Modeling Impacts Of Forest Management Practices On Water And Nitrogen Fluxes Within A First-Order Catchment

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EXTENDED ABSTRACT

Forest management practices such as clear-cutting, site preparation, ditching, and ditch network maintenance increase nitrogen (N) load to streams. In environmentally sustainable forestry, water protection actions are required to decrease the nutrient loading. These include e.g. use of uncut buffer zones between a clear-cut area and a waterbody, sedimentation ponds in the ditch network and overland flow fields. In practical forestry, there is an increasing need for developing design criteria for effective protective actions. Clearly, the efficiency of a protective construction depends on a complex interaction between the catchment, the treatment area, atmosphere, vegetation, microbes and soil.

We constructed a modeling tool (KUNTO) by integrating hydrological, ecological and water quality models. KUNTO describes a forested first-order catchment as a two-dimensional simplification (Fig. 1). The area of the first-order catchments may vary from tens of hectares to a few square kilometers. Boreal forested catchments usually contain upland mineral soil areas and peatland areas. Peatland areas can be ditched to enhance forest growth.

The development of KUNTO aims at combining computation schemes that describe the most important processes controlling the N export from a catchment. The models associated with KUNTO describe hydrological processes above the soil surface and along the hillslope. Net primary production and litter input to soil are described for trees and ground vegetation. Decomposition of organic matter on upland mineral soil and on peatsoil are assessed with separate submodels. Nitrification, denitrification, N uptake and transport with surface and ground waters, retention of N in soils, immobilisation of N into litter and logging residues are also calculated. Water and N input from different parts of the catchment are fed into an outlet stream or ditch network, where erosion, transport of suspended solids and sedimentation are calculated. With KUNTO we can assess the impacts of cutting, site preparation, ditching and ditch network maintenance on N export to water bodies and on catchment N fluxes. Furthermore, we can assess efficiency of buffer zones and sedimentation ponds.

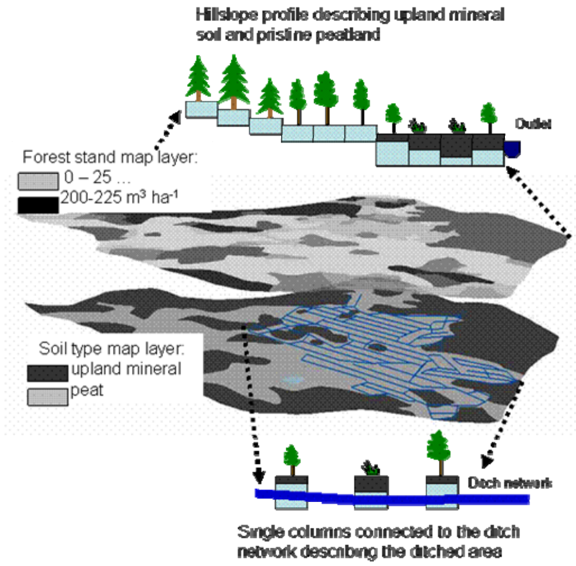

Figure 1. In KUNTO, the catchment is described as a two dimensional simplification: Upland mineral soil and pristine peatland areas form a hillslope extending from catchment border to the outlet. Ditched peatland areas are represented as single columns connected to the ditch network.

1. INTRODUCTION

Nitrogen (N) cycling in pristine boreal forested catchments is tight, with only minor leaching losses (Tamm, 1991). Forest management practices such as clear-cutting, site preparation, ditching and ditch network maintenance may disturb the N cycle and lead to an increase of N export to streams (Ahtiainen and Huttunen, 1999). In addition to dissolved N load, ditching and ditch network maintenance increase the transport of suspended solids (Joensuu et al., 1999) containing organically bound N. In environmentally sustainable forestry, water protection actions are required to decrease the nutrient loading to water bodies. These include e.g. use of uncut buffer zones between clear-cut areas and a water bodies, sedimentation ponds in the ditch network and overland flow fields. In practical forestry, there is an increasing need for developing design criteria for effective protective actions. One approach for this is to develop and apply process models describing the input, output, storage and transport processes of nutrients within a forested catchment.

