Simulation of Water and Carbon Fluxes in Agro- and forest Ecosystems at the Regional Scale

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Abstract: To investigate effects of different land use management practices on carbon fluxes at the regional scale we developed an integrated model by coupling an ecohydrological river basin model SWIM (Soil and Water Integrated Model) and a soil organic matter model SCN (Soil-Carbon-Nitrogen model). The latter is a submodel of the forest growth model 4C. The extended integrated model combines hydrological processes, crop and vegetation growth, carbon, nitrogen, phosphorus cycles and soil organic matter turnover. It is based on a three level spatial disaggregation scheme (basin, subbasin and hydrotopes), whereas a hydrotope is a set of elementary units in the subbasin with a uniform land use and soil type. The direct connection to land use, soil and climate data provides a possibility to use the model for analyses of climate change and land use change impacts on hydrology and soil organic matter turnover. Aim of this study is to test the model performance and its capability to simulate carbon pools and fluxes in right magnitude and temporal behaviour at the regional scale. As a first step, the model was parameterised and validated for conditions in East Germany, incorporating values known from literature and regionally available times series of carbon pools and fluxes. This provides verification of carbon pools and fluxes in the landscape and verifies the correct representation of the environmental processes therein. Based on this, different land management strategies (e.g. soil cultivation techniques, crop residue returns) and land use change options (e.g. conversion of agricultural areas to forest or to set-aside areas) can be simulated to assess the behaviour of water and carbon fluxes as well as carbon sequestration options.

Keywords: Ecohydrological modelling, soil carbon, soil nitrogen, soil organic matter turnover, global change

1. INTRODUCTION

The major anthropogenic input of CO_2 to the atmosphere is attributed to fossil fuel combustion, cement manufacturing and land use change. The latter involves deforestation, biomass burning, draining of wetlands, plowing, use of fertilisers and manure and other agricultural practices. This source is estimated to be a large global carbon flux of 1 - 2 * 10^{15} g C yr^{-1} [Houghton, 1996]. Land management practises (e.g. cultivation, land conversion) are seen to influence the rate and magnitude of this CO_2 flux.

To take these effects into considerations it is necessary to develop integrated ecological models which cover the main processes ruling the turnover of organic matter in the environment and hence the release of CO_2. Hereby soil processes of organic matter turnover play an important role.

The quantity of soil organic matter (SOM) is dependent on the balance between litter (dead plant biomass) production and the rate of litter and SOM decomposition. Further on the products of primary productivity are entering the soil column containing a mixture of dead plant and animal material derived substances with variable physical and chemical properties. These materials are subject to decomposition by the macro- and micro-organisms in the soil. Together with the decomposition and mineralisation of existing organic materials the heterotrophic soil respiration produces CO_2. These processes are influenced by environmental conditions like soil temperature, soil moisture and soil acidity status.

In the present work an extension of the eco-hydrological river basin model SWIM (Soil and Water Integrated Model, Krysanova et al. [1998])

by a new module for the turnover of soil organic matter and soil carbon and nitrogen dynamics (SCN- Soil-Carbon-Nitrogen model, a submodel of the forest growth model 4C, Lasch et al. [2002], Grote et al. [1999]) is presented. The advantage of this approach is a possibility to combine hydrological, soil carbon and soil nitrogen processes in both vertical and lateral dimensions for agro- and forest ecosystems in river basins.

As a prerequisite to perform land use change and land management impacts on SOM dynamics at the regional scale, detailed model verification for the main ecosystems has to be performed.

2. METHODS AND DATA

2.1. The ecohydrological model SWIM

SWIM (Soil and Water Integrated Model, Krysanova et al. [1998] is a continuous-time, spatially distributed model. SWIM works on a daily timestep and integrates hydrology, vegetation, erosion and nutrients at the river basin scale. The spatial aggregation units are subbasins, which are delineated from digital elevation data. The subbasins are further disaggregated into so called hydrotopes, hydrologically homogenous areas. The hydrotopes are defined by uniform combinations of subbasin, land use and soil type [Krysanova et al., 2000]. The model is connected to meteorological, land use, soil and agricultural management data. For detailed process descriptions, validation studies and data requirements it is referred to publications by Krysanova et al. [1998, 2000]. Following, the relevant processes for the presented work are described briefly.

2.1.1 Hydrological cycle

The hydrology module is based on the water balance equation, taking into account precipitation, evapotranspiration, percolation, surface runoff and subsurface runoff for the soil column which is subdivided into several layers. The water balance for the shallow aquifer includes ground water recharge, capillary rise to the soil profile, lateral flow, and percolation to deep aquifer [Krysanova et al., 1998].

