees if other soil layers play an important role, the data set of 1996 has been optimized using $\theta_D$ based on different soil layers. All stress functions except the $\theta_D$ stress functions were fixed. To put more emphasis on the relatively dry conditions, only data between mid June and end of September were used.

Taking different soil layers in account to determine $\theta_D$, while keeping the other $g_s$ dependencies fixed, did not change $R^2$ much (Fig. 7.5A). Only for $\theta_D$ based on $\theta$ measured at 0.75 m and 2.00 m, $R^2$ reduced from 0.66 down to 0.59 and 0.60 respectively (Fig. 7.5B). The difference in the function for $\theta_D$ at 0.03 m and at 0.10 m depth with the same $R^2 = 0.66$, reflects the fact that the layer at 0.03 m depth does not release soil water as fast as the soil layers deeper down.

For the pine forest of the Loobos site all relationships $g_s/g_{s,max}$ as a function of $\theta_D$ as shown in Fig. 7.5 demonstrate that for the relatively dry year of 1996, the vegetation is not severely stressed. For $\theta_D$ measured in 1996 (see Fig. 7.4), $g_s/g_{s,max}$ is always larger than 0.4, which is the limit at which severe stress starts to occur. For the deep layer this may be caused by the limited range of $\theta_D$ values, i.e. 0 - 0.52 available for the parameter optimization. It could however, also have been caused by these deep roots having access to the groundwater reservoir.

The frequency distribution of $\theta_D$ of the root zone of 0 - 0.25 m (using the same records as have been used for the analysis of $g_s$ for the years 1995-2009) is depicted
Figure 7.5: The relative stomatal conductance $g_s/g_{s,\text{max}}$ of the pine forest at the Loobos site as a function of soil water deficit $\theta_D$ in different soil layers (left panel, A) and for soil water deficits at the different depths at which the sensors were installed (right panel, B).

Figure 7.6: The frequency $N$ (-) distribution of the $\theta_D$ (-) for the top 0.25 m soil depth of the pine forest at the Loobos site. The data depicted have been selected using the same selection criteria as were used for the $g_s$ optimization (see Section 7.5).

In Fig. 7.6. This figure shows the large number of moist data points $\theta_D < 0.45$ as well as the relatively uniform distribution of dry data points at $\theta_D > 0.45$. This uniform distribution indicates that if $\theta_D$ of the root zone of 0 - 0.25 m drives the stomatal closure, it should be reflected in the data of $g_s$. However, the data of $g_s$ do not demonstrate a strong decrease with an increasing $\theta_D$ (see Fig. 7.5), not even for
the relatively dry years 1995-1997. Hence, it strengthens the hypothesis that pine
trees are able to access other, i.e. deeper water resources.

The poplar forest at the Fleditebos site demonstrated similar results for $g_s$ based
on $\theta_D$ of different soil layers. For this site a small improvement in $R^2$ was obtained
using $\theta_D$ measured at 0.03 m and at 0.10 m, i.e. $R^2 = 0.50$ and $R^2 = 0.51$ instead
of $\theta_D$ measured over the top soil layer of 0.60 m.

7.5.3 The effect of groundwater uptake by roots

One of the most important determinants of the maximum rooting depth in The
Netherlands is the depth of the groundwater level $z_g$ (van den Burg, 1996). For sites
with a relatively high groundwater level droughts are a combination of low precip-
ation amounts and dropping groundwater levels. Hence drought is a combination
of both a low soil water content in the top layer of the soil, where most roots of the
trees and undergrowth are allocated and a low groundwater level that can no longer
be reached by the tap or sinker roots of the trees.

In order to calculate soil water deficit $\theta_D$ of the top 0.50 m of the soil, a simple
soil water balance study has been made. The water balance has been calibrated
for periods when soil water content was measured. Under the assumption that roots
may adjust to an average groundwater level, periods with lower levels were earmarked
as periods in which tree roots were not able to tap into the groundwater reservoir.
Drought affecting the whole eco-system was defined as at least 10 consecutive days
of $\theta_D \geq 0.95$ with $z_g$ being below average.

In Fig. 7.7 the 15 year average groundwater level $z_g$ was computed for the pine
stand of the Loobos site, i.e. 2.90 m below the soil surface. Fig. 7.7 shows periods
of drought occurring not only in the years with the least amount of rain, but also in
wet years, such as 1998. This behaviour reflects the slow reaction of the groundwater
reservoir to surface fluxes as well as regional influences on the groundwater system.

In times of water shortages, it is to be expected that the surface conductance $g_s$
decreases more rapidly at lower groundwater levels. To test this hypothesis, the data
of 1995 - 2005 of the pine forest at the Loobos site have been split in two parts. In
the first data set $g_s$ was selected on the basis of $z_g < 2.3$ m below the soil surface.
The second data set consisted only of records of $g_s$ with $z_g > 3.3$ m below the soil
surface. As can be seen in Fig. 7.8B there is no clear effect of $z_g$ on $g_s$. Contrary
to what had been expected, at $z_g > 3.3$ m below the soil surface more high values
of $g_s$ occur at high $\theta_D$, than for the cases with $z_g < 2.3$ m below the soil surface.
The outliers in Fig. 7.8B are mainly cases with exceptionally low $e_D < 2$ hPa during
both winter and summer months.
7. Dry canopy evaporation

Figure 7.7: The combination of a deep groundwater level $z_g$ (top panel) and a high soil water deficit $\theta_D$ (bottom panel) is an indicator for periods of potential water stress, as shown by the triangles for the pine stand at the Loobos site. The dashed line at 2.9 m in the top figure shows the 15 year average $\bar{z}_g$.

