1 Introduction: forest growth and forest ecosystem carbon budgets in relation to climate change

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The central objective of the LTEEF-II project was to assess climate change impacts on European forests, in terms of water and carbon fluxes, regional differences, long-term effects, and the overall carbon budget for forests in Europe. The results of this assessment were used to identify forest management strategies that account for these impacts, and that maximise carbon sequestration. The LTEEF-II project mainly consisted of A) assessment and modelling of the long-term regional impacts of climate change on European forests, and B) upscaling of these regional responses to the European scale, to quantify the overall carbon budget and sustainable wood supply of European forests. As part of the long-term impact assessment, emphasis was on growth rates and water relations (drought), and on possible adaptive strategies for forest management. The overall forest sector carbon budget was quantified under present climate and under expected future climate change.

The LTEEF-II project (1998-2000) comprised the second phase of a major research effort undertaken as part of the EU Environment and Climate research program under the 4th Framework Program of the European Commission. In the first phase of LTEEF (1994-1997), existing forest models where extended and applied to conditions representative of a range of sites throughout Europe, under present-day and future climate scenario's. In this part of the project, emphasis was on model development and model comparison (Mohren, 1999; Mohren & Kramer 1997). In the second phase of the LTEEF project (LTEEF-II), model performance was evaluated by application to the EUROFLUX sites, by comparing model output with the eddy-covariance flux estimates. (EUROFLUX was a largely EU-funded European flux network, in which carbon and water fluxes over forests were monitored using eddy-covariance techniques, at more than 15 sites in a range of forest types from northern Sweden to Italy). The model comparison was done in close collaboration with the EUROFLUX consortium, and the most recent experimental data, such as from the ECOCRAFT project (Jarvis, 1998), was used as input data to parameterise the process descriptions in the models. In addition to the comparison against flux data, the models were evaluated against long-term growth and yield data from permanent plots as used in traditional growth and yield research. Based on this model evaluation, regional impact studies were carried out to assess potential climate change impacts for a range of forest ecosystems throughout Europe. Using the models in combination with climate scenarios as identified from global climate modelling, forest management response strategies were identified, and evaluated with respect to the consequences for forest ecosystem carbon budgets. The regional impacts assessments were scaled up to a European level, using a) national forest inventory data and b) remote sensing techniques (Karjalainen *et al.*, 1997; Grace *et al.*, 1999; Veroustraete, 1994; Veroustraete *et al.* 1996). This resulted in estimates of the current carbon balance for the European forest sector, as well as assessments of timber production and forest carbon budgets per country under future climate scenarios, including estimates of carbon sink strength.

1.1 Model evaluation

The proces models used were tested using the same site and species information so that differences as a consequence of differences in parametrisation is ruled out as much as possible. The criteria for the comparison and selection of models included: 1) model evaluation against short-term flux data; 2) model evaluation against long-term growth & yield data; 3) a sensitivity analysis, to determine the response of selected model output to climate change scenario's (temperature, CO_2 and precipitation, independently and jointly); 4) an uncertainty analysis to attribute uncertainties in the model output to uncertainties in model input; and 5) availability of technical documentation of the model.

1.2 Forest ecosystem carbon budgets

The components of the forest carbon budget include: the above- and below ground biomass, the soil organic matter and the forest products. A typical carbon budget of a managed forest is presented in Figure 1. A total of 15 Mg C $ha^{-1}yr^{-1}$ is annually fixed by gross photosynthesis. 7 Mg C $ha^{-1}yr^{-1}$ of this amount is transferred to the soil organic matter pool through litter fall and root turnover, 6 Mg C $ha^{-1}yr^{-1}$ of biomass C is respired, and an average annual increment of 2 Mg C $ha^{-1}yr^{-1}$, equivalent to some 8-10 m^3 $ha^{-1}yr^{-1}$ is harvested. The soil organic matter pool in this example releases somewhat less carbon as compared to the inputs through litter and root turnover, resulting in a net accumulation of 0.5 Mg C $ha^{-1}yr^{-1}$. The carbon in wood products that leave the forest is in the long-term brought back to the atmosphere by product decomposition. Consequently, the measured Net Ecosystem Exchange (NEE) of 2.5 Mg C $ha^{-1}yr^{-1}$ (15 Mg C $ha^{-1}yr^{-1}$ uptake by plant photosynthesis minus 12.5 Mg C $ha^{-1}yr^{-1}$ by ecosystem respiration) decreases to 0.5 Mg C $ha^{-1}yr^{-1}$ when product decomposition outside the forest is taken into account.