The major fractions of dissolved N present in soil solution are ammonium (NH_4), nitrate (NO_3) and dissolved organic N (DON). Atmospheric deposition and organic matter decomposition are the principal inputs of dissolved N into soil solution. The main outputs from the dissolved N pool are tree and ground vegetation N uptake, immobilization into microbial biomass, N_2, N_2O and NO release through denitrification and nitrification. The dissolved N fractions can be transported with ground water, soil water and with surface runoff. The transport of NH_4 and DON is reduced by sorption in soil. Once reached the outlet stream or the ditch network, the dissolved forms of N and particulate organic N (PON) are again subject to several biogeochemical processes. Dissolved inorganic nitrogen can be immobilised by autotrophic and heterotrophic uptake and returned to inorganic form by mineralisation. Nitrification and denitrification in the water body, erosion and sedimentation of solid particles also play an important role in the N mass balance of an entire forested catchment.

Catchments in the boreal zone usually contain upland and peatland parts, with characteristic biogeochemical processes. Ground vegetation species in pristine peatland sites are different from upland sites and usually the tree growth is inferior to that on mineral soil. Anaerobic conditions caused by excessive water supply in peatland sites slow the decomposition of organic residues and causes the accumulation of peat. Conditions in peatland also favor denitrification and other gaseous losses of N. Ditching of forested peatlands enhance remarkably the forest growth. To keep up the beneficial effect on the growth, maintenance operations of ditch network are required usually 20-30 years after the ditching.

We constructed a modeling tool (KUNTO) by integrating hydrological, ecological and water quality models. KUNTO describes a forested first-order catchment as a set of two-dimensional hillslopes or single soil columns connected to stream or the ditch network. The most important processes controlling the N export from a catchment are accounted for. With KUNTO we can assess the impacts of cutting, site preparation, ditching and ditch network maintenance on N export to water bodies and on catchment N fluxes. Furthermore, we can assess efficiency of buffer zones and sedimentation ponds. The aim of this paper is to present the structure and application prospects of the KUNTO-model.

2. KUNTO-MODEL

2.1. Overall structure

KUNTO describes forested, first-order catchments in a semi-distributed way. Upland mineral soil and pristine peatland areas in the catchment are described as a hillslope representing a typical flowpath of water. Water and N processes are calculated along the hillslope. Ditched peatland areas are described as small profiles or single columns connected to the ditch network.

In KUNTO (Fig. 1), the annual forest stand development is calculated with MOTTI simulator (Hynynen et al. 2002) and the ground vegetation succession is estimated as a function of tree stand age, species and stand volume. These models provide input parameters for vegetation net primary production model functioning on hourly time-step (Frolking et al., 2002) and calculating net primary production dynamics for trees, shrubs, sedges, herbs and moss. The above-ground hydrology model (Koivusalo et al., 2001) accounts for snow accumulation and melt and water input to soil. Two dimensional hillslope hydrological model (Karvonen *et al.*, 1999) simulates the water fluxes and storages along the hillslope. For each column along the hillslope, there is an organic matter decomposition and N release model. For upland mineral soil, the decomposition is calculated using ROMULN –model (basic model in Chertov et al., 2001, modification in Laurén et al., 2005). In peat soil areas, the decomposition routine of wetland DNDC –model (Zhang et al., 2002) is applied. The N (in forms of NH_4, NO_3 and DON) uptake, transport with surface and ground waters and retention by soil are calculated with FemmaN –model (Laurén et al., 2005), which also includes descriptions for nitrification, denitrification and gaseous N_2O losses.