Figure 7.8: Surface conductance $g_s$ as related to soil water deficit $\theta_D$ for the pine forest at the Loobos site, 1995-2009. In the left panel, A only data records with the ground water level $z_g < 2.3$ m below the surface are shown. In the right panel, B only data records with $z_g > 3.3$ m below the surface have been selected. The solid lines depict the results of a second order regression.

7.5.4 Modelling soil water feedbacks from deeper soil layers

At the pine forest of the Loobos site, both options to include possible feedbacks from the soil water deeper down in the soil $f(\psi(z_2))_A$ and $f(\psi(z_2))_B$, did not improve the
7.5. Stomatal conductance using the “big leaf” approach

Figure 7.9: The relative reduction of soil water stress in the deeper soil layers for all test sites based on option A for \( f(\psi(z_2))_A \) (see Eq. 7.2) as a function of the volumetric soil water content \( \theta \).

explained variance of the fit of \( g_s \).

Fig. 7.9 depicts \( f(\psi(z_2))_A \) as a function of soil water based on Eq. 7.2 for the different sites. This figure shows that sites with soils having a higher content of sand, demonstrate almost no reduction on \( g_s/g_{s,max} \) for a relatively large range of soil water content. Only at low water content \( g_s/g_{s,max} \) is reduced sharply. For the pine trees at the Loobos site because of changes in hydraulic conductivity the effect of water stress is almost non existent for most soil water conditions. Only at extreme dry conditions \( f(\psi(z_2))_A \) acts almost as a on-off switch for the Loobos site. The clayey and loamy soils of respectively the Fledite and Bankenbos site, show a much more gradual decline of \( f(\psi(z_2))_A \) with decreasing \( \theta \).

Fig. 7.10 shows for the results of the fitted \( g_s/g_{s,max} \) for the relatively dry year 1996 at the pine forest of the Loobos site using 2 different models:

- The classical model \( f(\theta)_{\text{classic}} \) (see Eq. 2.51) using \( \theta_D \) of the layer were 80-90% of the roots are found, i.e. the upper 0 - 25 cm of the soil, and

- The model using Eq. 7.1 based on option B, i.e. the combination of \( f(\theta(z_2))_B \) with \( z_2 = 0 - 2.87 \) m using Eq. 7.3 and \( f(\theta(z_1))_B \) with \( z_1 = 0 - 0.25 \) m using Eq.
Figure 7.10: The relative $g_s/g_{s,max}$ as a function of $\theta_D$ representing the upper 0 - 25 cm of the soil. Two models are depicted: the classical model $f(\theta)_{\text{classic}}$ using $\theta_D$ of the soil layer where 80-90% of the roots are found, i.e. the upper 0 - 25 cm of the soil, and the model $f(\theta) = f(\theta(z_1)) f(\theta(z_2))_B$. The latter model also takes into account $\theta_D$ of the soil layer 0 - 2.87 m, i.e. until the maximum rooting depth. The fitted functions are based on the data of the year 1996 at the pine forest of the Loobos site.

The fitted functions are based on the data of 1996 measured at the pine forest at the Loobos site. The deviations from the spikes in the curve of $f(\theta(z_2))_B$ and the combined function $f(\theta(z_1)) f(\theta(z_2))_B$ are caused by the differences in changes of $\theta$ in the soil layer 0 - 0.25 m and in the soil layer 0 - 2.87 m (see also Fig. 7.4). The soil water content of soil layer 0 - 0.25 m was used to calculate $\theta_D$ for the x-axis of Fig. 7.10. The graph shows the slow reaction of $g_s$ to decreasing $\theta_D$ of the root zone and the relatively fast reaction to $\theta_D$ of the upper 0 - 25 cm of the soil. The graph also shows that the standard model $f(\theta)$ and the model using option B fit the 1996 data of the pine forest at the Loobos site equally well.

Fig. 7.11 shows how the fitted model B behaves under more extreme conditions of soil water stress in upper 25 cm of the soil $\theta_D(z_1)$ and in the total rootzone $\theta_D(z_2)$. The effects on $g_s$ of the changes in $\theta_D(z_1)$ are largest for $\theta_D(z_2) < 0.6$. It should be noted that changes in $\theta_D(z_2)$ will include changes in $\theta_D(z_1)$, as demonstrated by the measured $\theta_D$ in Fig. 7.11. Therefore, especially the combination of low $\theta_D(z_1)$ and high $\theta_D(z_2)$ as depicted in Fig. 7.11 are unrealistic.

At the poplar forest of the Fleditebos site the use of $f(\psi(z_2))_A$ improved the
7.5. Stomatal conductance using the “big leaf” approach

Figure 7.11: The contour lines are the relative conductance $g_s/g_{s,\text{max}}$ as a function of $\theta_D(z_1)$ and $\theta_D(z_2)$ based on model option B. $\theta_D(z_1)$ represents the soil layer where 80-90% of the roots are found, i.e. the upper 0 - 25 cm of the soil. $\theta_D(z_2)$ represents the soil layer 0 - 2.86 m, i.e. from the surface to the deepest roots. The graph is based on the fitted data of the year 1996 at the pine forest of the Loobos site. The circles are the measured $\theta_D(z_1)$ and $\theta_D(z_2)$ in 1996.

explained variance by 5% if compared to the standard model. Option $f(\psi(z_2))_B$ did not improve the explained variance.

7.5.5 Seasonality in surface conductance parameters

In most cases found in literature the parametrizations for the surface conductance $g_s$ have been derived for the summer months. These relations are assumed to be valid also for the remainder of the year. In the period outside the summer months, the development of the leaf area has been used as the main driver representing growth and phenological changes over the year. Especially for evergreen vegetation evaporation outside the summer months can be substantial. This may also be the case for forest with an active undergrowth at the start and at the end of the growing season. Therefore it is important to know if similar relationships for $g_s$ as found in summer time also hold for the other months of the year.

