Enhancing the simulation of a hydraulic tree-soil system by an interface between the hydraulic models HYDRA for *Quercus petraea* (Matt.) Liebl. and the hydraulic soil model SilVlow

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Abstract Hydraulic processes within trees have long been subject of research activities. Thereby, many empirical research activities base on the assumption of Darcys law about hydraulic potentials and conductance including the soil space (e.g. Clausnitzer and Hopmans (1994)). These basic principles let Frh and Kurth (1999) create a model about the hydraulic structure within a tree including the relation between hydraulic properties and the architecture of a tree. They implemented the model in form of a simulation software they called HYDRA. HYDRA numerically simulates the water potential structure within a tree and is parametrised for conifers, in particular *Pinus sylvestris* L. HYDRA simulates the hydraulical structure of the tree over time (usually a single day). The hydraulical structure, thereby, depends also on a conductance model which gives as a result the transpiration rate. The conductance model relies on empirical obtained micro climate information. The numerical simulation of water potentials considering the architecture causes severe numerical problems which are taken care of by a moderate restructuring of tree architecture prior to simulation. HYDRA is a very sophisticated model for the description of the hydraulic situation within a tree crown but does lack a connection to the soil-root layer. In the contrary, the initial potential which is represented at the very bottom of the tree is given by a single parameter and has to be set artificially by the user. The aim of this work was to replace this parameter by an interface to a soil-root simulation system. Here, the model HYDRA was used in a greater project which aimed at the reparameterisation of HYDRA for the tree species Quercus petraea (Matt.) Liebl. Intensive measurements were conducted to get a sufficient amount of information for parameterisation as well as for validation purposes.
Hydraulic conductance and potentials are concepts well known in the area of soil sciences. In literature many models exist which describe the concepts of water flow within the soil layer. One approach is that of Blendinger (1995). He describes the hydraulic conditions in the soil layer using the finite element approach well known from physics. Blendinger (1995) created a two dimensional finite element space where the hydraulic potentials are attributed to the finite elements. Furthermore, the model allows to define root elements within these finite elements which then create a sink of hydraulic potential caused by differences of potential at the soil-root boundary. Using these root elements allows studying the impact roots have on the water flow conditions in the soil layer. Having only a two dimensional space available causes the necessity to average the hydraulic states and root information over the third dimension.
In this particular work, an interface between both above mentioned models was implemented to enhance the soil-root-tree connection in HYDRA. The aim was to improve the model in two ways: On one hand this opens the way to work with realistic initial potentials instead of an artificial single parameter, and on the other hand HYDRA gets a dynamic input at the tree-root-soil boundary. The similar concepts of both models allowed such an interface which, furthermore, allowed to study HYDRA regarding changing hydraulic soil conditions caused, e.g., by varying precipitation rates.
The preliminary results show that a higher degree of realism of the simulation can be obtained. Furthermore, the pattern of the potentials within a tree has become sensitive to the hydraulic conditions in the soil and beyond that to precipitation. Thus, by introducing the interface the model HYDRA has also obtained a further interface to the environment of the tree, additional to that provided by evapotranspiration.

Introduction

This work is embed into the larger project 'Numerical Simulation of the Hydraulic Tree-Soil System for (*Quercus petraea* (Matt.) Liebl.) '. Two different models were used for the numerical simulation: The hydraulic model HYDRA Früh [1995] for the trees and the hydraulic soil model SilVlow for the tree-root space [Blendinger, 1995]. In this particular work we focused on linking both models and investigated the impact of such an interface on the simulation results of HYDRA.

Parameterisation of HYDRA

The model HYDRA needs a tremendous amount of physiological input information like the sap flows within the tree. To give a comprehensive overview about all measurements taken place for the parameterisation would overextend the scope of a poster and would like to refer to Schulte [2002]. To give an however brad overview, for the purpose of parameterisation five 15 year old oak trees were intensively measured over a period of one week during the summer of 2000. The flowrates e.g. were estimated by the heat flow method of Cermk et al. [1973] (cf. figure 3 for exemplified results).

One speciality of HYDRA is that it contemplates the architecture of a tree. Thus, one greater parameterisation need was to supply such an architecture. Therefore, the investigated oak trees were at the end of the measurement period harvested and the architecture determined. The resulting architecture had, for numerical reason, to be simplified. For more detailed descriptions about that simplification process we refer to Früh and Kurth [1999].

