# PEATLAND SIMULATOR CONNECTING DRAINAGE, NUTRIENT CYCLING, FOREST GROWTH, ECONOMY AND GHG EFFLUX IN BOREAL AND TROPICAL PEATLANDS

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## SUMMARY

We built and applied peatland simulator Susi that allows simultaneous assessment of economic benefits and adverse environmental effects of peatland forest drainage. The process based simulator was constructed on the following theoretical framework: Forest growth in peatlands is nutrient limited; principal source of nutrients is the decomposition of organic matter. Excess water decreases $O_2$ diffusion and slows down the nutrient release. Drainage increases $O_2$ diffusion and consequently organic matter decomposition, $CO_2$ efflux, and nutrient supply, and enhances the growth of forest. Profitability of the drainage operation depends on costs, gained extra yield and its allocation into timber assortments, and the rate of interest. The performance of hydrology and forest growth part of the simulator was tested against independent datasets. The results showed a clear relation between the stand growth, nutrient availability, and $CO_2$ efflux. In the test data, potassium was the main limiting factor for the forest growth. In examples we demonstrate the computation of growth response, profitability and environmental effects of ditch cleaning. The simulator and its holistic approach has been successfully implemented in both tropical pulpwood plantations in Sumatra, Indonesia and in Finnish boreal forests.

***Keywords:*** *drainage, hydrology, mathematical modeling, nutrition, peatland forests*

## INTRODUCTION

Different criteria have been presented all over the world to evaluate the need of forest drainage, criteria being connected to water table depth (DWT), air-filled porosity (ea) or water potential (h) in the root zone (e.g. Wesseling and van Wijk 1957, Vompersky & Sirin 1997). While these criteria have their practical value in drainage design, they are difficult to generalize outside the experiment areas and the link between the criteria and the forest production remains weak. The problem of these static criteria is that they do not account for the numerous biotic and abiotic factors that affect the onset of oxygen stress (Bartholomeus *et al.,* 2008), such as consumption of oxygen ($O_2$), peat and stand characteristics, and weather and climate conditions. It is clear that there is no universally applicable critical DWT, ea, or h values, but the adequacy of drainage has to be evaluated dynamically in larger theoretical framework. Furthermore, an evaluation of the need of drainage requires computation of economic feasibility, because drainage is above all, an investment. Feasibility of drainage is decreased by adverse environmental effects such as increased $CO_2$ emissions, and export of suspended solids and nutrient into watercourses.

The results of numerous studies describing the effects of drainage on forest growth become more understandable if, instead of removing $O_2$ stress, we assume an indirect effect through nutrition. In peatlands the principal source of nutrients is the decomposition of organic matter. Excess water decreases $O_2$ diffusion and slows down the nutrient release. Drainage increases $O_2$ diffusion and consequently organic matter decomposition, $CO_2$ efflux, and nutrient supply, and enhances the growth of forest. Profitability of the drainage operation depends on costs, gained extra yield and its allocation into timber assortments, and the rate of interest.

Mathematical models are required for systematic and quantitative description of this complex of processes. We constructed Peatland simulator Susi that involves both process based and empirical components for computing above and below ground hydrology, gas diffusion in soil, decomposition of organic matter, nutrient release, forest growth response, $CO_2$ emissions, suspended solids and phosphorus exports, and economy. The aim of this study was to test the simulator against independent dataset and to apply it for assessing benefits and adverse effects of the main drainage issue in Finland, which is ditch cleaning. Benefits and limitations of the computational approach are discussed in the paper.

## METHODS

Simulator description and use. Susi simulator computes daily water fluxes and storages in two dimensions for a peatland forest strip located between drainage ditches. Above ground hydrology is computed using a ‗semi-physical' zero-dimensional vegetation model that provides a simplified description of water cycle in a scale of a single forest stand. Soil water storage, DWT, and vertical water content profile is calculated following a simple assumption of equilibrium water content in soil (Skaggs 1980). Soil water potential profile follows instantly the DWT and the soil water content along the vertical profile is calculated using the van Genuchten water retention characteristics. Lateral water movement to open drain takes place below the DWT and is computed explicitly using the Darcy law. Daily $O_2$ diffusion to soil is quantified using steady-state scheme presented by Glinski and Stepniewski (1985). Soil $O_2$consumption is computed from daily $CO_2$ flux model as a function of peat temperature and bulk density (Ojanen *et al.,* 2010). The $CO_2$ flux is scaled down so that the diffusion is adequate to satisfy the $O_2$demand of decomposition activity. Nitrogen (N), phosphorus (P) and potassium (K) release is computed from the peat nutrient content and the actual decomposition. Future expected growth of the stand is derived using Schumacher growth curve, stand volume and age. Nutrient demand (N, P, K) is calculated from the expected growth using nutrient accumulation models by Laiho (1997). Export of suspended solids is quantified using simulated runoff, soil type in the ditch bottom, and reported mean concentrations without or with ditch cleaning (Joensuu *et al.*, 1999). The required input for the simulation includes daily meteorological variables, peat type and bulk density, tree species, stand volume, ditch depth, and strip width.