Table 7.6 shows the parameter sets of the pine forest at the Loobos site being valid for each season. The dependency on air temperature $T_a$ has not been taken into account as this dependency reduced the goodness of fit in all periods for this site.
Table 7.6: Optimization results of surface conductance $g_s$ for different seasons for all years measured at the pine forest of the Loobos site. Also shown are the results for all years (1995-2009) and all seasons both with and without temperature $T$ dependency. As a measure of fit, $R^2$ and the Standard Error of Estimate (SEE) are given.

<table>
<thead>
<tr>
<th>Season</th>
<th>$g_{s,max}$</th>
<th>$a_R$</th>
<th>$a_T$</th>
<th>$c_{e_D}$</th>
<th>$a_{e_D}$</th>
<th>$c_{e_D}$</th>
<th>$a_{e_D}$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>15.6</td>
<td>212.7</td>
<td>-</td>
<td>1.279</td>
<td>0.180</td>
<td>0.42</td>
<td>0.11</td>
<td>0.63</td>
<td>1.4</td>
</tr>
<tr>
<td>Spring</td>
<td>11.3</td>
<td>323.9</td>
<td>-</td>
<td>0.700</td>
<td>0.101</td>
<td>0.12</td>
<td>0.41</td>
<td>0.63</td>
<td>1.0</td>
</tr>
<tr>
<td>Summer</td>
<td>11.9</td>
<td>403.2</td>
<td>-</td>
<td>0.156</td>
<td>0.095</td>
<td>0.01</td>
<td>0.42</td>
<td>0.66</td>
<td>0.9</td>
</tr>
<tr>
<td>Autumn</td>
<td>11.4</td>
<td>155.2</td>
<td>-</td>
<td>0.217</td>
<td>0.119</td>
<td>0.01</td>
<td>0.85</td>
<td>0.22</td>
<td>1.4</td>
</tr>
<tr>
<td>All seasons f($T$)</td>
<td>9.9</td>
<td>289.3</td>
<td>17.8</td>
<td>0.390</td>
<td>0.090</td>
<td>0.38</td>
<td>0.44</td>
<td>0.62</td>
<td>1.0</td>
</tr>
<tr>
<td>All seasons</td>
<td>12.0</td>
<td>280.4</td>
<td>-</td>
<td>0.097</td>
<td>0.099</td>
<td>0.38</td>
<td>0.49</td>
<td>0.64</td>
<td>1.0</td>
</tr>
</tbody>
</table>

In winter, soil water deficit $\theta_D$ plays no role and solar radiation $R_S$ is the main driver. In spring the main drivers were $e_D$, and to a lesser extend $\theta_D$. In summer $e_D$ had the strongest reducing effect on $g_s$, while $R_S$ plays almost no role. In autumn $g_s$ is dominated by $R_S$ and $\theta_D$. The results for the winter period indicate that the vegetation is active. The measured CO₂ uptake during parts of the day in winter at this site indeed confirms that photosynthesis is taking place and hence the stomata are open to take up CO₂ and release water vapour during winter. Comparing the parameter values for the different seasons with those of all seasons, shows that the main differences were found for winter and autumn. Especially $a_R$ is relatively low compared to the parameter values of all seasons. For both winter and autumn, the standard error is relatively high. For autumn also $R^2$ is low.

The higher value of $g_{s,max}$ in winter may be caused by the fact that even with the selection criteria of a preceding dry period of at least 48 hours does not warrant the undergrowth or trees to be completely dry.

### 7.6 Separating evaporation of trees and undergrowth

To study the different stomatal response functions of the undergrowth and the tree canopy, the dual source model has been used as described by Eqs. 2.52 to 2.61. The available energy of the upper $A_{Up}$ respectively lower layer $A_{Low}$ is given by:

$$
A_{Up} = A_{Tot} - A_{Low}
$$

$$
A_{Tot} = \lambda E_{Up} + H_{Up}
$$

$$
A_{Low} = \lambda E_{Low} + H_{Low}
$$

(7.7)
7.6. Separating evaporation of trees and undergrowth

Figure 7.12: Panel A: Net radiation $R_{net}$. Panel B: latent heat flux $\lambda E$ and sensible heat flux $H$ measured below the canopy as a fraction of the total flux measured above the poplar trees in 1997 at the Fleditebos site.

The latent heat flux of the tree canopy $\lambda E_{Up}$ is derived from $\lambda E_{Tot}$ i.e. the measured latent heat flux by the eddy-correlation system above the canopy, and $\lambda E_{Low}$, i.e. measured by the eddy-correlation system below the canopy. Hence:

$$\lambda E_{Up} = \lambda E_{Tot} - \lambda E_{Low}$$  \hspace{1cm} (7.8)

For the pine forest at the Loobos site and the poplar forest at the Fleditebos site the undergrowth is a well defined vegetation layer, being separate from the above tree canopy. To investigate if the undergrowth should be treated as a separate layer an additional flux station has been exploited in between the undergrowth and the tree canopy (See Section 4.3.1).
Fig. 7.12 shows the influence of emerging leaves of the poplar trees of the Fledite site from April to June. The appearance of the leaves also caused the Bowen ratio to change both above and below the canopy. In April almost all $\lambda E$ measured above the canopy originated from undergrowth and soil. In June $\lambda E$ originating from undergrowth and soil reduced to 0.25 to 0.30 of total $\lambda E$.

