BOREAL ENVIRONMENT RESEARCH 7: 389–397 ISSN 1239-6095
Helsinki 23 December 2002

Transpiration of a mixed forest stand: field measurements and simulation using SVAT models

Alexander Oltchev[1], Jan Cermak[2], Nadezhda Nadezhdina[2], Fedor Tatarinov[2], Alexander Tishenko[3], Andreas Ibrom[1] and Gode Gravenhorst[1]

[1] *Institute of Bioclimatology, Georg-August University, D-37077 Göttingen, Germany*
[2] *Institute of Forest Ecology, Mendel's University of Agriculture and Forestry, CZ-61300 Brno, Czech Republic*
[3] *Department of Cartography and Geoecology, Tver State University, 170002 Tver, Russia*

Oltchev, A., Cermak, J., Nadezhdina, N., Tatarinov, F., Tishenko, A., Ibrom, A. & Gravenhorst, G. 2002: Transpiration of a mixed forest stand: field measurements and simulation using SVAT models. — *Boreal Env. Res.* 7: 389–397. ISSN 1239-6095

Transpiration of a mixed spruce-aspen-birch forest at the Valday Hills in Russia was determined using sap flow measurements and two different SVAT (Soil–Vegetation–Atmosphere-Transfer) models. The more sophisticated Mixed Forest multi-layer SVAT model (MF-SVAT) considers water uptake and transpiration of each tree species individually, and the simple Multi-Layer (ML-SVAT) describes the forest stand using averaged effective parameters of canopy structure and tree physiology. Comparisons of modelled and measured transpiration rates under sufficient soil moisture conditions did not show any significant differences between two models. Under limited soil moisture conditions MF-SVAT described forest transpiration still realistically whereas ML-SVAT overestimated it by up to 50%. Drought in the upper soil layers reduced transpiration of spruces more than of deciduous trees due to differences in physiological properties and vertical root distribution. Individual regulation of the transpiration of different tree species is typical for mixed forests and cannot be accurately described with averaged parameterisation such as used in ML-SVAT.

Introduction

Evapotranspiration and transpiration of different vegetation types are at present very well represented in many SVAT models of different level of complexity (e.g. Geyer and Jarvis 1991, Henderson-Sellers *et al*. 1996, Sellers *et al*. 1997). Both aggregated "big-leaf" and "distributed multi-layer" approaches are commonly applied for such purposes (Raupach and Finnigan 1986). Aggregated simple "big-leaf" models do usually require a limited number of input parameters and can be successfully applied to describe forest evapotranspiration and land surface–atmosphere interactions at global and regional scales. More sophisticated "distributed multi-layer" SVAT models require more input parameters with detailed information about the spatial distribution of key biophysical properties of vegetation. This makes the application of such models in global and regional modelling approaches very difficult. However, application of such models for simulation of local processes allows both to predict more precisely energy, H_2O and CO_2 exchanges between soil, vegetation and the atmosphere and to describe in detail internal canopy microclimatic conditions.

In most of the available one-dimensional SVAT models horizontal homogeneity of the vegetation canopy is assumed (e.g. Raupach and Finnigan 1986). Internal variability of biophysical properties of vegetation and morphological properties of soils in such models are usually not directly considered. It is obvious that this assumption can be successfully applied to a mono-specific uniform forest plantation. However, accuracy of flux estimates with such models, for example, for mixed uneven-aged forest stands can be significantly decreased through the variation of biological, morphological and optical properties of individual tree species.

The main goals of this paper are:

- to describe the variation of water uptake and transpiration for different tree species within a mixed spruce-aspen-birch forest stand under different soil moisture conditions,
- to present results of a new one-dimensional SVAT model approach that considers the biophysical variability of different tree species in a mixed forest, and
- to assess possible effects of model simplifications on accuracy of transpiration estimations.

Two multi-layer SVAT models will be applied to describe the energy and water exchanges between soil, mixed forest stand and the atmosphere: MF-SVAT (multi–layer Mixed Forest SVAT) and ML-SVAT (Multi-Layer SVAT). Model results will be compared with field measurements.