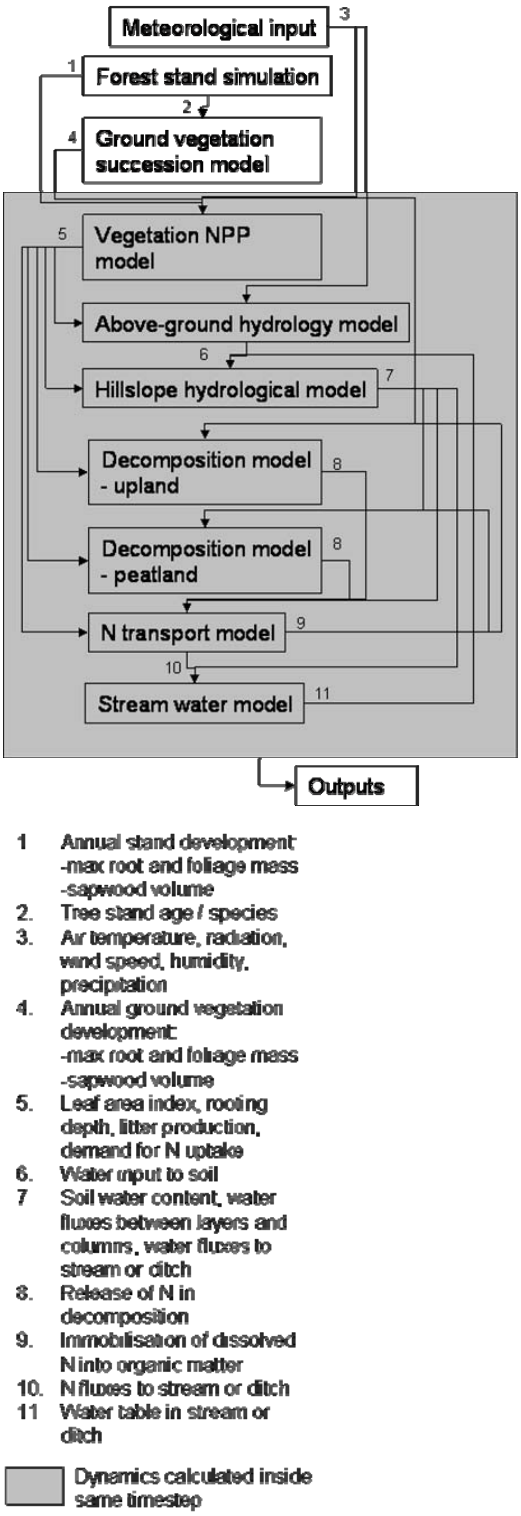

Figure 1. Overall structure of the KUNTO model and the variables transferred between the submodels.

Water and N are transported from mineral and organic soil areas into stream or ditch network, where erosion, sedimentation, and N processes are accounted for.

The water, sediment and N processes are calculated for the stream and the ditch network inside the studied catchment until the catchment outlet.

2.2. Catchment description

For KUNTO, the most relevant catchment characteristics (e.g. tree stand properties, site type, soil type and topography) are defined using GIS – analyses. The catchment area is subdivided into compartments according to stand volume separately for upland mineral soils and peatsoils. For each compartment, the development of the tree stand and the ground vegetation succession are simulated in annual time step using procedures described later.

Different spatial analyses are used for describing the topography and soil properties of ditched and the unditched parts of the catchment (Fig. 2). Areas without ditching, i.e. upland mineral soils and pristine peatlands, are described as hillslopes extending from the catchment border to the outlet stream or to the ditch network (Kokkonen et al. 2005; Laurén et al., 2005). The two-dimensional description of the catchment is based on the analysis of typical flowpaths of water inside the catchment. The raster-based digital elevation model (DEM) is used to calculate a flowpath of water from each catchment pixel to the outlet stream. The elevation differences between the catchment pixel and its receiving stream pixel are computed and categorised according to distance from the stream along the flowpath. Average values of the elevation differences at a given distance from the stream are used to describe the surface elevation of the hillslope. The soil depth is determined similarly, whereas the soil type in a certain part of the hillslope is gained as a mode class for the soil types at that part. The hillslope is divided into vertical columns and horizontal layers. This is the basic set-up of the hillslope hydrological model described later.

In the ditched areas the average flowpath of water to the ditch network is rather short, when the ditch spacing varies between 30 m and 50 m. Therefore these areas are described as short hillslopes or single columns that are connected to the ditch network. Using the GIS-based raster analysis, the mean depth of peat layer for the compartment is calculated. The mode class for the peat and underlying mineral soil type and site type are chosen to describe the soil part of the compartment. The relative share of each compartment from the catchmet area is calculated.