2.1.2 Soil temperature

Soil temperature is calculated on a daily basis at the center of each soil layer. The calculation is based on an empirical relationship between daily average, minimum and maximum air temperature and a damping factor for soil depth. The effect of current weather conditions and land cover (snow, above ground biomass) are considered [Krysanova et al., 2000].

2.1.3 Vegetation growth

Vegetation growth is simulated separately for annual (crops) and perennial (forest) plant types. For crop growth a simplified EPIC approach [Williams et al., 1984] is used for simulating all crops considered (wheat, barley, corn, potatoes, alfalfa and others) using unique parameter values for each crop. The simplified EPIC approach is based on growth dynamics for annual plants. To describe perennial, and especially forest growth dynamics, a different approach was adopted recently which is described by Wattenbach et al. [2004]. The central element of the approach is the use of an allometric relation for the ratio of leaf biomass to total biomass that is given by an age dependent exponential function [Bugmann, 1994]. The forest growth then is based on a robust computation of the temporal LAI (leaf area index) dynamics [Bugmann, 1994]. Based on the forest age and forest stand density dependent LAI the biomass energy ratio is used to calculate the daily biomass increase. The model also considers phenology, age-dependent mortality and simple forest management practices.

The vegetation growth dynamics and the related dead biomass production at the end of the growing season deliver the amount of litter (dead above- and below-ground biomass) entering the litter and soil layers.

2.2 The soil Carbon and Nitrogen Model SCN

The carbon and nitrogen cycle module is based on the tight relationship between the soil and the vegetation. On the one hand an input exists into the soil by addition of organic material through accumulating litter, dead fine roots and organic fertilizer, and on the other hand there is a withdrawal from the soil of water and nitrogen by the vegetation, release of CO_2 into the atmosphere and export of inorganic nitrogen by soil water flows (e.g. percolation into the groundwater, lateral flow processes).

To describe the carbon and nitrogen budget organic matter is differentiated into Active Organic Matter (AOM) as humus pool and Primary Organic Matter (POM) as litter pool. The latter is separated into 5 fractions for each vegetation and crop type. For forest types as example, the dead plant materials are cut into stems, twigs and branches, foliage, fine roots and coarse roots. The fine and coarse roots are further distributed into the soil layers according to rooting depth and a root mass allocation. For all pools of active and primary organic matter the carbon and nitrogen content is considered.

The carbon and nitrogen turnover into different stages (pools) can be pictured as a first order reaction [Chertov and Komarov, 1997; Franko, 1990; Parton et al., 1987, Grote et al., 1999] as shown in Figure 1. The processes are controlled by matter specific reaction coefficients.

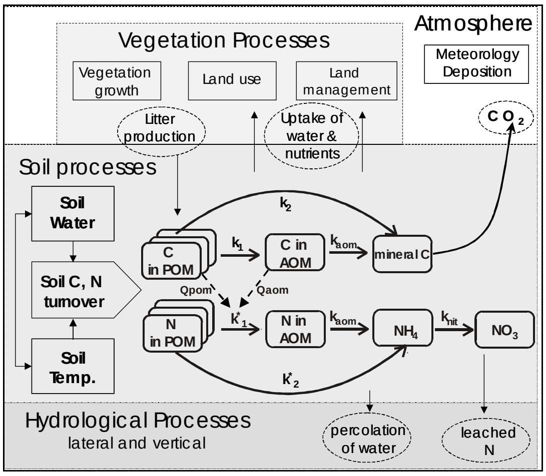

Figure 1. Illustration of main processes of the SWIM-SCN model.

The dominant process is the carbon mineralisation, which provides the energy for the whole turnover of the organic matter. Following the above concept, the basic turnover in each layer is described as a reaction of the first order. The carbon change in the primary organic matter C_{POM} is controlled by the reaction coefficient $k_{POM} = k_1+k_2$ (see Figure 1). The transformation of primary organic matter C_{POM} to active organic matter C_{AOM} is controlled by a synthesis coefficient k_{syn}, which is specific to the litter type (plant type and litter fraction) whereas $k_1 = k_{syn} \cdot k_{pom}$. The turnover of carbon in active organic matter is made up from the synthesised portion and the carbon used in the process of mineralisation.

How much nitrogen is absorbed into the active organic matter and what proportion is mineralised depends on the C/N ratio of both organic fractions and on the carbon used in the synthesis of the active organic matter. The change in nitrogen in the active organic matter takes place in a similar way to the turnover of carbon, whereas the C/N ratios of both organic fractions Q_{POM} and Q_{AOM} modify the synthesis coefficient k_{syn} to k^*_{syn} [Kartschall et al., 1990].

Heterotrophic (substrate induced) soil respiration is calculated through the decay of C_{POM} and C_{AOM} pools per day. Root respiration therefore is not considered.