The ratio of the daily average daytime (between 10h00 and 16h00) $\lambda E$ for dry conditions (defined as records preceded by at least 24 dry hours) at the poplar site for the undergrowth as a fraction of total $\lambda E$ changed from 1.0 in March down to 0.35 at the end of June. The latter coinciding with the start of the decline in $L_{AI}$ of the undergrowth and reaching the maximum $L_{AI}$ by the poplars.

At the pine site the average undergrowth $\lambda E$ as a fraction of total $\lambda E$ during the months July and August amounted to 0.10. At the end of August this increased to 0.20 which was maintained in the month September and the first part of October, later decreasing to 0.15.

### 7.6.1 The eddy-decay coefficient for undergrowth

The transport of scalars and momentum in the dual source model is determined by the eddy-decay coefficient $\eta$ (see Eq. 2.54).

At the poplar forest of the Fleditebos site no dependency on wind direction was found. Because of the large differences in plant height and leaf area of the undergrowth during the season, the surface roughness changed in time. Hence $z_{0M}$ and $u*/u$ (for near neutral conditions) were made dependent on plant height.

The presence of dunes underneath the pine trees at the Loobos site influences the measurements below the canopy. To minimise disturbance of dunes on the turbulent measurements, data were used only with the wind coming from directions between 130 and 230 degrees N. For the pine forest the data of the undergrowth were according to the wind direction classified into 2 groups. A distinction has been made between the wind directions 120 to 240 and 270 to 355 degrees N for one group and the remainder of the wind directions for the second group. Table 7.7 shows the roughness characteristics for the two wind directions at the Loobos site.

Table 7.7 shows the roughness characteristics at the start and at the middle of the growing season.

Based on wind speed measurements above and below the canopy, for the pine site on average $\eta = 2.3$ and for the poplar site $\eta = 2.1$.

### 7.6.2 Radiative forcing

An important driver for the opening and closure of the stomata and therefore of the evaporation rate is the radiation load. For the lower layer direct measurements
7.7. Surface conductance using the dual source approach

Table 7.7: Roughness characteristics \(d, z_{OM}, u_*/u\) (for near neutral conditions) and eddy-decay coefficient \(\eta\) for the undergrowth of the pine forest at the Loobos and the poplar forest at the Fleditebos sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Selection</th>
<th>(d)</th>
<th>(z_{OM})</th>
<th>(u_*/u)</th>
<th>(\eta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loobos (Pine)</td>
<td>120 &lt; (u_{dir}) &lt; 240</td>
<td>0.0</td>
<td>0.4</td>
<td>0.22</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>270 &lt; (u_{dir}) &lt; 355</td>
<td>0.0</td>
<td>1.4</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Fleditebos (Poplar)</td>
<td>Spring</td>
<td>0.1</td>
<td>0.35</td>
<td>0.18</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>0.1</td>
<td>0.95</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

of the incoming radiation are complicated because of the irregular structure of the tree canopy above in combination with the limited area that can be viewed by a radiation sensor. To overcome this problem, \(R_{down}\) for the lower vegetation layer was estimated using the radiative transfer scheme for sparse canopies as developed by Hanan (2001).

Fig. 7.13 shows for a clear day at the pine forest of the Loobos site the daily variation of the ratio between \(R_{down}\) for the lower vegetation layer and the total \(R_{down}\). For a cloudy day with primarily diffuse radiation the ratio becomes as a straight line, similar to applying a Beer-Lambert type equation with a fixed extinction factor (e.g. Whitehead and Kelliher, 1991). The average extinction factor for the pine trees at the Loobos site is 0.53, which corresponds well with the average extinction factor of 0.52 for 7 coniferous stands as reported by Pierce and Running (1988).

For the poplar trees at the Fleditebos site a large change in the ratio between \(R_{down}\) for the lower vegetation layer and the total \(R_{down}\), associated with the leaf development and senescence, was obtained. On top of this seasonal pattern, daily patterns similar to those of the pine forest were simulated.

7.7 Surface conductance using the dual source approach

The additional separate flux measurements taken below the tree canopy at the Fleditebos and Loobos site in combination with the dual source model, allowed to distinguish between the surface conductance \(g_s\) of the upper layer, i.e. the trees, and the undergrowth beneath the trees. In Table 7.8 the optimization results are shown of the stomatal conductance functions (see Section 2.5.3) for the separate vegetation layers.

As driving variables for \(g_s\) of the undergrowth, in Table 7.8 the separate measurements taken below the canopy of air temperature \(T_a\) and relative humidity \(\kappa\), and
The simulated diurnal variation of the incoming short wave radiation $R_{\text{down}}$ above the lower vegetation layer as the ratio of that above the higher vegetation layer for a clear day at the pine forest of the Loobos site.

Table 7.8: Optimized maximum surface conductance $g_{s, \text{max}}$ and stomatal conductance functions for the trees and/or undergrowth at the Fleitebos and Loobos sites. Two flux stations were used simultaneously above and below the canopy. The constants $a_R$, $a_T$, $c_D$, $c_{e_D}$, and $a_{e_D}$ refer to the equations of Section 2.5.3. As a measure of fit, $R^2$ and the Standard Error of Estimate (SEE) are given.

