Modelling and monitoring forest evapotranspiration. Behaviour, concepts and parameters
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2. MODELLING FOREST TRANSPERSION FROM DIFFERENT PERSPECTIVES*

ABSTRACT

Forest transpiration models have been developed in different disciplines such as plant physiology, ecology, meteorology, hydrology and soil science. In the present study, three different kinds of model perspectives for transpiration control are used: leaf cooling, CO$_2$ assimilation and the combined energy and water balance. All three process-oriented models are calibrated on measurements in a Douglas fir stand in the Netherlands. The performances of these models are equally good, although they have different complexities, different numbers of calibration parameters (ranging from 1 to 6) and the models are calibrated on different measurements (eddy correlation at canopy level or CO$_2$ measurements at leaf level). The resemblance of the model results is caused by the calibration procedure and by the high impact of radiation in all three cases. Significant discrepancies become apparent when differences between model responses are examined and when specific (short) periods are selected when input variables are uncoupled. The main differences between the models are caused by another formulation of leaf area index and vapour pressure deficit ($D$). Considerable differences in simulated transpiration occur in the afternoon due to the diurnal hysteresis between $D$ and radiation.

2.1 INTRODUCTION

For many decades models describing forest transpiration have been developed in many scientific disciplines such as plant physiology, ecology, meteorology, hydrology and soil science. Each of these disciplines applies its own methodology and studies transpiration at its own specific level of interest, resulting in a large diversity of forest transpiration models. Other reasons for this large diversity are the different aims of the models, different spatial and temporal scales, and the availability of data to parameterise the models.

From all different kind of process oriented forest transpiration models, we found four different perspectives: the cooling of leaves, the assimilation of CO$_2$, the energy balance (combined with bulk stomatal conductance) and the water balance.

Prazak et al. (1994) have presented a model based on cooling of leaves by air and evaporation, while the leaves are warmed by radiation. The advantage of this model is that it is based only on global radiation and temperature, which are easy to measure.

The second cluster of transpiration models covers models based on CO₂ assimilation. If stomata are open, gas exchange of CO₂ and H₂O takes place. Most models are based on Farquhar's model (Farquhar et al., 1980) combined with an empirical relationship to calculate stomatal conductance (Ball et al., 1987; Leuning, 1995). At the leaf scale, model parameters are species dependent. Because leaf assimilation is a non-linear function of radiation, it is necessary to simulate the radiation regime in the canopy (Castro and Fetcher, 1998; Cescatti, 1997; Falge et al., 1997; Wang and Jarvis, 1990).

The third group are the models based on the energy balance, which sometimes are enlarged with a stomatal conductance model. Models based on the energy balance are mostly derived from the Penman equation. Priestly and Taylor (Priestly and Taylor, 1972) have shown that transpiration is a rather conservative variable, which can be determined primarily by the available energy. Combined with temperature and vapour pressure deficit (D) they obtained good results for well-watered vegetation. Makkink (1957) demonstrated a simplified form of the Penman equation, which depends only on radiation and temperature. Usually the models contain several parameters, which are dependent on species, site and scale. Monteith (1965) enlarged the Penman model with a stomatal conductance model. In many cases, the leaf is described as a single big leaf where canopy conductance is composed of the bulk stomatal conductance (gₛ) and the remaining conductance when the stomata are closed (gₛ). Bulk stomatal conductance is often modelled as a product of reducing functions of leaf area index (LAI), D, radiation, temperature and soil water status (Bosveld and Bouten, 1992; Jarvis et al., 1976; Stewart, 1988).

The last group includes models based on the water balance, which are mostly used in catchment studies where the streamflow behaviour is related to the catchment properties (McCulloch and Robinson, 1993). In these models root water uptake is determined by a potential transpiration calculated from atmospheric conditions and a reducing function which depends on the soil water availability. Soil physicists calculate the root water uptake by solving the Richards' equation, which is extended with a sink term for root water uptake (Ball et al., 1987; Clothier and Green, 1997).