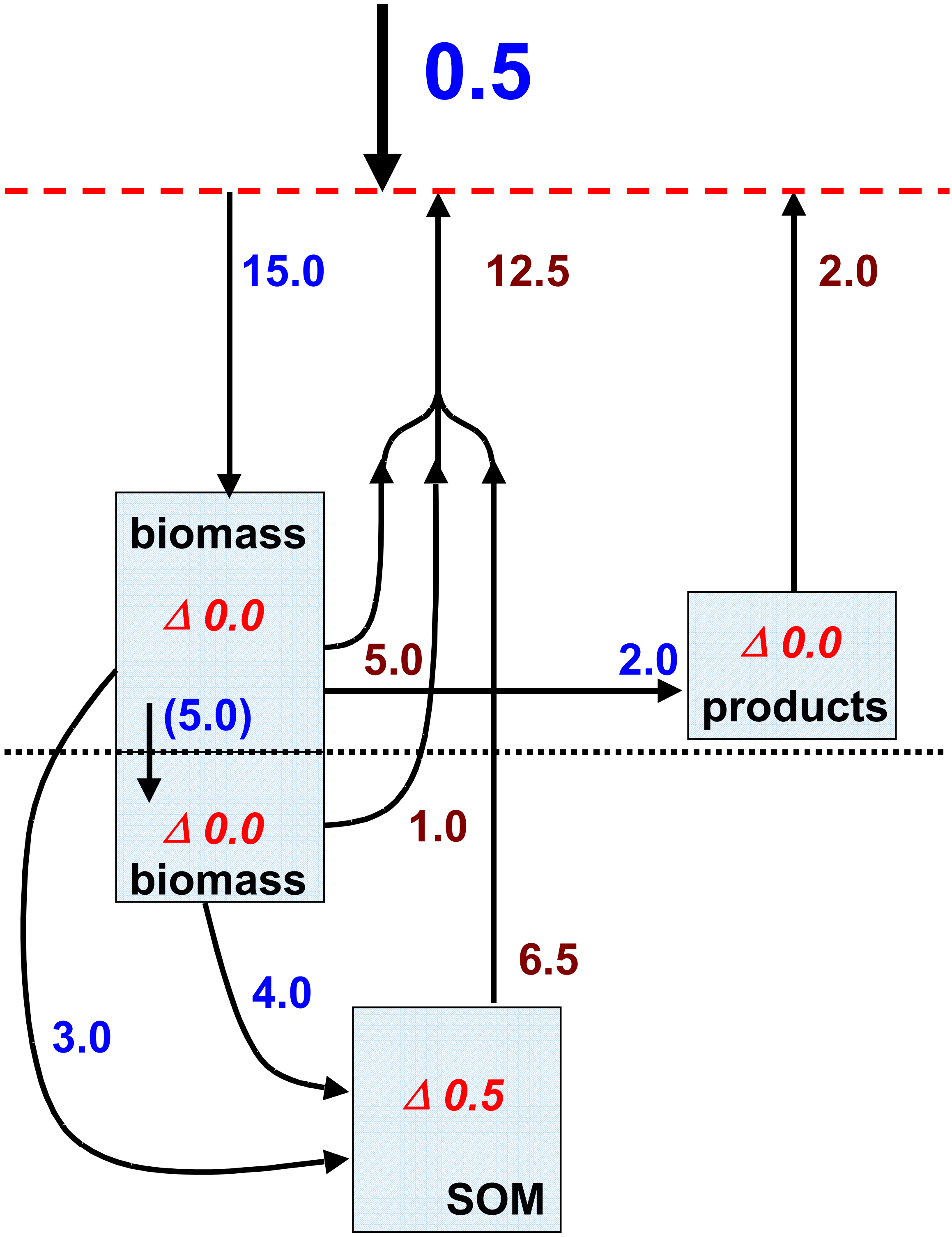

Figure 1.1: A general carbon budget for managed forest, accounting for wood harvest and product decay. All values refer to annual rates, in Mg C $ha^{-1}yr^{-1}$. Of the total annual uptake of 15 Mg C $ha^{-1}yr^{-1}$, 5 Mg C (35 %) is assumed to be allocated to below-ground biomass. Litter fall is assumed to be 3 Mg C $ha^{-1}yr^{-1}$, and root turnover is assumed to be equal to 4 Mg C $ha^{-1}yr^{-1}$. Average annual wood harvest is assumed to be equal to annual increment, i.e. 2 Mg C $ha^{-1}yr^{-1}$. The amount of carbon in soil organic matter (SOM) is assumed to accumulate at a rate of 0.5 Mg C $ha^{-1}yr^{-1}$. The total amount of carbon in products is assumed to be constant, hence the average amount of carbon harvested is equal to the amount of carbon released in product decomposition, i.e. 2 Mg C $ha^{-1}yr^{-1}$.

To assess the impacts of climate change on overall carbon budgets one needs to take into account all components described above, including the role of forest management. Changes in temperature, atmospheric CO_2 concentrations and precipitation directly affect the rates of gross photosynthesis and the decomposition of organic matter in the soil, which can be evaluated by process-based forest growth models. Forest management plays and important factor as it controls the rate at which carbon in woody products leaves the forest, and as it affects, through thinning and harvesting, also the growth rates of the remaining trees. Other disturbances of the forest ecosystem such as fires, storm, flooding and landslides need also be taken into account to quantify the carbon budget at the regional scale, but are outside the scope of this project.

1.3 Discussion and conclusions

The availability of fluxes of CO_2 and H_2O at the stand level provides an unprecedented opportunity to test stand-level forest growth models. Earlier attempts of this have been made (e.g. Vermetten et al, 1994), but the flux data currently collected by the EUROFLUX project and elsewhere in the world provide high resolution