<table>
<thead>
<tr>
<th>Site</th>
<th>Vegetation Layer</th>
<th>$g_{s, \text{max}}$</th>
<th>$a_R$</th>
<th>$a_T$</th>
<th>$c_D$</th>
<th>$c_{e_D}$</th>
<th>$a_{e_D}$</th>
<th>$R^2$</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fle-</td>
<td>Tree (Poplar)</td>
<td>7.2</td>
<td>0.1</td>
<td>22.0</td>
<td>0.001</td>
<td>0.055</td>
<td>0.38</td>
<td>1.47</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Under</td>
<td>11.0</td>
<td>540.0</td>
<td>19.0</td>
<td>0.767</td>
<td>0.114</td>
<td>0.49</td>
<td>1.00</td>
<td>0.33</td>
</tr>
<tr>
<td>Fle-</td>
<td>Tree &amp; under</td>
<td>5.5</td>
<td>51.0</td>
<td>22.0</td>
<td>0.001</td>
<td>0.065</td>
<td>0.49</td>
<td>1.68</td>
<td>0.22</td>
</tr>
<tr>
<td>Loo-</td>
<td>Tree (Pine)</td>
<td>12.9</td>
<td>254.8</td>
<td>19.7</td>
<td>1.756</td>
<td>0.055</td>
<td>0.54</td>
<td>1.00</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Under</td>
<td>5.9</td>
<td>376.4</td>
<td>12.1</td>
<td>0.001</td>
<td>0.047</td>
<td>0.01</td>
<td>1.10</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Tree &amp; under</td>
<td>7.8</td>
<td>354.7</td>
<td>14.9</td>
<td>0.001</td>
<td>0.050</td>
<td>0.11</td>
<td>0.01</td>
<td>0.64</td>
</tr>
</tbody>
</table>

The results for the poplar trees of the dual source approach are significantly different from the results obtained by the big leaf approach, marked as “Tree” in Table 7.2. The main reasons for the differences obtained by the two approaches are:
the different periods used, i.e. spring versus summer, possibly reflecting different
phenological stages, and the contamination of the signal by the undergrowth that
is still present in the data set used for Table 7.2. Based on the relatively small
leaf area of the undergrowth, it was assumed for the big leaf approach, that during
the summer months the tree evaporation was so dominant that the undergrowth
evaporation could be neglected. Although the measurements show the relatively
small contribution of the undergrowth to the total evaporation of the forest (see e.g.
Fig. 7.12), the undergrowth signal is still strong enough to influence the optimization
results of the big leaf model.

The undergrowth parameter set of the poplar forest also differs from that of Table
7.2. Especially $a_R$ and $a_T$ differ significantly. These differences may be caused by
the relatively low temperatures and radiation for the data set used for Table 7.2.

The combined trees and undergrowth parameter set of the pine forest at the
Loobos site compares relatively well with the parameter set for 1997 in Table 7.5. To
a lesser extent these parameter sets of the combined vegetation layers also compare
well for the poplar forest at the Fleditebos site.

Except for the combined trees and undergrowth of the Loobos site optimization,
the fitting results were less good, i.e. $R^2$ between 0.1 and 0.46, than when using
longer datasets, i.e. $R^2$ between 0.58 and 0.62 (see Table 7.5). This lesser fit implies
that there is a larger uncertainty associated with the results of the dual source model
if compared with the big leaf model. Partly this lesser fit is caused by the limited
length of the datasets available at both sites: after mid of April to the end of June
at the Fleditebos site and end of June to end of October at the Loobos site.

At the Fleditebos site, the data used reflect the first two months of the growing
season of the poplar trees. During this period $LAI$ changes rapidly and as a result
also total $g_s$. Fig. 7.14 shows that $g_s$ of the poplar undergrowth starts to decrease
faster than the trees with high $T_a$, $e_D$ and low $R_{down}$. Although the range of $\theta$ is
limited and therefore care should be taken when using the data, the results suggest
that the trees will reduce $g_s$ earlier than the undergrowth of the poplar forest.

At the pine forest of the Loobos site the differences between the trees and the
undergrowth is much less pronounced than for the poplar forest. The trees and the
undergrowth react almost identically to changes in $e_D$ and $R_{down}$ (see Fig. 7.15).
Even more pronounced than the undergrowth of the poplar forest, the undergrowth of
the pine forest reaches its optimum $g_s$ at lower $T_a$ than the trees. Also identical to the
poplar forest the pine trees experienced more water stress than the undergrowth. In
this data set of the Loobos site no water stress was detected at all for the undergrowth.

Fig. 7.16 shows the total maximum $g_s$ for the different vegetation layers at both
sites. The timing of the undergrowth contribution to total $g_s$ differs between the sites.
Where the undergrowth of the poplar forest at the Fleditebos site mainly influences
7. Dry canopy evaporation

Figure 7.14: The fractional surface conductances $g_s/g_{s,max}$ as a function of radiation $R_{down}$, air temperature $T_a$, vapour pressure deficit $e_D$ and soil water deficit $\theta_D$ for the tree layer, the undergrowth layer and for the total vegetation at the poplar forest of the Fleditebos site in 1997.

the total $g_s$ during the first 3 months of the growing season, the undergrowth of the pine forest at the Loobos site especially influences total $g_s$ during the summer months.

7.7.1 Evaluation of the dual source model

To validate the model performance the results were compared with the sapflow measurements of the pine stand at the Loobos site for the years 1997 and 1998. Because the sapflow data are lagging behind in time as compared to the actual evaporation rate, daily sums were used for the evaluation. Table 7.9 shows the evaluation results using the dual source model in combination with the calibrated parameters for the
7.7. Surface conductance using the dual source approach

Figure 7.15: The fractional surface conductances $g_s/g_{s,max}$ as a function of radiation $R_{down}^s$, air temperature $T_a$, vapour pressure deficit $e_D$ and soil water deficit $\theta_D$ for the tree layer, the undergrowth layer and for the total vegetation at the pine forest of the Loobos site in 1997.

Pine forest at the Loobos site been taken from Table 7.8. For both years the sapflow derived evaporation rate of the pine trees $E^{Sap}$ compares equally well with the modelled evaporation rate for the upper vegetation layer $E_{Up}$ using the dual source model. These data include dry as well as wet data.