Methods

Study area

For measurements of energy and water fluxes an experimental site was established in a mixed forest stand in the Upper Volga–Daugava watershed area, in the southern part of the Valday Hills, in Russia (56°58´N, 32°52´E). The forest consisted mostly of uneven-aged aspen (*Populus tremula* L.) and Norway spruce (*Picea abies* (L.) Karst) with an admixture of birch (*Betula verrucosa* L.), mostly young specimens of mountain ash (*Sorbus aucuparia* L.), alder (*Alnus incana* L.) and some old Scots pine (*Pinus sylvestris* L.) trees. Ground vegetation cover was rich and represented mostly by herbaceous species (e.g. *Hepatica nobilis* Miller, *Pulmonaria obscura* Dumort, *Stellaria holostea*, L., *Rubus saxatilis* L., *Milium effusum* L. in drier parts and *Athyrium filix-femina* (L.) Roth, *Filipendula ulmaria* (L.) Maxim, *Urtica dioica* L., *Equisetum sylvaticum* L., *Stachys sylvatica* L. in wetter parts). Forest soils consisted of brown sandy-loam about 60 cm deep at drier part of the site with relatively deep underground water level of about 1.0–1.5 m or dark-brown clayish-loam about 40 cm deep at wetter parts of the site with high underground water level.

Field measurements

Field measurements were carried out during growing periods of 1999–2000. They included standard meteorological measurements at a 40 meter tower above the forest canopy, forest transpiration measurements using the sap-flow technique and forest inventory.

Sap flow rates were continuously measured in 20 sample trees of the main overstorey tree species as well as understorey woody species at experimental plot with area of 1.1 hectares. Representative sizes of sample trees were calculated using basal area according to a method described by Cermak and Kucera (1990) and Cermak *et al.* (1995). Sap flow was measured at breast height about 1.3 m above ground by the Tree trunk section Heat Balance (THB) method (Cermak *et al.* 1973, Cermak *et al.* 1995) in some trees and in parallel by the Heat Field Deformation (HFD) method on all sample trees (Nadezhdina *et al.* 1998). Two sensors installed in opposite sides of stems were used on each sample tree. The radial pattern of sap flow density was measured with special 6 point sensors from four sides of stems before installing the standard sensors for long-term measurements and it was checked for possible changes at the end of the growing season. Application of these multi-point sensors allowed to describe both radial and circumferent sap flow patterns for each sample tree and thus to increase significantly the accuracy of water flow estimations.

Measurements were carried out from late phase of leaf flushing in broadleaf species in early summer to leaf fall in October 1999, and from May until the end of September 2000. Forest inventory parameters, e.g. number of trees, diameter at breast height and basal area, of all trees measured at the experimental plot were used for up-scaling transpiration data from sample trees to the entire forest stand. Total daily transpiration of individual trees was related to diameter at breast height or basal area. In the first step, all trees were divided into 35 diameter classes (from 0 to 70 cm with the step of 2 cm) in order to cover the whole range of available tree diameters in the forest stand. In the second step, transpiration rates for all tree diameter classes were calculated separately for broadleaf and coniferous tree species. In the third step, transpiration of each diameter classes of coniferous and broadleaf trees were multiplied by the number of trees in each diameter class and finally summarised for the entire stand area.

Additional biometric studies were performed on tree root systems in order to characterise differences in their architecture and absorbing capabilities between species at the site.

SVAT models

Two multi-layer one-dimensional SVAT models (ML-SVAT and MF-SVAT) were developed in order to describe energy and water exchange between mixed forest and the atmosphere at stand scale. Both of the models are based on the main parameterisations already applied in the SLODSVAT model which has been intensively tested and used to describe interaction of mono-specific forest stands and the atmosphere (Oltchev *et al.* 1996).

ML-SVAT and MF-SVAT consist of closely coupled sub-models describing the following processes:

- transfer of visible, near infrared and infrared radiation within a forest canopy depending on the structure and optical properties of forest overstorey and understorey;
- turbulent exchange of sensible heat, water vapour and CO_2 between soil, forest understorey, forest overstorey and the atmospheric boundary layer;
- interception of precipitation by forest overstorey and understorey;
- water infiltration, storage and drainage in different soil layers;
- transpiration and water uptake through each component of the ”soil–roots–stems–branches–leaves–atmosphere” system controlled by stomatal regulation, leaf and xylem water potentials and storage capacities;
- photosynthesis of the overstorey and understorey vegetation, respiration of the above ground tree phyto-elements, the root system and soil micro-organisms.