Feasibility of the drainage is assessed by comparing scenarios (length of simulation 1…5 yrs) without and with ditch cleaning. Changes in the environmental variables ($CO_2$ flux, export of P and suspended solids) are directly gained as difference between the scenarios. The economic benefit is computed as follows: First, the difference in the nutrient release is computed, and growth response is deduced according to the increase in the supply of the growth limiting nutrient and the nutrient accumulation model. The computed extra growth represents the maximum growth response and is extrapolated to the following 20 yrs by using an empirical scheme: the growth response increases from zero to maximum between 0…8 yrs, remains at maximum between 8…10 yrs and thereafter decreases linearly to zero between 10…20 yrs. The integrated growth response over the 20 yrs represents the total extra growth. Then, the gained extra growth is divided into timber assortments (pulp wood and sawn timber), which have distinctly different price. Drainage cost, and pulpwood and timber price, time series of the gained extra pulpwood and timber, and the rate of interest are used to compute the net present value of the drainage investment. Finally, the economic benefits and environmental effects are assessed simultaneously.

Field data and comparison. Susi-simulator performance was validated against independent dataset of 69 Scots pine (*Pinus sylvestris,* L.) dominated peatland sample plots located in Central Finland, measured in 1985 and reported by Hökkä *et al.* (2008). Stand dominant height (H), volume (V, 3m$^3$ ha$^{-1}$…303 m$^3$ ha$^{-1}$), and mean annual volume growth from 1980 to 1984 (0.1 m$^3$ ha$^{-1}$…11.7 m$^3$ ha$^{-1}$) were measured, and ditch depth (32cm…108cm), ditch spacing (23m… 111m), peat bulk density (53 kg m$^{-3}$…192 kg m$^{-3}$) and peat type of topmost 20 cm peat layer were determined. DWTwas monitored through growing season 1984 in ground water tubes. The measured volume growth was converted to stand net uptake of N, P and K using equations from Laiho (1997). Susi simulator was parameterized with the measured stand data and peat characteristics, and run using daily weather data from November 1, 1979 until October 31, 1984. The computed median DWT for growing season 1984 was compared to field measurements; and the computed nutrient release was related to stand net uptake of N, P and K (Fig. 1).

Scenarios. Economic benefit and adverse environmental effects of ditch cleaning were assessed by comparing scenarios without (ditch depth 35 cm) and with ditch cleaning (ditch depth 90 cm) in different regions (southern and northern Finland) for rainy and dry years, for different initial stand volume (40, 90, 150 m$^3$ ha$^{-1}$), and for different peat types occurring in high and medium fertility sites (bulk density 145, 100 kg m$^{-3}$). Ditch cleaning cost was 205.5 € ha$^{-1}$, stumpage price timber was 55.5 € m$^{-3}$ and 16 € m$^{-3}$ for pulp wood.

## RESULTS

Simulated DWT showed a reasonable fit to the measured DTW in the field, taking into account the limited parameterization data available (Fig.1). Comparison of the net uptake of N, P and K to the simulated nutrient release clearly shows that K was the growth limiting nutrient in the field sites (Fig.1). If the decomposition releases 100 g K ha$^{-1}$ yr$^{-1}$ more, it will be followed by 76 g increase in K assimilation, which can support extra growth of 0.2 m$^3$ ha$^{-1}$ yr$^{-1}$ at 50 m$^3$ha$^{-1}$ stand.

The simulation set highlights that the drainage growth response is a result of complicated interactions between weather conditions, stand dimensions and stand development phase, peat characteristics and the drain depth before and after ditch cleaning; and that the economic feasibility mainly depends on the allocation of the gained extra growth into timber and pulpwood assortments. In the simulated ditch cleaning scenarios, the growth response ranged from 2.2 to 15 m$^3$ ha$^{-1}$ in 20 yrs. The highest growth response occurred in rainy years and in northern Finland; the response was better in the high than medium fertility sites. Absolute value of heterotrophic $CO_2$ efflux was higher in south, whereas the increase in the $CO_2$ efflux due to ditch cleaning was greater in north. The export of suspended solids was higher in the north. The economic feasibility of ditch cleaning was better in north.

