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NUCOM: a dynamic vegetation model for peatlands and tundra including nitrogen cycling and mosses

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Introduction

In this paper we will describe the ecosystem model NUCOM, which stands for NUtrient cycling and COmpetition Model. NUCOM has been developed for the analysis of long-term effects of environmental and climatic changes on vegetation composition in several natural ecosystems (van Oene et al. 1999, Heijmans et al. 2008). It is a process-based model, which describes vegetation, carbon and nitrogen dynamics over decades to centuries.

Although the model was first developed for boreal peatlands (NUCOM-BOG), it might be interesting as well for tundra and taiga ecosystems. The model is unique in that it describes long-term changes in vegetation composition, such as the possible shift from moss- to shrub-dominated vegetation due to climate warming, and consequences for the carbon balance. Unlike most other dynamic vegetation models it includes nitrogen cycling and plant functional types such as mosses, graminoids and dwarf shrubs. Our research plan is to develop a tundra application of this model.

Future climatic change will undoubtedly affect northern ecosystems such as peat bogs, taiga and tundra. Field experiments have been conducted to study the response of bog and tundra plant communities to climatic changes. In these experiments temperature (Chapin et al. 1995, Weltzin et al. 2000; Gunnarsson et al. 2004, Walker et al. 2006), atmospheric CO_2 (Berendse et al. 2001, Heijmans et al. 2001) and water level (Weltzin et al. 2000, Breeuwer et al. 2008) have been manipulated during three to nine growing seasons. All these studies showed that the main response was a shift in the relative abundance of plant species. However, it takes longer before changes in the vegetation composition are reflected in the chemical composition of the organic soil, which strongly influences nitrogen mineralization, decomposition rates and therefore carbon accumulation rates.

Models are therefore necessary to analyse the long-term effects of climate change on ecosystems. However, many of the models describing the response of ecosystems to climate change do not take species composition into account. For peat bogs it is clear that long-term carbon sequestration will increase whenever *Sphagnum* mosses expand at the expense of vascular plants and vice versa, because *Sphagnum* is decomposed much more slowly than vascular plant material. Such vegetation changes not only affect carbon cycling, but also exchanges of heat and moisture (Chapin et al. 2005). Therefore, models that include vegetation dynamics and feedbacks between vegetation and soil are required to predict long-term carbon sequestration rates in northern ecosystems. In this paper we will describe the NUCOM-BOG model and some of its results, followed by how we intend to use this model in our study of vegetation – permafrost interactions in Siberian tundra.

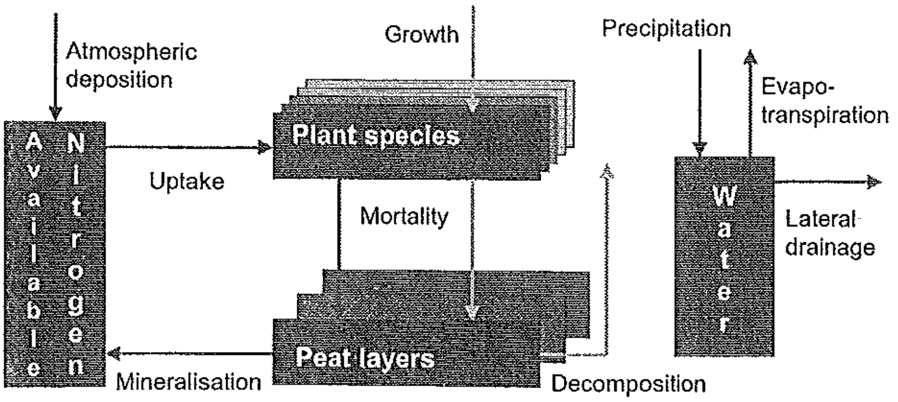

Fig. 1. Main pools and flows of nitrogen, carbon and water in NUCOM-BOG. Five groups of plant species compete for light and water.

NUCOM-BOG

Model description

NUCOM-BOG describes the vegetation, carbon, nitrogen and water dynamics of undisturbed open bog ecosystems in temperate to boreal climate. Five groups of plant species are included in the model: two groups of vascular plant species, dwarf shrubs and graminoids, and three groups of moss species, hummock, lawn and hollow *Sphagnum*. These species groups compete with each other for light and nitrogen.

The model contains general equations for ecosystem processes such as plant growth, decomposition, nitrogen mineralization and evapotranspiration (Fig. 1). Values for parameters such as potential growth rate, nitrogen requirement and relative decomposition rate are species specific so that species effects on soil processes such as nitrogen mineralization are included. To run the model, annual data on atmospheric CO_2 and N deposition, and monthly data on mean air temperature, precipitation and reference evapotranspiration are required as input.