The models use the same meteorological input data such as air temperature and humidity, wind speed, precipitation and global radiation at some reference height above the forest canopy.

Forest overstorey is represented by the models as an ensemble of individual trees of different species that are distributed uniformly over some homogeneous ground surface area. The modelling approaches are based on the following assumptions:

- the area of simulated forest stand is at least several times larger than the maximal height of the trees,
- trees of different species are distributed randomly, and

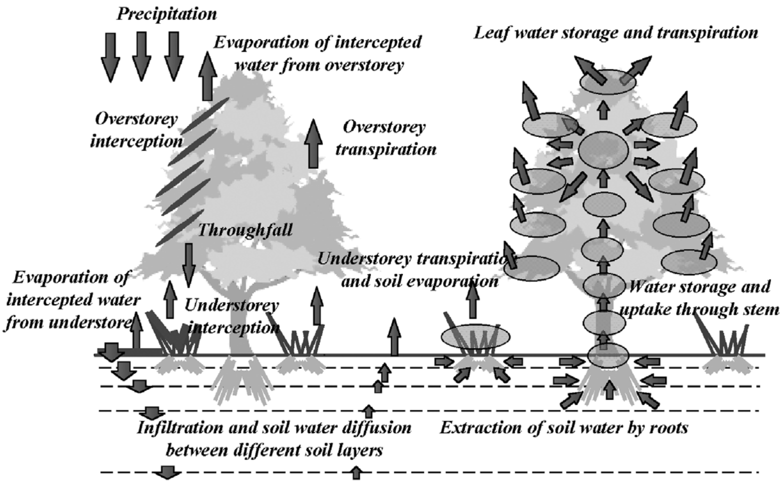

Fig. 1. The general scheme of water transfer pathways in individual trees and soil layers described in the ML-SVAT and MF-SVAT models. Ellipses represent water buffers in leaves and steams of overstorey trees and understorey plants.

— intra-specific variability of structural and physiological properties is neglected.

The vertical structure of overstorey trees and understorey plants depends in both models on species composition of forest community, tree density and height, and vertical distribution of leaf area density. Each of the tree species within the forest stand is characterised in the models by an individual set of optical (spectral reflectance and transmission coefficients of leaves and bark), morphological (leaf area index, tree density, basal area, root distribution) and physiological (leaf stomatal conductance, photosynthesis and respiration) parameters.

Soil and subsoil substratum in the models are described down to 2 meters depth and represented by four main layers. Thickness and properties of each soil layer vary depending on soil type, soil morphology and texture. In order to increase the accuracy of temperature and moisture estimations each layer is divided into several 5–10 cm sub-layers depending on soil type and morphology. Properties of soil layers and sub-layers within the forest area are assumed to be horizontally uniform.

Evapotranspiration of forest canopy in both models includes overstorey and understorey transpiration, evaporation of rain water intercepted by overstorey and understorey and direct evaporation of water from the soil surface (Fig. 1).

The water transport from the soil through the tree into the atmosphere is parameterised in both models by the non-steady-state approach (Hunt *et al*. 1991). It assumes that the tree transpiration rate is not equal to the water flow through each part of the soil–tree–atmosphere system and it is closely linked with the available water stored in both foliage and the woody tissue of the tree (Fig. 1). This non-steady-state description of water uptake in the soil–roots–stem–branches–leaves–atmosphere system enables to describe water flow through the tree organs and to assess internal stem, branch and leaf water storage, that is necessary for adequate parameterisation of stomatal regulation, water uptake and transpiration.

Biological regulation of transpiration by overstorey trees and understorey plants is described in both models through bulk stomatal conductance which is calculated by consecutive integration of leaf stomatal conductances over all vegetation layers. Leaf stomatal conductance is determined by leaf-level physiological processes and responds to incoming photosynthetically active radiation (PAR), the leaf temperatures, the atmospheric water vapour deficit, the leaf water potentials and the ambient concentration of CO_2. Dependence of leaf stomatal conductance on environmental conditions for different tree species are based on an empirical multi-factorial approach proposed by Jarvis (Jarvis *et al.* 1976). Air temperature and water vapour deficit in canopy layers is calculated by solution of coupled energy and water balance equations for forest overstorey, understorey and soil and equations for turbulent latent and sensible heat exchanges. Dynamics of the leaf water potentials of different tree species in different parts of tree crown is influenced by transpiration rate, available liquid water in shoot and stem buffers, hydraulic conductance of sapwood and is continuously estimated in both models by iteration procedures.