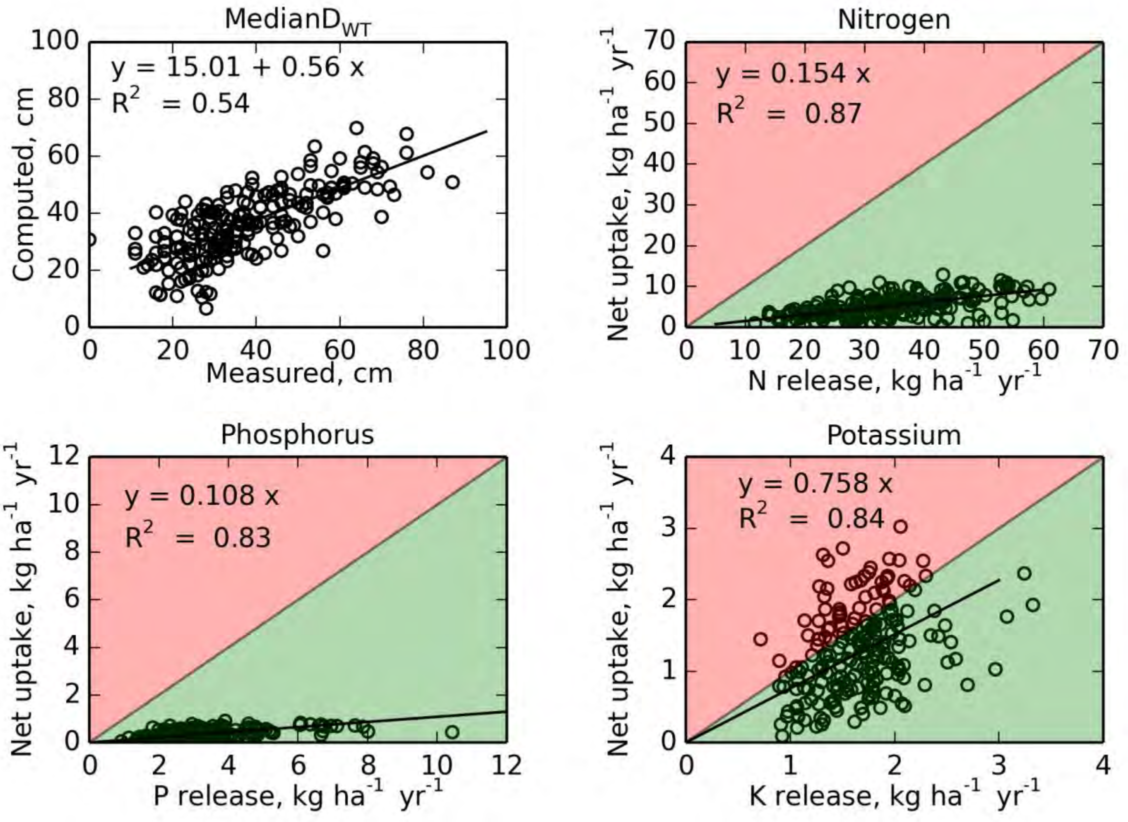

Figure 1: Field data and Susi simulator results. Measured and modelled median depth to water table; and the simulated release of nitrogen, phosphorus and potassium against the stand net uptake derived from the observed stand growth and nutrient accumulation equations (Laiho 1997).

## DISCUSSION

Susi peatland simulator is based on extensive theoretical framework and describes the chain of dependencies from the drainage control, via soil biogeochemistry to forest growth, and finally to economy. It allows evaluating the drainage as an investment with distinctive costs and returns; and a simultaneous evaluation of benefit and adverse environmental effects of the drainage. It allows approaching drainage as a multi-target optimization task. The most relevant uncertainties in the in the simulation are connected to parameterization soil hydraulic properties and soil chemical composition. This inevitably causes deviation in the results, but accepting a slight uncertainty allows us to use parameter values reported in literature for each site type, which expands the applicability of the simulation approach.

The simulation set reproduced a general phenomenon that has been earlier shown in field experiments: the growth response was higher in the north than in south. This is due to the fact that the climate in the north is more humid and excess water tends to decrease nutrient release, and in this situation the drainage of the excess water enhances the growth. The calculated range (2…15 $m^3$ $ha^{-1}$) of the growth response corresponds to the range in the observed growth responses in field conditions (6…17 $m^3$ $ha^{-1}$, Ahtikoski *et al.*, 2008).

Susi simulator is based on process modeling, therefore it is widely applicable in boreal, temperate and tropical conditions provided that the stand growth and decomposition models are parameterized according local conditions, and the model is run using local weather data. The simulator and its holistic approach have been successfully implemented in both tropical pulpwood plantations in Sumatra.

## CONCLUSION

The study clearly shows why mathematical simulation models are necessary in the decision making concerning drainage. The occurrence of the growth response, economic feasibility and the environmental effects are a result of complicated interactions between weather, vegetation, soil biogeochemistry, drain depth and spacing, and economics. Due to this complicity, widely applicable general guidelines for drainage are of limited use only, and instead of static guidelines we should pursue towards computerized planning and decision support systems. These systems apply the existing stand, soil, weather and GIS data, and mathematical models that process the data into quantitative estimates of benefits and adverse effects of the drainage, silviculture and other management.

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