Parameterisation of SilVlow

SilVlow uses the finite element method for representing the soil/root space. The finite elements have to be fed with length densities $[cm/cm^3]$. During the measurement process it became clear that measuring the length densities for all contemplated trees was an impossible task. Thus, the densities were estimated by choosing only one tree out of the population and estimate the length densities from fine root mass densities. It is clear that such a method lacks the necessary amount of precision and accuracy. Thus, in addition to that we relied on experience from literature [Abelson and diSessa, 1982, e.g.];

Implementation of the Interface

The interface as such had no need for parameterisation; hence was a sole technical endeavour. HYDRA always provided an interface to the soil-root space in form of a node which represents the entry point to the root system. That point represents a border condition in form of a potential. In all simulation runs without the soil interface that potential was abstractively set to -0.05 MPa.

The Interface used that connection to deliver dynamic potentials simulated by SilVlow. For that purpose the model softwares had to be technically merged and the simulation runs timely synchronised.

Simulation runs

Two simulation runs were undertaken – one without and one using the interface – to enable the assessment of the effects of the interface. All simulations simulated a solar day using the microclimate conditions measured at 4 July 2000 on the field trial. To get a picture about the model behaviour we employed a sensitivity test by changing the precipitation values for the model SilVlow. Four different situations were tested:

- Scenario 1: Precipitation 1.2 cm/d / start value -0.05 ψ_{soil} MPa
- Scenario 2: No precipitation / start value -0.05 ψ_{soil} MPa
- Scenario 3: Precipitation 1.2 cm/d / start value -0.07 ψ_{soil} MPa
- Scenario 4: No precipitation / start value -0.07 ψ_{soil} MPa

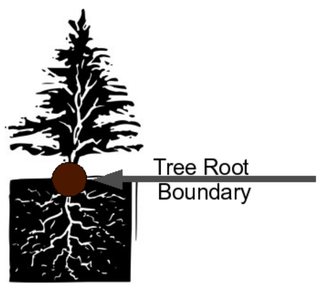

Figure 1: Boundary between the tree represented by HYDRA and the root/soil space represented by SilVlow. With the interface it is attempted to link both models through that boundary.

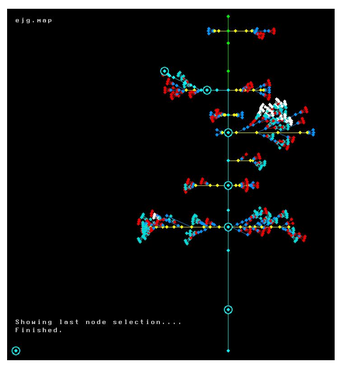

Figure 2: The HYDRA architectural representation of tree 'ejg'. In HYDRA the output is controlled by selecting nodes. For these nodes HYDRA gives potentials and flows.

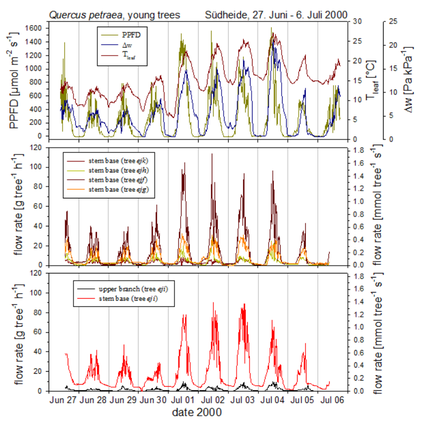

Figure 3: Sapflow of five *Quercus-petraea* trees (ejf, ejg, ejh, eji, ejk) located on the field trial in central Germany. A second sapflow sensor was installed at a sun exposed branch of the tree eji.

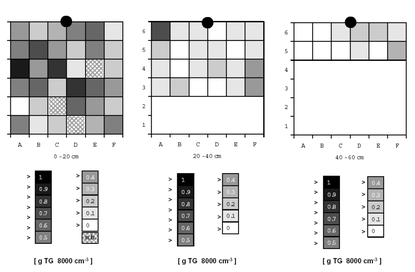

Figure 4: Root distribution of three different horizons (0-20,20-40,40-60cm) of tree ejg. TG = dry mass (Trockengewicht).