Evaporation rate of intercepted rain water by overstorey and understorey depends in the models on amount of available water in interception pools and meteorological conditions within and above the forest canopy. The maximal interception capacity is determined primarily on leaf area, and physical and morphological properties of the leaves of different tree species. It is assumed that the amount of intercepted water can be changed due to direct evaporation of intercepted water as well as mechanical shake off of rain drops from the leaves under strong wind within a forest canopy.

Infiltration of rain water in soil and its transport between different layers are described in the models through the gradients in water potentials and the resistances to water movement. These resistanses depend on soil texture and hydraulic conductivities of each soil layer.

Penetration and distribution of solar radiation within the forest stand is described using modified two-stream approximation described by Dickinson (1983). Both models assume horizontal homogeneity of forest canopy taking into account foliage clumping effects, different optical properties of the leaves of different tree species and probability for gaps between tree crowns.

Description of vertical turbulent regime above and within the forest canopy and calculation of aerodynamic and bulk conductances in the ML-SVAT and MF-SVAT models is based on the numerical solution of the system of hydrodynamic equations. The model algorithm assumes a random distribution of the trees within forest stand and the leaves within each canopy sublayer, and ignores the behaviour of individual eddies in the atmospheric boundary layer.

The principal difference between ML-SVAT and MF-SVAT models is that ML-SVAT describes the total forest transpiration using only one set of average effective parameters for canopy structure and tree physiology whereas MF-SVAT considers the water uptake and transpiration of individual tree species within the forest stand in detail as controlled by tree species specific physical and biological properties. Effective input parameters of the trees used in ML-SVAT are calculated by basal area weighted averaging of optical, morphological and physiological properties of individual tree species. The tree internal water fluxes of the main species of the investigated forest in MF-SVAT are calculated in parallel and integrated afterwards. With this approach the total forest and species transpiration and the feedback to the stands microclimate are estimated. This new approach allows to couple the process description of both individual tree species and entire forest stand within a one-dimensional model approach.

Results

Sap-flow measurements

Results of sap-flow measurements during vegetation periods of 1999–2000 showed significant variability of transpiration and water uptake rates among different trees and tree species. Diurnal patterns of measured water uptake rates corresponded to the relatively long duration of summer days at the experimental site in the transition zone between temperate and boreal forest zones. The water uptake patterns of individual sample trees reflected different shading by neighbours and also the different root distributions. Highest daily amplitudes of water uptake were reached under non-limiting soil moisture conditions, while low amplitudes were typical for soil drought. Total daily transpiration rates of individual trees were clearly related to their size as represented by tree diameter at breast height. This was true for both coniferous and broadleaf species. However, transpiration rates of broadleaf species were about 10%–20% larger than of spruce trees. No significant differences were found between transpiration rates of the different broadleaf tree species. Pronounced differences occurred between trees with different crown sizes and those growing in different social positions. Particularly, trees which grew at places, where the canopy was opened by accidental windfall transpired significantly more than trees of the same size growing in places,