In addition the modelled total evaporation rate $E_{Tot}$ is compared to the measured evaporation rate using an eddy-correlation system above the canopy $E^{EC}$. As may be expected the period $170 < DOY < 300$ in 1997 for which the model was calibrated gives the best fit. The same period in 1998 also gives a reasonable fit. Both full years 1997 and 1998 show an overestimation of 25 to 30% of $E_{Tot}$ as compared to $E^{EC}$. In this comparison only days with $E_I < 0.1$ mm d$^{-1}$ were used.
7. Dry canopy evaporation

Figure 7.16: The total maximum surface conductance $g_s$, i.e. correcting $g_{s,max}$ for $LAI$ with all reduction functions set to 1, for the trees, the undergrowth and the combination of trees and undergrowth. The results are based on the period of 20 April to 17 June 1997 at the poplar forest of the Fleditebos site (panel A), and the period 20 June to 1 November 1997 at the pine forest of the Loobos site (panel B).

Table 7.9: Evaluation of the dual source model evaporation results for the pine forest at the Loobos site for the years 1997 and 1998. The tree evaporation $E_{Up}$ is validated using sapflow measurements $E^{Sap}$ and total evaporation $E_{Tot}$ using eddy-correlation measurements taken above the canopy $E^{EC}$. For $E_{Tot}$ the total year as well as the period for which the calibration was done are provided. In both cases only days with modelled interception evaporation $<0.1 \text{ mm d}^{-1}$ were used. As a measure of fit $R^2$ and $p$ are given. *) This dataset is used to calibrate the model.

<table>
<thead>
<tr>
<th>Year</th>
<th>Evaluation Period</th>
<th>Regression results $E^{Sap}$</th>
<th>$E^{EC}$</th>
<th>$R^2$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>Sapflow $120 &lt; \text{DOY} &lt; 252$</td>
<td>$E^{Sap} = -0.13 + 1.03E_{Up}$</td>
<td>$0.75$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eddy corr. $170 &lt; \text{DOY} &lt; 300$</td>
<td>$E^{EC} = -0.07 + 0.95E_{Tot}$</td>
<td>$0.86$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eddy corr. $1 &lt; \text{DOY} &lt; 365$</td>
<td>$E^{EC} = 0.31 + 0.69E_{Tot}$</td>
<td>$0.79$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Sapflow $140 &lt; \text{DOY} &lt; 228$</td>
<td>$E^{Sap} = 0.28 + 0.96E_{Up}$</td>
<td>$0.73$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eddy corr. $170 &lt; \text{DOY} &lt; 300$</td>
<td>$E^{EC} = 0.63 + 0.84E_{Tot}$</td>
<td>$0.79$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eddy corr. $1 &lt; \text{DOY} &lt; 365$</td>
<td>$E^{EC} = 0.40 + 0.76E_{Tot}$</td>
<td>$0.76$</td>
<td>$&lt;0.0001$</td>
<td></td>
</tr>
</tbody>
</table>

The satisfactory modelling results in comparison to the sapflow data together with the overestimation of $E^{EC}$ suggests that the model overestimates the evaporation rate of the undergrowth. During the months May to September the ratio of $E_{Low}$ to $E_{Up}$ ranges on average between 15 to 22% (see Fig. 7.17 B). This ratio increases
7.8. General discussion

Soil water stress is an important, but a difficult to parametrize aspect regulating stomatal opening and closure. Especially in mid latitude regions with relatively high
during the other months of the year to between 20 and 35%. The high contribution
of the undergrowth $E_{\text{Tot}}$ during the months October to March, suggests that the
overestimation for the total year is mainly because of the overestimation during
these months by the simulated $E_{\text{Low}}$. At the poplar forest of the Fleditebos site the
relative contribution of the undergrowth compares well with the ratio based on the
measurements of 1997 (see Fig. 7.12 B).

Figure 7.17: The ratio of the simulated daily evaporation rate of the undergrowth $E_{\text{Low}}$
to the total evaporation rate $E_{\text{Tot}}$ for the poplar forest at the Fleditebos side (A) and the
pine forest at the Loobos site (B) in 1998. These data represent the dry evaporation rate,
i.e. transpiration, and do not include evaporation of intercepted rain.
groundwater tables and rain showers well distributed in time these conditions may be hard to detect. Still, with the expected increase of relatively dry periods in these regions, knowledge of the effect of water stress on evaporation rate is important.

**Main drivers of surface conductance \( g_s \) at the different forest stands**

*Poplar* forest is most sensitive to radiation and least sensitive to soil water. *Oak* forest is least sensitive to radiation and most sensitive to soil water. *Mixed* forest is most sensitive to vapour pressure deficit and has the lowest optimum air temperature of all 5 forest stands. Soil water does not seem to have a great effect on the surface conductance of the poplar pine and larch forest. Granier et al. (2000) showed that for forest the critical value for soil water deficit \( \theta_D \) equals 0.6. Above this value the transpiration rate reduces rapidly. The most important unknown in the amount of available water is the rooting depth that determines the total available soil water.

**Soil water availability determined by rooting depth**

In most models water stress is parametrized as a mean value over the depth where 80 - 90% of the roots are present. For agricultural crops that are harvested every year the rooting depth is well known, however for perennial grasslands and trees with permanent rooting systems the root distribution is less uniform (see e.g. Canadell et al., 1996) and the rooting depth may vary between years. Root growth and mortality will depend among others on available soil water. For coniferous trees in the Netherlands Olsthoorn (1998) found a critical soil water pressure of \( \psi = -10^{2.1} \) Pa above which primary roots started to die. This growth and mortality of roots implies that in a relatively dry year the depth to which the roots are active, is not a fixed depth, but is the result of a complex process of growth and decline depending among others on soil water availability. This change in depth of active roots, is however not reflected in the soil water deficit \( \theta_D \) stress functions for the sites of this study. Optimizing \( g_s \) for different soil depths showed for the sites with relatively deep roots, i.e. Loobos and Edesebos, the best fit was obtained, by using soil water of the root zone where most roots are found, and not necessarily by using \( \theta \) of the total root zone.