Model evaluation

The model was tested by comparing the outcome with vegetation and carbon dynamics of the past 250 years, reconstructed from peat cores. Peat cores were collected at Lille Vildmose, Denmark and Walton Moss, England, two intact ombrotrophic mires (Mauquoy et al. 2002). For each 1 cm thick layer the species composition of the macrofossils was determined and expressed as volume percentages. Many layers were precisely dated using ^{14}C wiggle-match dating. In addition, bulk densities and carbon and nitrogen concentrations were determined. We used monthly climate data back to AD 1766 from the Global Historical Climatology Network and from the Hadley Centre for Climate Prediction and Research as input to the model.

The main changes in the species composition since 1766, such as a shift from hollow to lawn *Sphagnum* species and fluctuations in dwarf shrub abundance in the English peat core, were simulated by the model (Fig. 2) and carbon accumulation was in good agreement with observations in the peat cores (Heijmans et al. 2008).

Model analysis

The next step was to simulate the effects of future climate change on the species composition and carbon storage in peat bogs. Climate input came from the Hadley Centre climate models. Simulations for a future warmer, and slightly wetter climate with doubling CO_2 concentrations suggest that little will change in species composition due to the contrasting effects of increasing temperatures, favouring vascular plants, and CO_2, favouring *Sphagnum* (Heijmans et al. 2008).

Further analysis of the effects of temperature showed that simulated carbon sequestration is negatively related to vascular plant expansion (Heijmans et al. 2008). Model results suggest that increasing temperatures may still increase carbon accumulation at cool, low N deposition sites, but decrease carbon accumulation at high N deposition sites (Heijmans et al. 2008). Changes in *Sphagnum* species composition have also the potential to affect carbon accumulation. Bog vegetation dominated by hummock *Sphagnum* would sequester most carbon in the more continental Danish site, which contrasts with the oceanic English site were hollow *Sphagnum* vegetation would sequester most carbon (Fig. 3).

Our results demonstrate that when analyzing long-term effects of climate change, vegetation changes should be taken into account and predictions should not be based on temperature increase alone.

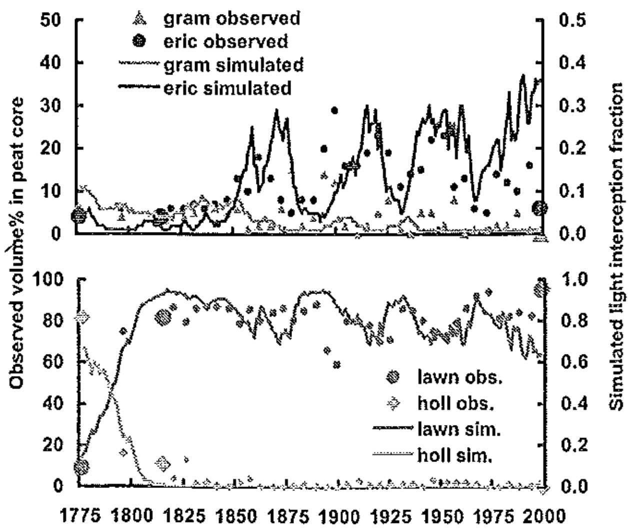

Fig. 2 simulated and observed historic species composition for peat core WLM19 (Walton Moss, UK). Large symbols represent ^{14}C-dated 1-cm peat layers; the small symbols represent the layers inbetween of which the age is estimated by interpolation. gram = graminoids, eric = dwarf shrubs, lawn = lawn *Sphagnum*, holl = hollow *Sphagnum*.

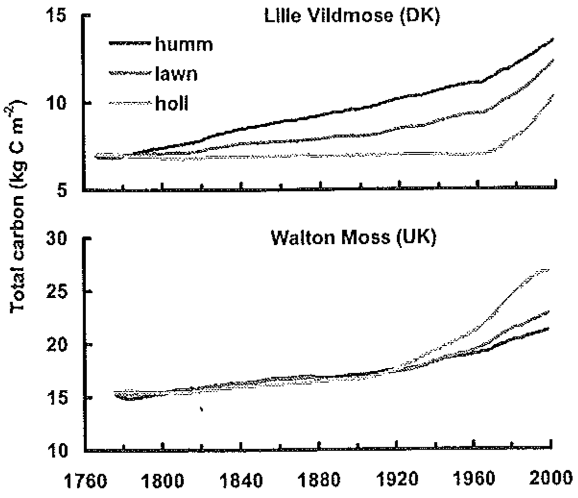

Fig. 3 Simulated carbon accumulation in bog vegetation with prescribed differences in dominant *Sphagnum* species group.

New research: vegetation–permafrost feedback

Background

Climate warming, as predicted for the 21st century, is likely to initiate widespread permafrost thawing. This is of global concern because when permafrost thaws, organic matter in soil that was previously frozen, will be decomposed, resulting in the emission of large amounts of carbon dioxide and methane, important greenhouse gases, into the atmosphere. The question we would like to answer with our new research is: Will changes in vegetation halt or speed up permafrost thawing?