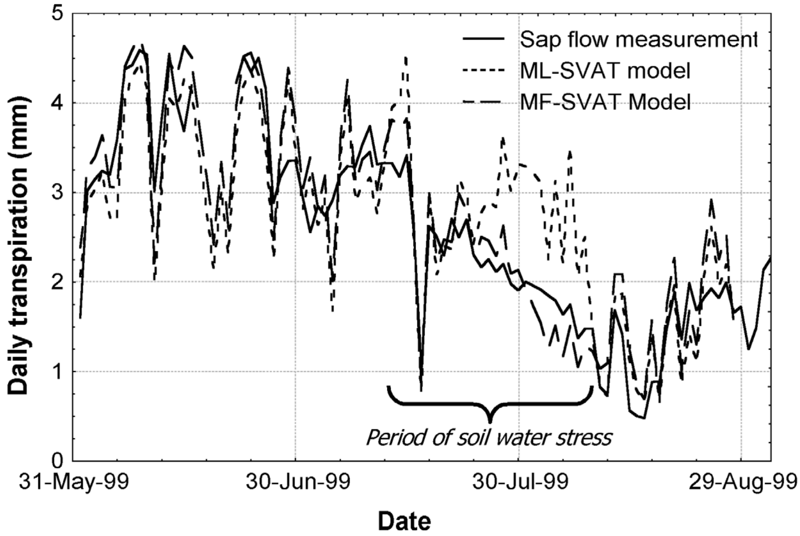

Fig. 2. Comparisons of daily transpiration of the mixed forest stand modelled by ML-SVAT and MF-SVAT models and measured by the sap flow method.

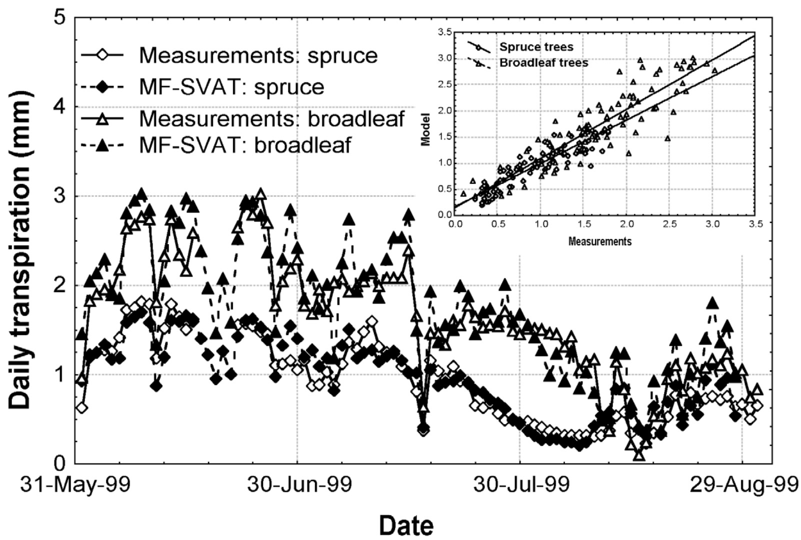

Fig. 3. Comparisons of daily transpiration of spruce and broadleaf tree species modelled by MF-SVAT models and measured by the sap flow method.

where they were more shaded by neighbouring trees. Transpiration of the trees with partially damaged crowns was significantly less than of healthy trees.

Total forest transpiration rates calculated from the sap flow measurements at the species level revealed significant differences between the years 1999 and 2000. Summer weather conditions were evidently much drier during 1999 (47.0 mm from June to July) than in the year 2000 (97.8 mm). Total measured forest transpiration during summer 1999 was 242.1 mm. Maximal transpiration rates (up to 4.6 mm/day) were observed in May-June 1999 that were associated with growth of new foliage in broadleaf trees. Low precipitation and increasing soil water depletion led to a gradual decrease of forest transpiration (Fig. 2). In July and beginning of August 1999 the ground water level decreased down to 100 cm below soil surface. Moisture content of the upper 20-cm soil layer ranged between 34% and 42% of full field capacity at the beginning of August. During this period spruces responded most sensitively to the soil drought, indicated by the reduction of daily transpiration rates down to 20% of the maximum rate that was observed in early June (Fig. 3). Transpiration of broadleaf species, however, was about 40% of the maximal June values at the same time. The higher sensitivity of spruces to upper soil layer depletion can be explained by their shallower root system and lower root and stem xylem conductance when compared with birch and aspen trees. The transpiration pattern changed significantly after strong rains in August 1999. Despite non-critical soil water content, transpiration rates were significantly smaller during late summer and autumn than during early summer. One of the possible reasons might be the die-back of fine roots during the summer drought, which was not investigated here.

Despite of surplus precipitation total forest transpiration during summer 2000 did not exceed 160.0 mm. Early summer transpiration rates in the wet year 2000 did not reach the high spring values of 1999 (3.3 mm day^{-1} at maximum). During the rest of the growing season 2000 transpiration rates were maintained at this relatively low level. Thus, these results indicate both limiting soil water supply during drought 1999 and limited root water uptake even under excess of soil water in 2000. The latter can be interpreted as a lack of soil aeration due to surplus water content that in turn can limit root respiration and subsequently metabolism and water uptake.