Redistribution of groundwater to the upper soil layers by hydraulic lift is a possible explanation although not observed in our soil water measurements. However, the latter could have been caused by the relatively low detection rate of the sensors used.

**Rooting depth of trees**

Canadell et al. (1996) reported average maximum rooting depths of 2.6 ± 0.2 m for temperate grassland, 3.9 ±0.4 m for temperate coniferous forest and 2.9 ± 0.2 m for temperate deciduous forest. Maximum and minimum values for these biomes differ by at least a couple of meters. Coniferous forests were among the eco-systems with the deepest root profiles. For the temperate coniferous forest of
their study the percentage of roots observed at 20 cm varied between approximately 25% and 80%. In a review of rooting patterns of forest trees in the Netherlands, van den Burg (1996) reported that besides ploughing depth, only the groundwater table depth explained a part of the variance in the rooting depth for fir, poplar and oak trees. The stand average maximum rooting depth reported by van den Burg (1996) were for larch 1.00 m, poplar 1.62 m, oak 1.4 m (for the tree species found at the Edesebos site, Quercus rubra the depth was 0.95 m) and for Scots pine 4.25 m. These values are somewhat low when compared with the study of Canadell et al. (1996), but correspond well with the data of our study. These rather shallow root systems may be caused by the relatively shallow groundwater table in the Netherlands in comparison to other countries. The relatively large rooting depths for Scots pine were attributed to the existence of a tap root in soil types such as are found at the Loobos site, i.e. an inland dune system with poor sandy soils. Taking into account the capillary rise of water in the combination with the existence of tap roots means that these eco-systems are often well in reach of groundwater resources. At the same time the average groundwater table depth will limit the maximum rooting depth, but as long as the groundwater table does not fall below levels that can be compensated by capillary rise, these trees will not experience serious stress because of water shortage. These conditions seem to have prevented severe water stress during the period the 5 sites were studied. The importance of the groundwater reservoir has also been demonstrated by among others Nadezhdina et al. (2007) and Vincke and Thiry (2008). The latter reported for Scots pine with a maximum groundwater table at 180-200 cm below soil surface, a contribution of 61% of the groundwater reservoir during the growing season, with a maximum of 98.5% during the drought period in June.

Rooting depth of undergrowth

The maximum rooting depths as reported by Canadell et al. (1996) suggest that the undergrowth of forest has rooting depths similar to those of trees. Neither in the pine forest, nor in the poplar forest, which had the most prominent undergrowth, such deep roots for the undergrowth were observed. Also at both sites the undergrowth partly died in the middle of the growing season and demonstrated a regrowth at the start of autumn. For the poplar forest dying and regrowth will also be caused by the competition for light. At the site with pine trees with only a minimal variability in the tree leaf area over the year, water shortage is more likely to cause the dieback of the undergrowth in the middle of the growing season. Bakker et al. (2006) observed the highest rooting densities for maritime pine in the first 20 cm of the soil profile. This was also true for the undergrowth species at their sites, except for Molinia that had a significant amount of roots at 40 cm depth. These findings are in line with the observations at the pine site Loobos. At this site 90% of the roots were found in the
top 30 cm of the soil, with most roots found in the lower part of the litter layer and the first 20 cm of the mineral soil (see Fig. 3.24). Still little is known about what environmental factors govern the variation in root growth and how this may affect the functioning of plants (Brunner and Godbold, 2007), making it difficult to include dynamic roots in land surface models.

It is possible to use total available soil water as an optimization parameter, which implies that an optimal combination is sought for the root distribution and the soil hydraulic characteristics. The thus derived parameter set will however only be applicable for the site under study and will be difficult to apply to other sites. Even for the site studied such a technique does not guarantee a root distribution that resembles reality, see e.g. van Wijk and Bouten (2001).

Modelling root water stress under extreme conditions

Under extreme conditions the water uptake by deep roots is of paramount importance. It was shown that under moderate conditions the use of the soil water content of the total rooting depth gives less optimal results, if compared to the soil water content of the top soil layer. To accommodate the fact that for extremely dry conditions also the water content at the deeper soil layers should be taken into account as is done in the proposed model (see Fig. 7.1). Although the proposed model compared well to the data measured for this study (see Fig. 7.10), severe drought conditions were not observed and an additional test under more extreme conditions is recommended. The proposed model for the simulation of the feedbacks of water stress on the stomatal conductance \( g_s \) works well in combination with a model that distributes the root water uptake over the different soil layers based on the optimality-approach (see e.g. Schymanski et al., 2008). This approach assumes that plants have evolved mechanisms that minimise costs related to the maintenance of root system while meeting their demand for water.

Contribution of undergrowth to total evaporation rate

The undergrowth at the two sites with additional measurements showed a clear decrease in evaporation in the summer. This decrease relative to that of the trees could be caused by the low sensitivity to radiation, low optimum temperature and low sensitivity to soil water deficit \( \theta_D \) of the undergrowth at the pine and poplar site. In addition at the poplar site also the high sensitivity of the undergrowth to vapour pressure deficit \( e_D \) plays an important role.