The location of the ditch network is obtained from existing maps. The longitudinal profiles of the ditch network, the depth of the peat layer and thickness of the mineral soil layers are taken from the respective GIS-data. The cross-sectional data of the ditches has to be defined manually separately for the drainage ditches, the collector drains and the main streams.

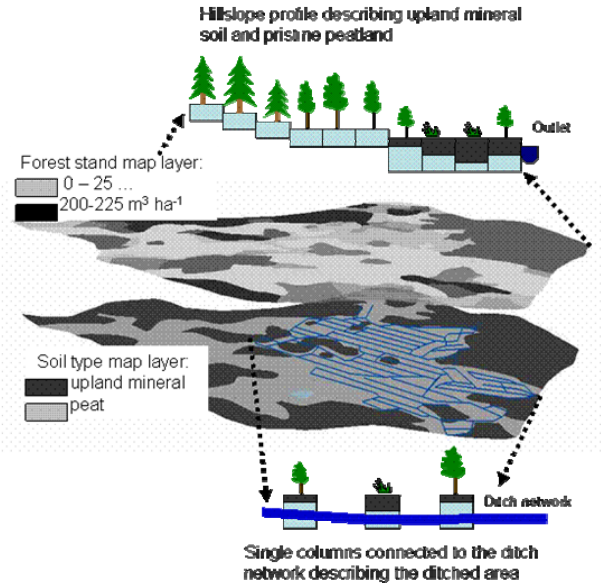

Figure 2. In KUNTO, the catchment is described as a two dimensional simplification: Upland mineral soil and pristine peatland areas form a hillslope extending from catchment border to the outlet. Ditched peatland areas are represented as single columns connected to the ditch network.

2.3. Forest stand growth

Annual forest stand development is calculated using MOTTI-model, based on empirical data from the Finnish National Forest Inventory (Hynynen et al., 2002). It accounts for stand regeneration and ingrowth, growth and mortality and their respond on forest management practices, such as thinning, ditching and ditch network maintenance. Separate equations are used for upland mineral soil and peatland stands. As an input, MOTTI requires location of the stand, tree diameter distribution, species composition and site fertility class, all of which can be acquired from standard forest management plans. MOTTI produces the tree stand annual maximum and minimum leaf mass, tree stand sapwood volume and the relation of above to below ground biomass for the Vegetation net primary production model. Stand age, volume and the dominant tree species are transferred for the ground vegetation succession model. MOTTI also provides the annual tree stand litter production for the decomposition submodels.

2.4. Ground vegetation succession

For upland sites, the annual biomass for lichen, bryophytes, herbs and grasses and dwarf shrubs are estimated from the tree stand age and the main tree species using empirical model presented by Peltoniemi et al. (2004) (1).

$$B\ (kg\ ha^{-1}) = a + bt + ct^2 + dt^3 \qquad (1)$$

where B is the above ground biomass of understorey species group, t is the stand age in years and a…d are parameters. Parameter values are presented in Peltoniemi et al. (2004). According to the model, the above ground biomass of the ground vegetation for a Scots pine (*Pinus sylvestris* L.) stand increases from 1900 kg ha^{-1} to 3200 kg ha^{-1} when the age of the stand increases from 0 to 200 years. The below ground biomass for herbs, grasses and dwarf shrubs can be estimated to be twice the above ground biomass. For peatland sites, the above ground biomass for the field and ground layer vegetation are estimated from the volume of the forest stand according to empirical functions presented by Reinikainen et al. (1984). The total ground vegetation biomass (field layer + ground layer) decreases logarithmically from 3000 kg ha^{-1} to 1300 kg ha^{-1} when the stand volume increases from 0 to 150 m^3 ha^{-1}. The below ground biomass and turnover rates are gained similarly to the upland sites. The ground vegetation succession models produce annual maxima and minima for the leaf mass and the relation of above to below ground biomass, which are used as input parameters for the Vegetation net primary production submodel.