Model validations

Most attention at model validations was focused on the comparison of measured and modelled hourly and daily water uptake and transpiration rates of both: simulations of the averaged forest canopy (ML-SVAT) and simulations with MF-SVAT, where broadleaf and coniferous tree species were treated separately. For model validations the entire period of the forest transpiration measurements from 1999 to 2000 was used. All optical, morphological and physiological parameters of different tree species as well as physical characteristics of the different soil layers used in both SVAT models were estimated in the field or taken from previous measurements at the same area.

Comparisons of modelled and measured fluxes showed that both SVAT models described the seasonal dynamics of total daily transpiration appropriately under non-stressed soil water conditions, when the water content of the upper 20-cm soil layer exceeded 190 kg m^{-3} ($r^2 = 0.79$ for ML-SVAT and $r^2 = 0.82$ for MF-SVAT). Under these conditions transpiration rates of individual tree species estimated with MF-SVAT showed also a good agreement with measured fluxes of these tree species ($r^2 = 0.82$ for spruce and $r^2 = 0.81$ for broadleaf tree species) (Fig. 3). Despite the observed differences in hourly water uptake rates among trees of different species, age, height and basal area, ML-SVAT described the diurnal pattern of the water uptake for the entire forest adequately ($r^2 = 0.91$). Taking into account the specific properties for individual tree species in the MF-SVAT model increased the accuracy of predicted hourly total water uptakes slightly ($r^2 = 0.93$).

During the period of soil water stress in July and August 1999 modelled and measured hourly water uptake and daily transpiration rates revealed larger differences between the quality of the two model predictions (Fig. 2). As was shown already in a previous section the tree species at experimental site have a different structure and taking into account individual physiological properties they should respond differently to soil drought. Broadleaf trees have a relatively deep root system (about 50–70 cm) which can extract soil water from deeper layers compared to shallow spruce roots (about 10–20 cm). The soil water potential of the root zone of broadleaf species decreased down to –1.5 MPa at beginning of August 1999, whereas water potential of spruce rooting zone reached at the same time the level below wilting point, down to –2.5 MPa. All these differences are taken into account by MF-SVAT but not by ML-SVAT. Thus, modelled soil water potential of the root zone for such averaged tree as modelled in ML-SVAT was about –1.9 MPa, that is higher than wilting point level. Moreover, averaged physical xylem properties and leaf physiological parameters in ML-SVAT reproduced daily patterns of leaf water potentials, tree water uptake and transpiration that differed from those of individual tree species.

Comparisons of model estimations with field measurements show that the explicit description of water uptake of different tree species in MF-SVAT increased the accuracy of the prediction remarkably as compared with the averaged parameterisation in ML-SVAT. This was true both for daily transpiration rates of different tree species during the period of soil drought and for the transitional decrease of daily transpiration of spruce and broadleaf species following the progressive soil drying (r^2 = 0.83 for spruces and r^2 = 0.86 for broadleaf trees species) (Fig. 3). Averaged parameterisations in ML-SVAT model does not consider the response of different forest species to water stress and thus results in poor representation of the daily water uptake patterns (r^2 = 0.36) and the systematic over-estimation of daily transpiration by up to 50%. Over the entire period of the field measurements in 1999 and 2000 ML-SVAT model described 76% and MF-SVAT model 83% of the observed variation of the daily transpiration.

Conclusions

Results of sap-flow measurements in a mixed forest stand at the Upper Volga–Daugava watershed area in Russia during growing seasons of 1999 and 2000 showed a significant variation of transpiration and water uptake rates between different trees and tree species. Different tree species responded individually to specific environmental and soil moisture conditions. The influence of soil drought was significantly larger for spruce trees when compared with deciduous tree species mainly due to their shallower root system and to lower adaptation to the lack of soil water. Averaged daily transpiration rates of birch, aspen and alder trees under non-limiting soil water conditions were larger than transpiration of spruces. Despite of the surplus of soil water in the wet summer of 2000 forest transpiration was slightly lower the measured in 1999. This decrease is probably caused by previous draught or by oxygen deficiency in the soil.

