Quantification of the mutual relationships between forest growth and forest water use: determining factors, feedbacks and strategies

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1. INTRODUCTION

Terrestrial ecosystems play a crucial role in modulating the carbon balance of the earth system. (Luo et al., 1999). The study of plant and ecosystem responses to a changing environment is necessary to provide explanatory and predictive understanding of carbon, water and energy exchange in the current climate and in possible climate change scenarios. Simulation models are essential tools in this study to provide formalised statements of hypothesis as a framework that encapsulates disparate pieces of information and knowledge (Mäkelä et al., 2000).

In the study presented here, simulation models were used to quantify and obtain more knowledge about the mutual interactions between forest growth and forest water use. Carbon exchange of forested ecosystems, the latter of which form one third of the terrestrial ecosystems, is directly important for the quantification of carbon storage in the biosphere. Water is an important factor in energy exchanges between the atmosphere and terrestrial ecosystems, and has many direct and indirect influences on the functioning of (forested) ecosystems. These interactions receive increased attention, because with aforestation and reforestation of large areas, for example in South-America and in the Sahel, the water and energy cycles change, both on local and regional scales. These changes can result in shifting precipitation patterns, which can have dramatic consequences for land use.

The relationships between water and tree growth are complex and working at different time and spatial scales. The direct linkage is at the leaf level. In Figure 1 a global overview is given of gas exchange taking place at the stomata. The regulation of the stomatal conductance, influencing directly the uptake of CO$_2$ and the release of water vapour, is a complex process in which many factors like radiation, assimilation, vapour pressure deficit, transpiration and the CO$_2$-concentration at the leaf boundary layer interact (see Ball et al., 1987; Aphalo and Jarvis, 1993; Leuning, 1995; Monteith, 1995). In experimental conditions correlations that exist in field conditions between driving variables like radiation, temperature and vapour pressure deficit can be broken, but because correlations also exist between radiation and assimilation, and also vapour pressure deficit and transpiration, the precise driving mechanisms are not clear. Increasing radiation and assimilation increase stomatal conduction until a certain maximum is reached, whereas high vapour pressure deficit and transpiration values have a negative influence on stomatal conductance. Increased CO$_2$-concentrations at the leaf boundary layer also have a negative effect on the stomatal conductance.

Another negative feedback related to water is the negative influence of soil water stress on stomatal conductance. Also here the precise mechanisms are not clear yet. Anyhow, with the occurrence of soil water stress a signal is received at the leaf level, for tree seedlings and small plants this probably is the plant
hormone ABA (Abscisic Acid) sent from the roots, and for tall trees it is believed to be a decrease in leaf water potential that leads to a decrease of stomatal conductance (Whitehead, 1998). Other feedback relations are playing at a longer timescale even, involving effects of water on mineralisation and nutrient transport to the roots. This influences the nutrient uptake by the trees and thereby can lead to effects on the photosynthetic capacity and the amount of leaves. Shortage of water available for trees can also influence tree growth in another way. The expression 'available for trees' is crucial here, because this water limitation can also occur when in principle enough water is available in the ecosystem, but in a for the trees unattainable way. A major constraint for the growth of boreal forests is for example the onset of snowmelt in spring. As soon as the overlying snow starts to melt and the temperature of the upper soil horizon rises towards 0 °C, the switch from a small net daily loss of carbon to a large net gain, representing forest growth, occurs over just a few days (Jarvis and Linder, 2000). In boreal conifers, the availability of soil water is a prerequisite for the recovery of photosynthetic capacity in spring and early summer (Bergh and Linder, 1999).

In this study simulation models were used to gain quantitative insight in the shorter time scale (~ growing season) interactions between forest growth and forest water use. The most important mechanisms, processes and driving vari-
ables determining forest growth and forest water use were analysed and quantified. Because of the enormous amount of data available on the short-term exchange of carbon and water (see for Europe for example Valentini et al., 2000; Tenhunen et al., 1998), the first part of this thesis (Chapter 2 – 5) concentrates on the modelling of the exchange of carbon and water between coniferous forests and the atmosphere. Several models were developed, parameterised and tested on the same data to make a thorough comparison possible between different modelling strategies.