In addition, changes of nitrogen in the pools of ammonia N_{NH4} and nitrate N_{NO3} are considered.
The reduction functions for mineralisation and nitrification r_{min} and r_{nit}, respectively, show the effect of soil water content and soil temperature on these processes [Franko, 1990; Kartschall et al., 1990]. The mineralisation is inhibited, if the water content decreases below half of the saturated water content. The reduction of nitrification by drought is similar to the reduction of mineralisation, despite the decrease in nitrification under conditions of a very high water content, which results from the deficiency of oxygen.

The influence of soil temperature on the mineralisation is described by van't Hoffs rule [Van't Hoff, 1884]. The temperature depending reduction function for nitrification is analogous to that for mineralisation.

2.3 Parameterisation

The model parameterisation was done under the premise to simulate soil organic matter and relevant processes for eastern German conditions with a special focus on the lowlands. Therefore related environmental studies in the region and literature were used for parameterisation. The reaction coefficients k_{pom} and k_{syn} have to be determined for each plant species (forest types, crop types) and primary organic matter fractions (fine roots, foliage, etc.). Determination of these coefficients is mainly done either by field experiments (litter bag experiments) or under laboratory conditions (incubation experiments). Main source for these parameters for the region under study are for agricultural plants investigations by Klimanek [1990 a, b] and Franko [1990]. For forest types information can be found in Bergmann [1999] and Berg & Staaf [1980].

The coefficients k_{aom} and k_{nit} are soil and land cover specific and can be found e.g. in Franko [1990] and Bergmann et al. [1999].

2.4 Verification sites description

Two field sites for verification were chosen for this presentation. For forest sites the Level II monitoring plot Kienhorst with Scots pine (*Pinus sylvestris* l.) investigated in the framework of the Pan- European Programme for intensive and continuous monitoring of forest ecosystems (Level II, http://www.fimci.nl) was used. For agricultural sites data from the experimental field for cultivation of energy crops at the Leibnitz – Institute of Agricultural Engineering Bornim ATB [Hellebrand et al., 2003] were applied. Both sites are in the state of Brandenburg (east Germany), on sandy to loamy soils and sub-continental dry climate (long term annual precipitation average of 600 mm).

3. RESULTS AND DISCUSSION

The model was verified for the main processes of soil organic matter turnover described above. For the verification sites meteorological data, soil parameterisation and management practices of the sites have been used to ensure that environmental conditions are represented.

At first simulations of soil moisture conditions and soil temperature were compared with observed data. These are the deciding environmental factors influencing decomposition of organic material and humus mineralisation accounted for by the model. For the forest site soil moisture in three soil depths and soil temperature in two soil depths were compared with simulation results for a period of 5 years (1997 – 2001). For the agricultural site only soil temperature measurements at 20 cm soil depth for a period of one year (02/1999 – 02/2000, Hellebrand et al., [2003]) were available. Both sites showed a good agreement between observation and simulation.

The vegetation growth and the formation of litter determine the input of primary organic matter. For the forest site, vegetation growth was verified for LAI development, biomass increase, total biomass and litter, which is described in detail by Wattenbach et al. [2004]. The measured and simulated litter production for a period of 4 years (1996 – 1999) show an adequate accordance. For the agricultural site, yearly harvest yields for Triticale and Rye (3 years, 1995 – 1997) were measured. For Triticale a 3-year average dry matter yield of 9 t_{dm} ha^{-1} a^{-1} on fertilized sites (150 kg N ha^{-1} a^{-1}) was obtained. Rye dry matter yield was measured with 10.6 t_{dm} ha^{-1} a^{-1} on fertilized sites. Total dry matter values for the agricultural site represent the total aboveground biomass harvested. For a comparison to model results these values have to be multiplied by the harvest indices for Triticale (0.42) and Rye (0.40). Simulated harvest yields for the respective period deliver for Triticale an average yield of 3.7 t_{dm} ha^{-1} a^{-1} and for Rye 3.8 t_{dm} ha^{-1} a^{-1} with corresponding measured values of 3.8 and 4.2 t_{dm} ha^{-1} a^{-1} respectively. Hence, for the agricultural site vegetation growth and litter production is well represented through the model.

For the decomposition of primary organic matter no measurements were done at the agricultural site. For agricultural species decomposition experiments in the field with litterbags were taken from literature. In Figure 3 data from Henriksen and Breland [1999] were adopted to show the ability of the model to represent decomposition of primary organic matter for barley straw and wheat straw residues. It has to be noted that the field experiment was carried out in southeast Norway. Due to different climatic situation the decomposition behaviour is different than for eastern German conditions. On average climate is warmer and drier than in southeast Norway. Warmer temperature may enhance decomposition due to enhanced microbial activity. In contrary drier climate weakens decomposition activity. The soil conditions are comparable for both sites. So data from that source is seen to be representative to show the models ability to simulate decomposition of primary organic matter for crops.