Comparison of two different modelling approaches with results of sap-flow measurements showed that under sufficient soil water conditions both approaches described the hourly water uptake and daily transpiration rates of mixed forest stand adequately. However, under insufficient soil water conditions the more sophisticated MF-SVAT model described the behaviour of transpiration of the mixed forest and the individual tree species in a much more realistic way than the simplified ML-SVAT model. It was shown that neglecting the individual response of different tree species in the simulation of water fluxes in a mixed forest under these conditions can result in an overestimation of daily transpiration by up to 50%.

Results presented in this paper illustrate the effects of model simplifications on the quality of predictions of mixed forest transpiration by SVAT models. The MF-SVAT model can be successfully applied for simulation of energy, H_2O and CO_2 exchanges between forest stand and the atmosphere, as well as for description of partitioning of water uptake and transpiration among different tree species within a complex multi-specific forest stand in different geographical regions.

It is obvious that algorithms included in the MF-SVAT model cannot be used to describe land surface–atmosphere interaction in meso- and global scale models. However, it can be used for calibration and validation of evapotranspiration algorithms in these models. These parameterisations could be also easily applied in regional high resolution catchment models to improve predictions of grid and entire catchment transpiration and evapotranspiration.

Acknowledgements: Field measurements and modelling experiments were supported by the European Commission within the framework of the INCO-COPERNICUS research program (Grant IC15-CT98-0120). The authors are very thankful to Mr. V. Nadezhdin from Institute of Forest Ecology (Brno, Czech Republic) for technical assistance in organisation of the field measurements.

References

Cermak J., Deml M. & Penka M. 1973. A new method of sap flow rate determination in trees. *Biologia Plantarium* 15: 171–178.

Cermak J. & Kucera J. 1990. Scaling up transpiration data between trees, stands and watersheds. *Silva Carelica* 15: 101–120.

Cermak J., Cienciala E., Kucera J., Lindroth A. & Bednarova E. 1995. Individual variation of sap flow rate in large pine and spruce trees and stand transpiration: A pilot study at the central NOPEX site. *Hydrology* 68: 17–27.

Dickinson R.E. 1983. Land surface processes and climate-surface albedos and energy balance. *Advances in Geophysics* 25: 305–353

Geyer B. & Jarvis P. 1991. *A Review of models of soil–vegetation–atmosphere transfer schemes (SVATS). A report to* *the TIGER III Committee*. March 1991, Edinburgh, 69 pp.

Henderson-Sellers A., McGuffie K. & Pitman A.J. 1996. The Project for intercomparison of land-surface parameterization schemes (PILPS): 1992 to 1995. *Climate Dynamics* 12: 849–859

Hunt E.R., Running S.W. & Federer C.A. 1991. Extrapolating plant water flow resistances and capacitances to regional scale. *Agric. For. Meteorol.* 54: 169–195

Jarvis P.J. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. Royal Soc.* B 273: 593–610

Oltchev A., Constantin J., Gravenhorst G., Ibrom A., Heimann J., Schmidt J., Falk M., Morgenstern K., Richter I. & Vygodskaya N. 1996. Application of a six-layer SVAT model for simulation of evapotranspiration and water uptake in a spruce forest. *Phys. Chem. Earth* 21: 195–199.

Nadezhdina N., Cermak J. & Nadyezhdin V. 1998. Heat field deformation method for sap flow measurements. *Proceedings of the 4 International Workshop on Measuring Sap Flow in Intact Plants*. Zidlochovice, Czech Republic, Oct. 3–5, 1998: 72–92.

Raupach M.R. & Finnigan J.J. 1986. Single-layer models of evaporation from plant canopy are incorrect but useful, whereas multi-layer models are correct but useless: Discuss. *Aust. J. Plant Physiol.* 15: 705–716.

Sellers P.J., Dickinson R.E., Randall D.A., Betts A.K., Hall F.G., Berry J.A., Collatz G.J., Denning A.S., Mooney H.A., Nobre C.A., Sato N., Field C.B. & Henderson-Sellers A. 1997. Modelling the exchanges of energy, water, and carbon between continents and the atmosphere. *Science* 275: 502–509.

Received 23 January 2002, accepted 5 October 2002