Results

During the simulation process it was apparent that SilVlow needed a certain amount of time to level off (see figure 5) as the model results fluctuated in the beginning of the simulation process. We solved that problem by simulating two days: One for the level off process and the second as the ultimate simulation run.

The results show that the interface changes the outcomes of the HYDRA simulation not dramatically but supplies the model with dynamic initial conditions at the root-tree boundary. Here, the boundary is represented by the results for node #1788 at the stem basis. The results also show that a given precipitation for the soil model has impact on the overall HYDRA simulation results.

The results are more realistic as in simulation runs without interface in the way that HYDRA reacts more sensitively on changes in the soil-root space. It is noteworthy, that these changes may be due to precipitation which, or course, changes the hydraulic conditions in the soil-root space.

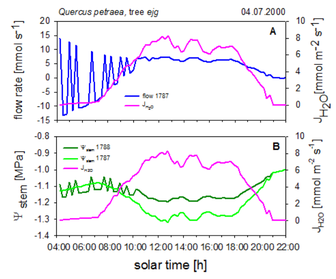

Figure 5: Results (**A**: flow rate, J_{H_2O}, **B**: ψ_{leaf}, J_{H_2O}) of a simulation run using the interface and micro climate data from ($PPFD$, T_{leaf},δ_w) 4 July 2000 and simulated leaf potentials (ψ_{leaf}) at 9 July 2002. Here, the level off process is shown which takes place during the simulation run is SilVlow does not get time to numerical adapt.

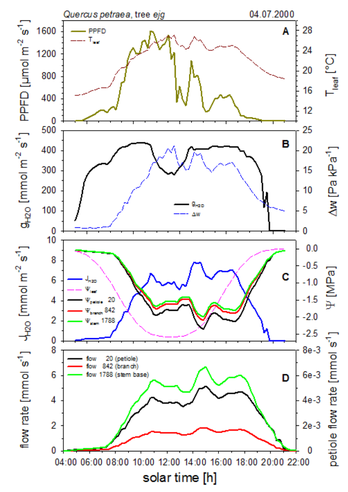

Figure 6: Simulation run for tree 'ejg' without interface using the micro climate situation at 4 July 2000 (**A**: $PPFD$, T_{leaf}; **B**: δ_w) and simulated leaf potentials at 31 July 2002 (**C**: ψ_{leaf}). Shown are the results of a petiole at the crown top (node #20), a whorl at medium height (node #842), and at stem basis (node #1788) of tree 'ejg'. **C**: Simulated Potentials ($\psi_{petiole}$, ψ_{branch}, $\psi stem$). **D**: Simulated flow rates. The radiation flow (**A**: $PPFD$), the leaf conductance (**D**:g_{H_2O}) and the transpiration rate (**C**: J_{H_2O}) relate to a leaf near the crown top (node #20). Not the deviating scale for the petiole flow rate (**D**)