2.5. Vegetation net primary production

Vegetation net primary production model adopted from Frolking et al., (2002) calculates photosynthesis, respiration, phenology, dormancy and carbon allocation for the tree stand and ground vegetation. Photosynthesis and respiration are calculated in hourly or smaller time step and the others in daily time step. The vegetation is described in five classes: trees, shrubs, sedges, herbs and moss. Each class forms a canopy stratum, uppermost being the tree-layer and the lowermost the moss-layer. Each layer can intercept a part from the incoming photosynthetically active radiation (PAR) according to their leaf area index (LAI). The gross photosynthesis is calculated from the maximum phosynthetic rate adjusted with temperature, water availability and PAR functions. The water content and the depth of the ground water table are received from the hillsope hydrological model described later. For upland mineral soils the water availability is adjusted with linearly decreasing function from field capacity to wilting point moisture (Nijssen et al., 1997). Respiration is calculated separately for foliage, roots and sapwood. The current plant net primary production is gained by subtracting the respiration from the gross photosynthesis. Phenology, i.e. the discharge of the winter dormancy and the leaf development for vascular plants, is estimated according to annually cumulating temperature sum. The leaf drop and start of the winter dormancy are calculated from cumulative frost sum. The litter production is distributed over a longer period of time according to frost sum at the start and the end of littering period.

The net primary production is later used to construct the plant N demand. The current leaf area index is assessed according to leaf biomass and transferred to the Above-ground hydrology submodel. The produced litter is sent to the organic matter decomposition submodels.

2.6. Above-ground hydrology

Above-ground hydrology routine simulates solar radiation, long-wave radiation and wind speed beneath the tree canopy and throughfall amount from meteorological variables characterizing conditions above the canopy (Koivusalo and Kokkonen, 2002). Relative humidity and air temperature are assumed not to be affected by the canopy. The snow routine is based on the energy balance approach and it describes the snow accumulation and melt (Koivusalo et al., 2001). The submodel also calculates the temperature of soil. Canopy and snow routine is run at an hourly or smaller time step. This submodel provides the water input to soil for the hillslope hydrology model and soil temperature for decomposition and N transport models.

2.7. Hillslope hydrology

Soil water movement and runoff generation along the hillslope are simulated with the characteristic profile model, CPM (Karvonen et al., 1999). Infiltration into a soil column is controlled by the available air-filled pore volume in the column. Water that does not infiltrate is transported downslope as surface runoff until it is discharged to a stream or ditch. After the vertical fluxes and the resulting groundwater levels have been resolved, the lateral groundwater flows between vertical soil columns are computed according to Darcy’s law. Groundwater flow from the column next to the stream constitutes the baseflow component. When groundwater level in any column rises above the soil surface, water flows downslope as exfiltration. The water flow into the ditch network is calculated using Hooghhoudt’s formula (Skaggs 1980). The drain flow out of a soil column is proportional to the difference between the computed elevation of water table and the bottom elevation of the ditch. The hillslope hydrology model provides input for the organic matter decomposition models, Vegetation net primary production model, N transport model and Steam water model. The inputs include the current soil moisture, water fluxes between columns and layers and water fluxes to stream and ditch network.

2.8. Decomposition of organic matter and N release in upland areas

Organic matter decomposition in each upland mineral soil column is simulated using ROMULN – model (Laurén et al., 2005). The decomposition of organic matter is simulated in three different stages of decomposition: fresh litter material (L), complex humic substances with undecomposed organic debris (F) and humus material (H). Calculation is carried out separately for different litter fractions e.g. foliage, branches and roots. ROMULN allows microbial immobilization of N from the soil solution into litter (L) and partly decomposed (F) organic matter. The immobilization continues until a critical concentration of N is reached in a certain litter fraction after which the immobilization is ceased. The N released in the decomposition and the demand for N in microbial immobilization is transferred to the N transport submodel.

2.9. Decomposition of organic matter and N release in peatland areas

For calculating the decay of plant residues and peat, we included the decomposition submodel of wetland DNDC (Zhang et al., 2002) into KUNTO. The decomposition follows a sequence of pools for residues, microbes, humads and stabile humus. These pools (excluding stabile humus) are further divided into labile and resistant pools. Each pool has a constant carbon (C) - N ratio and specific decomposition rates. The amount of soluble N released to the soil solution corresponds to the release of CO_2 from each organic matter pool. Furthermore, soluble N is released when organic matter is transferred from a pool with lower C/N to a pool with higher C/N. Correspondingly, if the transfer is towards lower C/N, N is immobilized from the soil solution. The decomposition in saturated soil is restricted by redox potential. The N released in the decomposition and the demand for N in microbial immobilization is transferred to the N transport submodel.