For the forest site decomposition of Scots pine needles are shown in the following figure, adapted from a research site closed to the forest site [Bergmann et al., 1999]. Figure 2 show that the model represents the decomposition of primary organic matter in an appropriate way.

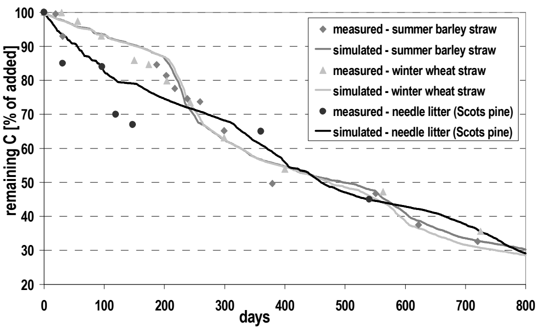

Figure 2. Simulated decomposition of winter wheat, summer barley straw and needle litter (Scots pine). Measured values from mesh bag experiments were adopted from *Henriksen and Breland* [1999] and Bergmann et al. [1999].

The fact that different plant types (e.g. fine roots, stems, foliage) have different decomposition rates is accounted for through the separation into litter compartments by the model.

For soil humus the long-term behaviour has to be investigated. For agricultural soils for a time span of 40 years the conditions of the static long term field experiment in Bad Lauchstädt / Halle (Saxony-Anhalt / Germany) were simulated. Data were adopted from Franko [1990] and simulations for the active organic matter pool showed good accordance in the long run with the measured data. For forest sites representative values for humus dynamics were taken from Bergmann et al. [1999]. In this study humus material was collected and decomposition was measured for approximately 900 days in the humus layer with so-called rhizobags. The humus was almost decomposed after approximately 45 – 54 years (calculated with a mass loss model using the measured data, ref. Bergmann et al. [1999]). The humus dynamic for the forest site could also be simulated in the right magnitudes and temporal behaviour for a period of 50 years (not shown here).

The integral quantity determining POM and AOM processes is the formation of substrate induced soil respiration. For forest and agro-ecosystems measured soil respiration known from literature and from available experimental field data have been compiled and are shown in table 1. It has to be noted that field measurements of soil respiration include both, the heterotrophic (microbes and soil fauna) and autotrophic (root) respiration. Model estimates deliver only values for heterotrophic respiration. To consider that fact, values proposed by Hanson et al. [2000] were used to separate root / rhizosphere contributions to total soil respiration for various vegetation types in different ecosystems. Table 1 shows that simulation results meet measured magnitudes for agro- and forest ecosystems for East German conditions.

Table 1. Simulated yearly soil respiration (SR) values for 3 land cover types compared with literature cited values and measurements.

Land cover	SR [gC m^{-2} a^{-1}] simulated	SR [gC m^{-2} a^{-1}] measured	Ref.
Crop	295 - 840	410 - 660	Beyer [1991]
Crop - triticale	300	250	ATB*
Crop - rye	275 (1999) 250 (2001)	211 (1999) 236 (2001)	ATB*
Forest deciduous	100 – 375	292 - 710	Buchmann [2000]
Forest evergreen	300 – 525	475	Beyer [1991]

* Data provided by the Leibnitz – Institute of Agricultural Engineering Bornim (ATB) from their experimental field site.

4. CONCLUSIONS AND OUTLOOK

The presented results show that the SWIM-SCN model is able to represent main processes of soil organic matter turnover for agro- and forest ecosystems at the regional scale. The model can be described as robust and modest in data requirement, which can be done using regionally available data sets and literature values. Further verification for additional crop and forest species still has to be performed using not yet available data from long-term field experiments in East Germany. Additionally, detailed sensitivity and uncertainty analyses of input data and model parameters will be performed in order to provide error margins for model results. This delivers necessary information for the evaluation of model performance.

Currently two modules for nitrogen cycling are used within the extended SWIM-SCN model. The original was already tested at the basin scale, and the second one is coupled to the carbon cycle. Both have to be compared and then combined into one to preserve their advantages. It is further on relevant to consider coupled C and N cycles in order to properly regard feedbacks and interactions between them which highly influence the process of soil organic matter turnover.

The verification results shown here are a prerequisite to investigate humus and soil respiration dynamics at the regional scale under the impact of global change. Especially changed land use conditions, imposed through socio-economic changes in a region, have to be quantified in respect to soil organic matter dynamics and hence carbon sequestration possibilities. Here the impact of agricultural and forest management practices might play an important role, too. The proposed model framework may help here to investigate effects of land use and land management change on water, carbon and nitrogen dynamics. This information can deliver useful hints for policy and decision-making.

5. ACKNOWLEDGEMENTS

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