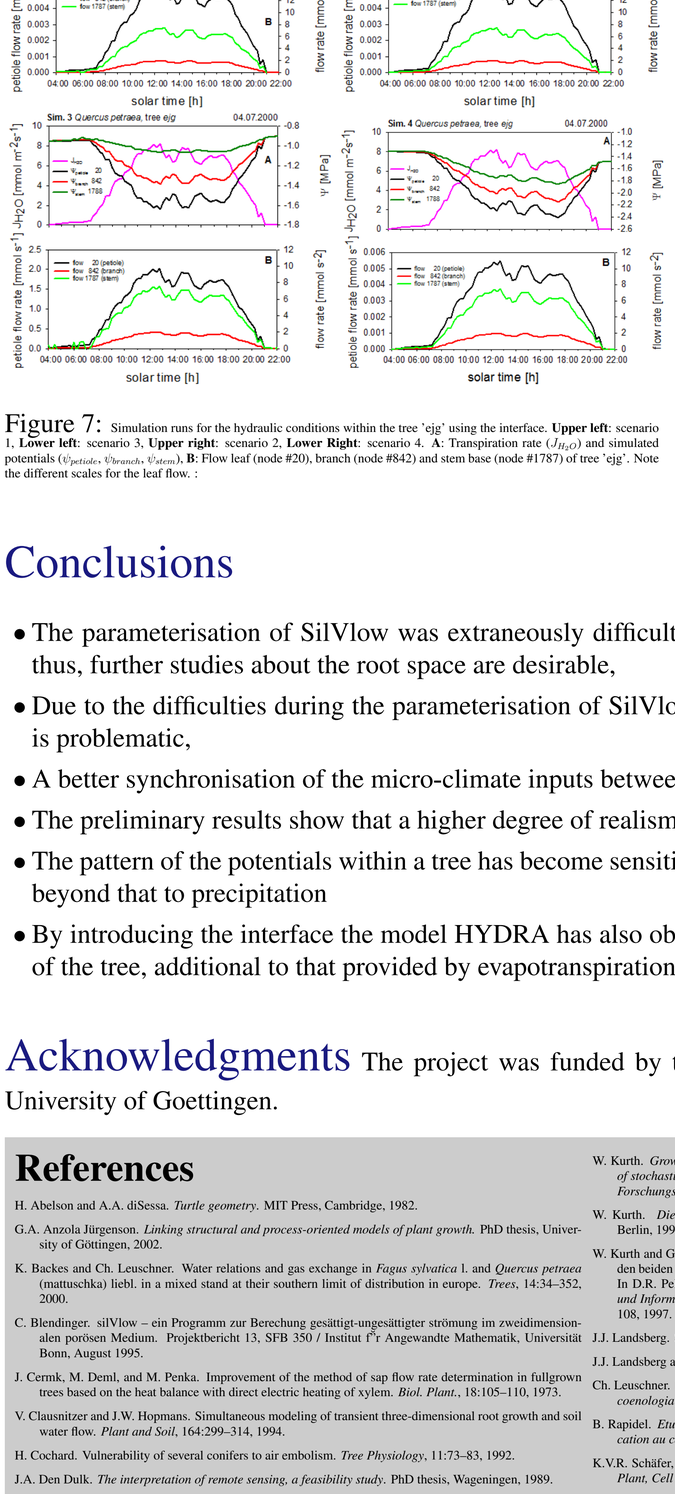

Figure 7: Simulation runs for the hydraulic conditions within the tree 'ejg' using the interface. **Upper left**: scenario 1, **Lower left**: scenario 3, **Upper right**: scenario 2, **Lower Right**: scenario 4. **A**: Transpiration rate (J_{H_2O}) and simulated potentials ($\psi_{petiole}$, ψ_{branch}, ψ_{stem}), **B**: Flow leaf (node #20), branch (node #842) and stem base (node #1787) of tree 'ejg'. Note the different scales for the leaf flow. :

Conclusions

- The parameterisation of SilVlow was extraneously difficult due to the amount of data to be measured, thus, further studies about the root space are desirable,
- Due to the difficulties during the parameterisation of SilVlow a quantitative interpretation of the results is problematic,
- A better synchronisation of the micro-climate inputs between HYDRA and SilVlow is desirable
- The preliminary results show that a higher degree of realism of the simulation can be obtained,
- The pattern of the potentials within a tree has become sensitive to the hydraulic conditions in the soil and beyond that to precipitation
- By introducing the interface the model HYDRA has also obtained a further interface to the environment of the tree, additional to that provided by evapotranspiration.

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References

H. Abelson and A.A. diSessa. *Turtle geometry*. MIT Press, Cambridge, 1982.

G.A. Anzola Jürgenson. *Linking structural and process-oriented models of plant growth.* PhD thesis, University of Göttingen, 2002.

K. Backes and Ch. Leuschner. Water relations and gas exchange in *Fagus sylvatica* l. and *Quercus petraea* (mattuschka) liebl. in a mixed stand at their southern limit of distribution in europe. *Trees*, 14:34–352, 2000.

C. Blendinger. silVlow – ein Programm zur Berechung gesättigt-ungesättigter strömung im zweidimensionalen porösen Medium. Projektbericht 13, SFB 350 / Institut f"r Angewandte Mathematik, Universität Bonn, August 1995.