These findings are in contrast to the findings by Körner (1985), who marked pine trees as sensitive to high \( e_D \) values, and grass species as much less sensitive. The average transpiration rate of the grass undergrowth was 30% of that of the pine trees under non water-limiting conditions. During a drought period the transpiration rate of the undergrowth became twice that of the pine trees. Similar high evaporation
ratios between trees and undergrowth were reported by Roberts et al. (1980) and Black et al. (1980). Other researchers such as Lindroth (1984) and Kelliher et al. (1986) reported much lower ratios, which are more in line with our results for the undergrowth of the poplar forest at the Fleditebos site and of the pine forest at the Loobos site.

The effect of trees shadowing the undergrowth depends on the canopy cover and the inclination of the sun. Running the radiative transfer model with a tree crown diameter of 4.0 m for different tree densities showed that although the canopy cover reached its maximum value at 300 trees ha\(^{-1}\), the fraction of short wave radiation reaching the undergrowth already reached its minimum at 210 trees ha\(^{-1}\) at low solar elevation angles (winter) and at 390 tree ha\(^{-1}\) at higher solar elevation (summer). In winter time this fraction is especially high at the beginning and the end of the day, while in summer the maximum values are reached at mid day.

Modelling undergrowth and tree evaporation

The dual source model allowed to simulate the tree and undergrowth contribution to the total evaporation rate separately. The relatively high modelled contribution by the undergrowth at the Loobos site in autumn and winter, i.e. 20 to 40\% of total evaporation \(E_{Tot}\), is in contrast to the observed values in October 1997 which were approximately 15\%. This overestimation could mainly be attributed to the high simulated undergrowth evaporation.

Although the location of the lower eddy correlation system was selected carefully and as much as possible in the footprint of the higher eddy correlation system, differences may be expected due to the much smaller (factor of 100) footprint of the lower system as compared to the system above the canopy. Wilson et al. (2001) estimated that due to high frequency loss of flux, the flux of the undergrowth may be low by 5-10\%. The main cause of uncertainty in the sapflow evaporation data is in the up-scaling to stand level evaporation. The up-scaling is based on the relationship between sapflow, sap wood, trunk diameter and tree density of the stand. At the Loobos site the tree density is variable and changes slightly within the footprint area of eddy correlation set-up on top of the tower. This variability has been taken into account as added uncertainty in the sapflow evaporation data and amounted to 14\% of the total stand level sapflow evaporation. The uncertainty in the evaporation rate measured by the eddy correlation equipment was estimated to be between 5 - 15\% (see Chapter 5). Taking these uncertainties into account the modelled evaporation of the trees compared well with the sapflow derived evaporation of the pine trees at the Loobos site.

The findings of our study are in line with the undergrowth strategy towards limited water resources as reported by Baldocchi and Xu (2007). At the Loobos and Fleditebos site undergrowth avoids summer drought and is active only during spring
and autumn, when soil water is ample and for the poplar site the tree leaf area is limited.

7.9 Conclusions

The main driver for surface conductance $g_s$ at all sites was vapour pressure deficit $e_D$. Although a parabolic response function was used for the temperature relationship of $g_s$, this relationship was not well established at the lower air temperature $T_a$ range. At lower temperatures i.e. below $a_T$ there was no clear reduction of $g_s$ found for these sites at a mid latitude location. This behaviour may be caused by the fact that at lower $T_a$ at these sites the dew on the undergrowth never completely disappeared.

This unclear relationship of $g_s$ at lower $T_a$ and the strong correlation between $T_a$ and $e_D$ for higher $T_a$ makes the temperature relationship of $g_s$ redundant.

Hence, in view of the limited variation between the sites, the parameter values for $g_s$ as $f(T_a)$ may be set to a fixed value. Based on the improved $R^2$ for almost all years at the different sites after setting $f(T_a) = 1$, it is recommended to use $f(T_a) = 1$ for all forests sites in the Netherlands.

The low sensitivity of the forests to $\theta_D$ shows that these forests are not very sensitive to the range of changes in soil water experienced during this study. Whether these forests are sensitive to more severe droughts cannot be concluded from the present data sets. The proposed soil water stress model including a separate soil water feedback from deep soil layers, worked well for the conditions of this study, but needs to be tested for more extreme dry conditions.

The important contribution of the undergrowth to total evaporation rate $E_{Tot}$ has been demonstrated for 2 forest sites in The Netherlands, i.e. the pine forest with its undergrowth mainly consisting of grass at the Loobos site and the poplar forest with its undergrowth mixture of grass, nettle and cleavers at the Fleditebos site.

The results of the tree evaporation applying the dual source model compared well (see Table 7.9) with the sapflow measurements at the Loobos site. The overestimation of the simulated undergrowth evaporation $E_{Low}$ was most likely because of the limited data set being used for the derivation of the parameter set of Table 7.8. Such datasets are still limited. More extensive datasets will help to decrease the uncertainty in the modelled undergrowth evaporation rate. The considerable contributions of the undergrowth at the pine and the poplar forest during a large part of the year showed the importance of this component of the total forest water use.

Considering $\lambda E$ of the trees and the undergrowth separately will enable an improved understanding of the functioning of the forest ecosystem. It will also improve
our interpretation of changing conditions affecting trees and undergrowth differently and to determine the combined effect such a change may have on $E_{Tot}$ of the forest. To support such a set-up, the rather limited number of plant functional types (pfts) as are being used at the moment to describe forests need to be replaced by pfts describing tree species in combination with undergrowth species. These pfts should not only allow to take $L_{AI}$ of the undergrowth into account, but also the different phenological phases of the trees and of the undergrowth. The latter will help to improve the simulation of the seasonal differences in the behaviour of $g_s$, which will provide better estimates of $E_{Tot}$ also outside the growing season.