data that make model testing over a wide climatic range and over different forest types possible. In an earlier model comparison the different models showed highly divers results because of differences in model assumptions and description of processes (Sonntag, 1997). The availability of independent data now allowed selection of those models that are most relevant for specific climatic regions and forest types. This selection was critical to assess the sensitivity of the different forest types in Europe to changes in climatic parameters like temperature and precipitation, and atmospheric CO_2 concentration. Carefully formulated and validated models are the only means to do this as large scale experiments over long time horizons are impossible to perform. Sensitivity of model output to changes in climatic parameters provided insight into the relevance of the mechanisms involved in the impact of climate change on forests. The first of such sensitivity analyses have evaluated the importance of water and water-stress (Van Wijk *et al.*, 1999; Loustau *et al.* 1997), and the importance of differences between species in phenological response to temperature (Kramer, 1995; Kramer & Mohren, 1996).

The selection of models was also critical for the scaling up from the stand to the regional level in a future climate. The principle ways of scaling up were aplied in the LTEEF project: 1) by the adjustment of growth and yield tables of many forest types based on the sensitivity to climatic parameters of the selected forest growth models, combined with a large database of the distribution of these forest types over Europe; 2) by formulating simple models that adjust the radiation use efficiency (Bartelink *et al.*, 1997) also based on the sensitivity to climatic parameters of the selected forest growth models; and 3) simplified process models. These approaches allowed to assess the sink strength of European forests in the coming decades (Nabuurs & Mohren, 1995; Nabuurs *et al.*, 1997; Martin *et al.*, 1998).

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