J. Cermk, M. Deml, and M. Penka. Improvement of the method of sap flow rate determination in fullgrown trees based on the heat balance with direct electric heating of xylem. *Biol. Plant.*, 18:105–110, 1973.

V. Clausnitzer and J.W. Hopmans. Simultaneous modeling of transient three-dimensional root growth and soil water flow. *Plant and Soil*, 164:299–314, 1994.

H. Cochard. Vulnerability of several conifers to air embolism. *Tree Physiology*, 11:73–83, 1992.

J.A. Den Dulk. *The interpretation of remote sensing, a feasibility study*. PhD thesis, Wageningen, 1989.

Th. Früh. Entwicklung eines Simulationsmodells zur Untersuchung des Wasserflusses in der verzweigten Baumarchitektur. In *Berichte des Forschungszentrums Waldökosysteme*, volume B 131, page 192, 1995.

Th. Früh and W. Kurth. The hydraulic system of trees: Theoretical framework and numerical simulation. *Journal of Theoretical Biology*, 201:251–270, 1999.

D. Hertel. *Das Feinwurzelsystem von Rein- und Mischbeständen der Rotbuche: Struktur, Dynamik und interspezifische Konkurrenz*. PhD thesis, University Göttingen, 1999.

P.G. Jarvis. Water transfer in plants. In D.A. De Vries and N.H. Afgan, editors, *Heat and mass transfer in the biosphere*. John Wiley & Sons, New York, 1975.

P.G. Jarvis. The interpretation of the varations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. R. Soc. Lond*, 273:593–610, 1976.

W. Kurth. *Growth grammar interpreter GROGRA 2.4. - A software tool for the 3-dimensional interpretation of stochastic, sensitive growth grammars in the context of plant modelling.*, volume B 38 of *Berichte des Forschungszentrums Waldökosysteme*. Göttingen, 1994.

W. Kurth. *Die Simulation der Baumarchitektur mit Wachstumsgrammatiken.* Wissenschaftlicher Verlag, Berlin, 1999.

W. Kurth and G.A. Anzola Jürgenson. Triebwachstum und Verzweigung junger Fichten in Abhängigkeit von den beiden Einflußgrößen Beschattung und Wuchsdichte: Datenaufbereitung und -analyse mit GROGRA. In D.R. Pelz, editor, *Deutscher Verband Forstlicher Forschungsanstalten, Sektion Forstliche Biometrie und Informatik, 10. Tagung, Freiburg i.Br., 24.–28.9.1995, Ljubilana, Biotechnische Fakultät*, pages 89–108, 1997.

J.J. Landsberg. Some useful equations for biological studies. *Expl. Agric.*, 13:273–286, 1977.

J.J. Landsberg and N.D. Fowkes. Water movement through plant roots. *Annals of Botany*, 42:493–508, 1978.

Ch. Leuschner. Patterns of soil water depletion under coexisting oak and beech trees in a mixed stand. *Phytocoenologia*, 23:19–33, 1993.

B. Rapidel. *Etude expérimentale et simulation des transferts hydriques dans les plantes individuelles. Application au caféier (Coffea arabica L.).* PhD thesis, Université Montpellier II, Montpellier, 1995.

K.V.R. Schäfer, R. Oren, and Tenhunen J.D. The effect of tree height on crown level stomatal conductance. *Plant, Cell Environment*, 23:365–375, 2000.

T.M. Schlichter. *Die Entwicklung eines Simulationsmodells fr den Wasserhaushalt in einem Buchenbestand im Hochsolling*. PhD thesis, University of Göttingen, 1980.

M. Schulte. Final report of the project: Numerische Simulation des hydraulischen Systems Baum-Boden bei der Traubeneiche (Quercus petraea, (Matt.) Liebl.) granted by the DFG: Sl 11/8-3. Technical report, DFG, 2002.

J. Sperry, V. Stiller, and U. Hacke. Soil water uptake and water transport through root systems. In Waisel Y.and Eshel A. and Kafkafi U., editors, *Plant Roots: The hidden half*. Decker, New York, 3 edition, 2002.

M.T. Tyree and J.S. Sperry. Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? Answers from a model. *Plant Physiology*, 88:574–580, 1988.

M.H. Zimmermann, editor. *Xylem structure and the ascent of sap*. Springer Verlag, Berlin, 1983.