Comparisons between models of evaporation and transpiration have been made by Barr et al. (1997), Garatuza-Payan et al. (1998) and Bosveld and Bouten (1992) who all
compared models based on the energy balance or combined energy balance and stomatal conductance models. Price and Black (1989) compared a CO2 assimilation model with the Penman-Monteith model, although they could not parameterise the more complex CO2 assimilation model because of a lack of data.

The purpose of this study is to find similarities and discrepancies in simulated transpiration fluxes at half hourly periods of completely different forest transpiration models to find improvements of descriptions of forest transpiration processes. Three model concepts, leaf cooling, CO2 assimilation and a combination of cluster 3 and 4, e.g. energy balance and water balance, are selected and are all calibrated on a Douglas fir stand (Pseudotsuga menziesii) in the Netherlands. These models have different perspectives, different complexities and they are calibrated on different types of measurements.

2.2 MATERIALS AND METHODS

Research site

The research site, Speuld, is located in a 2.5 ha Douglas fir forest in the central Netherlands, near Garderen. The forest is dense with 780 trees ha\(^{-1}\) without understorey and planted in 1962. Average tree height between is 21.6 m, lowest living whorl 10.4 m, mean diameter at breast height is 0.249 m and the single sided leaf area, including stem area, ranging from 9.0 m\(^2\) m\(^{-2}\) to 12.0 m\(^2\) m\(^{-2}\) in summer (Jans et al., 1994). The soil is a well-drained Typic Dystrochrept (Soil survey staff, USDA, 1975) with a distinct forest floor of 5 cm, on heterogeneous ice-pushed sandy loam and loamy sand textured river deposits. The water table is at a depth of 40 m throughout the year. The 30-year average rainfall is 834 mm y\(^{-1}\) and is evenly distributed over the year, mean potential evapotranspiration is about 712 mm y\(^{-1}\). Yearly transpiration reduction by water stress is low (about 5 \%), although short periods with considerable drought stress occur (Tiktak and Bouten, 1994).

Measurements

Half-hourly measurements of meteorological driving variables were measured by the Royal Meteorological Institute of the Netherlands (KNMI) on a 36 m high guyed mast. Short wave incoming radiation was measured with a CM11 Kipp solarimeter. Temperature and humidity were measured with ventilated and shielded dry bulb and wet bulb sensors at 18 m above the forest floor. Wind speed was measured with a three cup-anemometer at
18 m above the forest floor. Over 43 days, eddy correlation of water vapour flux was measured 30 m above the forest floor with a fast response Ly-α hygrometer and a sonic anemometer-thermometer system (Bosveld et al., 1998).

**Model choices and calibration**

Three selected models were calibrated on the Douglas fir stand. Comparison between model results and measurements was based on eddy correlation measurements. Because the eddy correlation technique measures total evapotranspiration, only periods with a dry canopy were selected. Forest floor evaporation was fairly constant during the year at about 0.15 mm d⁻¹ (Schaap and Bouten, 1997). Models and measurements are compared after adding the forest floor evaporation fluxes to the calculated transpiration fluxes.

**Leaf cooling model**

The leaf cooling (LC) model of Prazak (Prazak et al., 1994) was chosen. This model calculates transpiration on basis of the requirement of water for cooling the canopy. Trees are simultaneously warmed by incident solar radiation and cooled by ambient air and by transpiration. Global radiation and temperature are the driving variables. Properties of the forest are expressed in two calibration parameters for the effective absorptivity of the radiation and the effective thickness of the leaves.

The model was calibrated on eddy correlation measurements. Optimum canopy temperature was set constant at 25°C. The two calibration parameters were optimised by an inverse modelling approach and found at 0.211 (-) for the effective absorptivity and 0.16 mm for the effective thickness of the leaves. Explained variances between the measurements and model results is $R^2 = 0.777$ and standard deviation of the error is 30.3 W m⁻². Because the true thickness of a needle is about 1 mm we conclude that both parameters are calibration parameters and do not have any physiological or physical meaning.

**CO₂ assimilation model**

The CO₂ assimilation (Assim) model we have chosen is the frequently used Farquhar model (Farquhar et al., 1980), which describes photosynthesis at the leaf scale. Combined with the stomatal conductance model of Ball et al. (1987), photosynthesis and transpiration are modelled at the leaf scale. No energy balance is included in this model. To obtain canopy fluxes, this leaf model is scaled using the three-dimensional light...
interception model Standflux (Falge et al., 1997).

Driving variables are photosynthetically active radiation (PAR), temperature, $D$ and wind speed. System variables are detailed LAI and stand characteristics to scale from leaf to stand. Net photosynthesis is calculated with temperature response functions and transpiration is calculated from the calculated stomatal conductance and the $D$ gradient.

Three parameters of the leaf model were calibrated on measured CO$_2$ fluxes at the leaf level using CO$_2$ gas exchange chamber measurements (Dekker et al., 2000) and scaled up by the use of detailed stand characteristics (Jans et al., 1994). Dekker et al. (2000) found that an extra temperature response function must be included in Ball’s model to obtain realistic canopy fluxes. The explained variance between model results and measurements is $R^2 = 0.804$ and standard deviation is 30.1 W m$^{-2}$.

**Combined energy balance with stomatal conductance and water balance model**

The Single Big Leaf (SBL) model we used is based on the Penman-Monteith equation (Monteith, 1965) where stomatal conductance is modelled as a product of reducing functions. It is assumed that the environmental factors that influence stomatal conductance ($g_s$) are day number of the year to calculate a seasonal trend of LAI, $D$, solar radiation, air temperature and soil water pressure head. The seasonal trend of LAI is caused by shoot growth and needle fall, where new needles may have a different stomatal conductance. To calculate the soil water pressure head a detailed soil water model (Tiktak and Bouten, 1994) was coupled to this model.

Driving variables are net radiation, global radiation, temperature, $D$, wind speed and precipitation. System variables are LAI and soil properties. For every response function (LAI, $D$, solar radiation, air temperature and soil water pressure) one parameter was optimised. Together with $g_{s,ref}$ this results into 6 calibration parameters. Calibration was performed by Bosveld and Bouten (1992). The soil water model was calibrated on soil water measurements, measured with TDR (Tiktak and Bouten, 1994), and the response functions were calibrated on latent heat fluxes measured with eddy correlation during dry canopy. The explained variance between model results and measurements is $R^2 = 0.834$ and standard deviation is 28.1 W m$^{-2}$.
2.3 RESULTS AND DISCUSSION

Model output comparison

Large differences in predicted transpiration between models were expected with the use of completely different model concepts. During the analysis, however, comparable explained variances and standard deviations between models and measurements at half-hourly

![Figure 2.1](image)

**Figure 2.1:** Comparing modelled and measured transpiration on 30 minutes interval base. Modelled transpiration was added with a forest floor evaporation model. Explained variances and standard deviations are: LC ($R^2 = 0.796, \sigma = 30.3 \text{ W m}^{-2}$), Assim ($R^2 = 0.804, \sigma = 30.1 \text{ W m}^{-2}$), SBL ($R^2 = 0.855, \sigma = 28.1 \text{ W m}^{-2}$). Dashed lines are 1:1 line, curved lines are fitted functions. Figure 2.1D shows the non-linearity of the measurements if an extra noise of 30 W m$^{-2}$ is added to the measurements.
basis were found (Figure 2.1A-2.1C). The fact that the Single Big Leaf (SBL) model produces slightly better results is not surprising because of the use of six parameters. As shown in Figure 2.1, maximum-modelled transpiration is about 190 W m\(^{-2}\) in all cases, whereas some measurements are somewhat higher than 200 W m\(^{-2}\). These high measurements are not related to a wet canopy. In some cases a somewhat higher flux may be caused by a wet forest floor, although values of more than 25 W m\(^{-2}\) for forest floor evaporation were never established. High measured fluxes are also related to a higher noise of the measurements. In all three models a non-linearity is found, represented by the fitted curved line shown in Figure 2.1. The differences in non-linearity between the models are small. This non-linearity can be caused by two reasons, (i) a missing link in the model or (ii) the fact that the model error is nearby zero while the error in the measurement is large. If an extra noise of 30 W m\(^{-2}\), which equals the error between model and measurement, is randomly added to the measurements and plotted against the true measurements, an identical non-linearity is found (Figure 2.1D). This means that the non-linearity found in Figure 2.1, can be explained by the one-sided noise at the x-axis. In addition of similarities of explained variances between models and measurements of the selected periods, model results of a total year are also almost identical. Annual totals for the LC, Assim and SBL are respectively, 310, 315 and 304 mm. The latter includes a reduction in annual transpiration of 20 mm as a result of soil water stress. Figure 2.2

![Graph showing modelled forest transpiration](image)

**Figure 2.2:** Thirty day moving average of modelled forest transpiration in mm day\(^{-1}\)
shows the 30-day moving average transpiration of the three models. Their dynamics are comparable although deviations of 20% occur around day 150. These deviations are caused mainly by including a LAI function over the growing season in the Assim and the SBL models. Differences between these two models are caused by the different impact of the LAI variation. Light extinction in the three-dimensional canopy model of the Assim model is very strong because of the high LAI. A 30% reduction of LAI reduces transpiration by only 10%, whereas the SBL model is calibrated to a 40% variation in transpiration during the growing season.

On a half-hourly basis, explained variances and standard deviations between the models are for LC - Assim, SBL - LC and SBL - Assim respectively $R^2 = 0.836, 0.897$ and 0.861. With all these similarities we cannot reject any one of the model concepts. This is not surprising because all these model types are still used in many studies. There are two reasons for these similarities. The first reason is the calibration procedure. For all three models, the final calibration was based on eddy correlation measurements. Although the idea of the Assim model is that calibration is not necessary, we used the extra temperature calibration to have comparable results between the models in terms of explained variances.

The second reason is the conservative behaviour of transpiration to radiation. A linear regression between eddy correlation measurements minus forest floor evaporation and global radiation of the total period, including the drought stress periods leads to $R^2 = 0.765$ and a standard deviation of 31.2 W m$^{-2}$ (Figure 2.3), which is comparable to the model results. It means that any calibrated model is able to describe transpiration to an acceptable level as long as radiation is included in the model. Because of strong correlation between input variables, for instance temperature is correlated with $D$ and radiation, a mean response is easy to find and gives reasonable estimates. Short periods when these correlation are uncoupled are very rare and hardly influence the overall fit criteria.

The magnitude of the uncertainties in the measurements also make it difficult to choose between the models. A standard deviation of the eddy correlation measurements of 21 W m$^{-2}$ at half-hourly intervals was calculated for atmospheric statistics. Owing to variation of the foot print and the fact that the buffer capacity for vapour below the measurement level is about 15 W m$^{-2}$, the uncertainty range is even wider. Because standard deviations between model results and measurements are 30.3, 30.1 and 28.1 W m$^{-2}$ on average half-hourly basis, better estimates are not directly foreseen.
Figure 2.3: Linear regression equation between global radiation ($R_g$) and eddy correlation measurements.

Discrepancies

From the above analysis we conclude that all models are able to describe transpiration, mainly because of the strong correlations between radiation, temperature and $D$ at ambient environmental conditions. This means that more observations during ambient conditions will not lead to a validation of one type of model. However, observations outside the range of calibration, for instance during manipulation experiments, may give misleading results if conditions are changed in an unnatural way. Therefore, to compare the models’ performance it is better to focus on periods where discrepancies occur. To do this, periods are selected when input variables were uncoupled.