Trends in temperature of permafrost at 20 m depth, measured at 5 locations in north-Alaska show that temperature in permafrost is rising, but this permafrost temperature rise levels off in recent years (Romanovsky et al. 2007). It is well possible that changes in vegetation are responsible for this pattern. Several studies suggest that tundra plants became more productive due to the climatic changes of the past decades, resulting in denser vegetation. A hypothesis is that denser vegetation will reduce the rate of permafrost thawing because in denser vegetation less solar radiation will reach the ground. This may explain the observed levelling off in Alaskan permafrost temperatures. An alternative hypothesis is that in the long term the enlargement and expansion of shrubs, which is widely occurring in Alaska, will eliminate the moss layer. As mosses are well known for their insulating effect, the loss of mosses would than increase the rate of permafrost thawing.

Although mosses are known for contributing to stable permafrost conditions, they are currently not included in dynamic global vegetation models used with climate models to predict the climate change effects on Arctic ecosystems. In these models, climate warming causes tundra vegetation to be replaced by boreal forest. However, conversion of tundra into forest is unlikely to be extensive in the current century. In the meantime changes within the tundra biome take place, which have consequences for atmospheric heating and permafrost thawing. Therefore, the rate of change in tundra ecosystems can only be assessed when vegetation – permafrost interactions are taken into account and when mosses, shrubs and grasses are included in dynamic vegetation models.

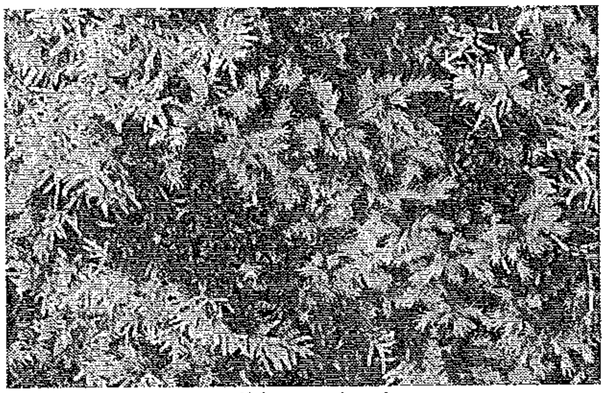

Fig. 4. Mosses are well known insulators.

Research plan

The aim of our new research is to quantify the effects of mosses, shrubs and grasses on permafrost thawing and soil nutrient availability, and analyze how that further affects species composition and the carbon balance (Fig. 5). For example, if shrub vegetation would eliminate the insulating mosses this would speed up permafrost thawing which would make soil nutrients available that were earlier safely stored in permafrost from which the more productive shrubs would benefit, so accelerating changes in vegetation and so on: in other words a positive feedback loop. All three components, vegetation composition, permafrost thawing and soil nutrient availability affect the carbon balance in tundra ecosystems.

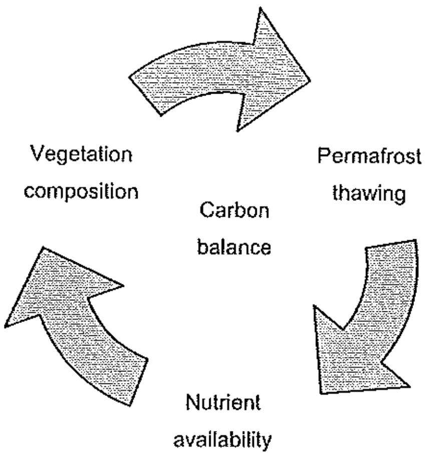

Fig. 5. Vegetation – permafrost feedback loop. See text for explanation.

The approach of our new research is a combination of field experiments and ecosystem modelling at a Siberian tundra site. Field experiments are essential to understand mechanisms of change. In the experiments, species composition of the vegetation is manipulated so that the direct effects of mosses, shrubs and grasses on soil processes can be determined, without confounding changes in soil properties and hydrology as is the case in observational studies. For the removal experiment we started last summer at the Kytalyk site near Chokurdah, first 10 plots of similar species composition were selected, than in 5 of these plots the shrubs have been removed. By comparing heat fluxes, thawing depth, nutrient availability in the plots where shrubs are removed with plots with undisturbed moss-shrub-grass vegetation, the direct effects of changes in vegetation can be quantified.

While the field experiments address the relatively short-term effects of changes in vegetation, ecosystem modelling is necessary to assess the long-term effects, by taking the vegetation – permafrost feedback loop into account. I will use NUCOM, which unlike other ecosystem models includes dynamic vegetation in terms of mosses, shrubs and grasses. In addition, NUCOM includes carbon-nitrogen-water interactions. The currently used vegetation models do not include nitrogen, while it is the most important driver of changes in tundra vegetation. The plan is to adjust NUCOM for tundra vegetation and to incorporate a permafrost module. This enables analysis of the rate of change in tundra vegetation structure and composition and its effects on permafrost thawing and carbon exchange, which will contribute to realistic predictions of the future of the Arctic's permafrost and its frighteningly large carbon stores.

To conclude, the proposed research is unique in that it combines field experiments with ecosystem modelling and that mosses, which are known for their cooling effects, are included. To predict the long-term tundra ecosystem response to climate warming requires a dynamic vegetation model, including mosses, nitrogen cycling and permafrost.

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