2.10. N transport in terrestrial system

The transport of different N fractions down the hillslope or directly from a drained organic soil column to the ditch network is calculated with solute transport model, FemmaN (Laurén et al., 2005). The modelled N fractions are NH_4-N, NO_3-N and DON. The atmospheric deposition of N is distributed into all N fractions, whereas decomposition is assumed to produce NH_4–N and DON fractions only. The demand for N uptake of the vegetation is calculated according to the net primary production and nutrient use efficiency parameters. The horizontal and vertical transport of N through the soil (and from soil to stream or ditch) is calculated from the water fluxes between the layers and concentrations in the layer (Jansson and Karlberg, 2001). Retention of N fractions is computed with layer-specific adsorption coefficients. Nitrification and denitrification fluxes are calculated as a function of soil NH_4-N and NO_3-N concentrations, temperature and moisture for each soil layer (Jansson and Karlberg, 2001). Depending on soil pH, a share of N is released as N_2O in nitrification (Laurén et al., 2005). The N transport submodel provides the immobilizing N for the decomposition submodels and N transported from the terrestrial part of the catchment to the stream and ditch network.

2.11. Water, N and sediments in stream or ditch network

The stream and ditch sub-models calculate water elevation, flow depth and flow velocity in the whole ditch network by solving the full Saint Venant equations using finite difference method. The stream nitrogen submodel simulates the transport of various N forms in ditch network (Thouvenot and Karvonen, 2004). The variables modelled are NH_4-N, NO_3-N, DON and dissolved total N. In the model, two compartments are defined (water and sediments). The inorganic nitrogen may be reduced due to denitrification, sedimentation and biological uptake, while organic nitrogen may increase due to biological production or decrease by sedimentation and mineralisation.

The sediment sub-models calculates erosion and deposition of both non-cohesive and cohesive soils (Graf and Alinakar, 1998; Malve *et al*., 2003). In non-cohesive soils both bed load and suspended load are calculated. The most important parameters of the sediment sub-models are grain size distribution and critical shear stress for erosion and deposition.

3. APPLICATION PROSPECTS

In the Water Framework Directive, the European Union has committed into improving the status of all waters by 2015. Improving or maintaining a good status requires controlling the nutrient loads from every source, including forest ecosystems. Simultaneously Finland is aiming at intensifying timber harvesting and management of forests. Peatland ditching and ditch network maintenance are considered to be the most harmful forest management practices for the waters. In this context, KUNTO is responding to an increasing need of tools for estimating the nutrient exports from managed forested areas and for assessing the impacts of water protection actions on it. With KUNTO we can assess the impacts of cutting, site preparation, ditching and ditch network maintenance on N export to water bodies and on catchment N fluxes. Furthermore, we can assess efficiency of buffer zones and sedimentation ponds.

For the set up of a KUNTO application, most of the required data are available in forest management plans and maps. The submodels in KUNTO are reported with parameter values in literature, thus reducing the number of parameters to calibrate. In development and application of process oriented models for predicting N export from the catchment, we must invest great deal of effort in understanding the processes contributing to the N export. For example, sensitivity of the modelled N leaching to errors in estimating the dominant N fluxes, such as rates of decomposition and plant uptake, may easily lead the modeler to false conclusions. At the present level of knowledge we still have to calibrate the models prior to use and such calibration data exist only for experimental sites.

Using modeling approach together with experimental studies provides us a way to combine data and understanding concerning e.g. soil physical, biological, hydrological, vegetation and stream/ditch processes under the same task of explaining the solute transport from the catchment to the stream. We can detect the important processes in N export and identify critical combinations of forest management options, site type, soil type, catchment dimensions and climatic conditions where the risk of load formation is high.

This information can be applied in the practical forest management.

4. ACKNOWLEDGMENTS

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