Several techniques can be used to find periods with uncoupled input variables. For instance, in Figure 2.4A, when for four days model outputs are selected where the $D$ ranged between 10 and 30 mbar. Largest deviations between the models occur in the afternoon where the Assim model shows a delay for all days. Observations between 14.00 and 19.00 hour are selected in a subset. Explained variances between model and measurements of this subset are for LC, Assim and SBL respectively $R^2 = 0.717$, $0.690$ and $0.784$. This delay is caused by the time lag of $D$ with respect to global radiation (Figure 2.4b). Because the Assim model is most sensitive to $D$, the transpiration is delayed.
Figure 2.4: (A) The model results and eddy correlation measurements of 4 selected days with different vapour pressure deficit ($D$). (B) The delayed diurnal dynamics of $D$ and global radiation ($R_g$) during these selected days.

Hysteresis between $D$ and radiation is shown in Figure 2.5, where the same four days are plotted. Several researchers have reported diurnal clockwise hysteresis of measured leaf stomatal conductance (Pereira et al., 1987; Takagi et al., 1998). Because leaf stomatal conductance cannot be compared with bulk canopy stomatal conductance, we compare transpiration rates. Figure 2.6 shows the average deviation between measurements and model results plotted against $D$. The largest deviation occurs between 10-20 mbar for the Assim model, although the Assim model gives better estimates at high and low $D$. 

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Figure 2.5: Clockwise hysteresis between global radiation ($R_g$) and vapour pressure deficit ($D$). Numbers indicate day number as shown in Figure 2.4.

Figure 2.6: Mean deviation between observations and model estimates of transpiration in the afternoon, between 0.6 and 0.8 day.
Figure 2.7: Differences between the models in $W \text{ m}^{-2}$ against global radiation ($R_g$) and vapour pressure deficit ($D$). Shaded part is the 15 $W \text{ m}^{-2}$ reliability range of eddy correlation measurements. (A) the difference of LC and SBL; (B) the difference between Assim and LC; (C) the difference between Assim and SBL; (D) the measurement combinations used for this analyses.

To find differences of model behaviour in relation to input variables, the correlation between radiation and $D$ is again used. All half-hourly simulated transpiration values between day of year 91 and 365 are used to make contour lines of the differences of modelled transpiration plotted against radiation and $D$ (Figure 2.7). Contour lines are made by interpolation. The shaded parts are the 15 $W \text{ m}^{-2}$ similarity intervals between the models. As the confidence interval of the eddy correlation measurements is even larger, it is clear that we will never find differences between LC and SBL (figure 2.7A). It means that $D$, which is included in SBL and not in the LC model, does not directly influence transpiration. The largest deviations occur with the Assim model at $D$ between 10 and 25 mbar and radiation between 100 - 400 $W \text{ m}^{-2}$ (figure 2.7B and 2.7C). Figure 2.7C shows a larger deviation at radiation of 500 $W \text{ m}^{-2}$ and $D$ of 15 mbar than shown in Figure 2.7C. These periods correspond to days with soil water stress and differences of LAI effect.
between the model results.

It should be possible to improve some model responses on the basis of the discrepancies found in the sub data sets. We realise, however, that these model responses of the system do not necessarily give the behaviour of the true mechanisms. This is certainly the case if models are calibrated on these system responses as shown in this analysis. This together with the relatively large error of the eddy correlation measurements makes it impossible to rule as invalid any of the different processes included in the three model types.

2.4 CONCLUSIONS

Forest transpiration can be modelled successfully from different perspectives because of the high correlation with radiation and the fact that we calibrate mean responses of coupled input variables. It means that all models confirm the observations, even a linear regression model with only radiation. As long as we calibrate transpiration models, focusing on similarities does not provide information about the validity of the models. To evaluate model concepts, we need to focus on discrepancies and selected periods of specific combinations of environmental conditions by either selection of periods of uncoupled input variables or selection of differences of model behaviour in relation to the input variables.

The diurnal hysteresis of vapour pressure deficit (D) causes large differences in the afternoon. Although differences in model responses can be observed and explained in terms of the model concepts, a rejection of one of the model concepts is impossible because the model results depend on calibration procedures. Consequently, all three model concepts may still describe the true mechanisms.

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REFERENCES