In Chapter 2 the question 'what input do we need for a reliable modelling of the half-hourly fluxes of carbon and water exchange of a set of coniferous forests?' is dealt with. For this, the performance of general applicable models was compared to the performance of models developed for specific, individual forests. Subchapter 2.1 deals with the application of artificial neural networks to both carbon and water fluxes of a set of 7 coniferous forests. In Subchapter 2.2 fuzzy logic was applied to the latent fluxes of 6 coniferous forests to compare the performance of the method to artificial neural networks. By also modelling the carbon and water exchange of the Douglas-fir forest in Speuld, the technique was compared with other models and more thoroughly tested.

In Chapter 3 the model applied to the forest in Speuld was no longer totally empirical, but the model formulation was derived from expert knowledge about the most important processes governing the exchange of carbon and water of a forest ecosystem. The parameterisation of the model was still totally measurement-based. This simple model was applied to the Speuld-dataset consisting of two years of flux measurements. The second year of measurements was obtained after a thinning took place in which one third of the trees were cut. Therefore, the changes in parameter values of the simple model optimised on these two years separately could be evaluated in terms of changes in ecosystem functioning due to the thinning.

In Chapter 4 a process-based model consisting of a forest growth model, FORGRO (Mohren, 1986; Kramer, 1996), coupled to a soil water balance model, SWIF (Tiktak and Bouten, 1992), was applied to the two years of data available for Speuld. Both the forest growth model and the soil water model need detailed ecosystem knowledge for the parameterisation: the forest growth model for example needs the leaf photosynthetic characteristics and respiration coefficients. Photosynthesis and respiration are taking place on a different time and spatial scale than the large-scale flux-measurements on which the model was tested. The parameterisation of these processes can be done without using the measurements on which the model will be tested. The process-based model therefore is another step in the range from the totally empirical models of Chapter 2, the semi-empirical model of Chapter 3, to Chapter 4. The FORGRO-SWIF model was not parameterised totally independent of the carbon and water flux measurements: two parameters were still optimised using the data. In Subchapter 4.1 the FORGRO-SWIF model was used to test three different stomatal conductance models with regard to the way they could incorporate soil water stress. In Subchapter 4.2 the model was further tested on the second year of flux data
available for Speuld, and then run for ten years to estimate the inter-annual variability in carbon and water exchange for the Douglas-fir forest.

In Chapter 5 an integrative and thorough comparison of the models presented in the previous 3 Chapters, is performed. This could be done because all models were parameterised or optimised on the same dataset. The models were evaluated on the basis of their performance, their ability to increase our knowledge of forest ecosystem functioning and their application possibilities for estimating possible climate change effects and upscaling issues.

The second part of the thesis concentrates on two characteristics that all models of the first part have in common. First, all models ignore or neglect spatial interactions and variability. In Chapter 6 a spatially explicit model based on eco-hydrological dynamics, simulates a spatial and temporal competition between trees and grasses in semi-arid systems. Quantitative knowledge about the occurrence of water stress simulated by a point model was used to affect settlement and death chances of trees and grasses, thereby influencing the competition for space.

A second common feature of all models is that they are data-driven: using measured data the responses of the models were optimised to minimise the model-output versus measurements mismatch. The optimised responses thereby represent a quantification of the hidden strategy of the vegetation to deal with their environment. In Chapter 7 these concepts are reversed: no longer the measured values of the model output determine the strategy in which the forest deals with its environment, but now a tree strategy is assumed. The applied strategy was an optimisation strategy: hypothetically, the current vegetation uses the resources of the environment in an optimal way as a result of natural selection working millions and millions of years. This strategy was assumed to determine the best root distribution: the one that optimises the amount of water transpired by the forest. As the amount of water transpired by a forest is strongly linked to the growth of the forest, implicitly also the growth of the forest was optimised.

REFERENCES


Kramer, K., 1996. Modelling comparison to evaluate the importance of phenology and spring frost damage for the effects of climate change on growth of mixed temperate-zone deciduous trees. Climate Research 7:31-41.


A second common feature of all models is that, in order to be of use, they must build in the ability to predict the responses of the environment to an optimal way, or a near-optimal way, of managing stem flow. This is usually done by means of measuring values of the model parameters in the field over time and using these measurements to calibrate the model. The model parameters are then used to generate predictions of future stem flow under different management regimes.

References: