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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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Abstract

The Swedish Nuclear Fuel and Waste Management Co (SKB) is currently investigating the Forsmark and Oskarshamn areas for possible localisations of a repository for spent nuclear fuel. Important components of the investigations are characterizations of the land surface ecosystems in the areas with respect to hydrological and biological processes, and their implications for the fate of radionuclide contaminants entering the biosphere from a shallow groundwater contamination. In this study, we simulate water balance and carbon turnover processes in forest ecosystems representative for the Forsmark and Oskarshamn areas for a 100-year period using the ecosystem process model CoupModel.

The CoupModel describes the fluxes of water and matter in a one-dimensional soil-vegetation-atmosphere system, forced by time series of meteorological variables. The model has previously been parameterized for many of the vegetation systems that can be found in the Forsmark and Oskarshamn areas: spruce/pine forests, willow, grassland and different agricultural crops.

This report presents a platform for further use of models like CoupModel for investigations of radionuclide turnover in the Forsmark and Oskarshamn area based on SKB data, including a data set of meteorological forcing variables for Forsmark 1970–2004, suitable for simulations of a 100-year period representing the present day climate, a hydrological parameterization of the CoupModel for simulations of the forest ecosystems in the Forsmark and Oskarshamn areas, and simulated carbon budgets and process descriptions for Forsmark that correspond to a possible steady state of the soil storage of the forest ecosystem.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) bedriver undersökningar för ett framtida slutförvar av förbrukat kärnbränsle på två platser i Sverige, i Forsmark och utanför Oskarshamn. Som ett led i dessa undersökningar karaktäriseras de ytnära ekosystemen med avseende på hydrologiska och ekologiska processer, och dessa processers betydelse för upptag och omsättning i biosfären av radioaktiva föroreningar från grundvattnet till följd av ett eventuellt läckage från djupförvaret. Denna studie presenterar simuleringar med en numerisk ekosystemmodell av vatten- och kolomsättningen i de typer av skogsekosystem som dominerar Forsmark- och Oskarshamsområdet; tall- och granskogar på jordar av varierande fuktighet, alltifrån torra hällmarkstallskog till granskog på fuktiga låglänta områden.

Modellen som använts i denna studie, CoupModel, beskriver kopplingen mellan fysikaliska flöden av vatten och värme med biogeokemiska flöden av kol, kväve och olika spårämnen. Modellen kan och har använts för att beskriva olika landekosystem, t ex gran/tall, energiskog, ängsmark och åkermark. Den beskriver flöden och tillstånd i en dimension för en vertikalt skiktad markprofil med en eller flera vegetationsskikt på ytan. Drivande randvillkor för simuleringar är i regel tidserier av meteorologiska variabler.

Den här rapporten beskriver dels hur CoupModel har använts för att simulera kol- och vattenomsättningen under representativa 100-års perioder för typiska skogsekosystem i Forsmark och Oskarshamn. Data från Riksskogstaxeringen och data från SKBs egna undersökningar i områdena visar att modellen ger trovärdiga resultat trots en viss osäkerhet kring valet av parametervärden och strategierna för att välja dessa. Framförallt utgör dock denna rapport en plattform för fortsatta studier av radionukelidomsättningen i SKBs undersökningsområden med hjälp av modeller liknande CoupModel. De viktigaste resultaten är: ett komplett drivdataset för Forsmark för åren 1970–2004 har sammanställts, vilket kan användas för 100-årssimuleringar för att representera dagens klimat, en hydrologisk parameterisering av CoupModel för simuleringar av Forsmark och Oskarshamn, samt simuleringar av kolomsättning motsvarande ett möjligt tillstånd av oförändrade kolförråd i marken.

Contents

1 Introduction

1.1 Background

Swedish Nuclear Fuel and Waste Management Co (SKB) started investigations in the Forsmark and Oskarshamn areas for localisation of a deep repository for spent nuclear fuel in 2002. The aim of these investigations was to describe the current state and long-term evolution of the biosphere and the geosphere as a basis for the design and safety assessments of the repository. One of the main concerns with the repository is the risk for groundwater contamination and transfer of radionuclides to the biosphere. Models for simulation of the long-term behaviour of contaminants in the surface ecosystems in the repository areas are crucial for the safety assessment.

CoupModel /Jansson and Karlberg 2004/ is an ecosystem process model, which describes the interaction between biogeochemical and hydrological processes in a soil-plant-atmosphere system. The model is an integration of the SOIL /Jansson and Halldin 1979/ and SOILN /Johnsson et al. 1987, Eckersten et al. 1998/ models, which have previously been parameterized for many of the vegetation systems that can be found in the Forsmark and Oskarshamn areas (spruce/pine forests, willow, grassland and different agricultural crops). A trace element sub-model for simulations of radionuclide uptake in the vegetation and turnover in the soil was recently implemented /Gärdenäs et al. 2006/. The radionuclide is considered as a trace element that follows fluxes of water and carbon in the system. The uptake from the soil to the vegetation is calculated either as a function of root water uptake or as a function of carbon assimilated to the plant. Initial tests showed that the model was able to describe a wide range of accumulation scenarios depending on the parameterization of uptake mechanisms and the governing carbon, nitrogen, and water fluxes in the system. However, it has not been demonstrated how the model would respond to a long-term (10,000's of years) contamination at a very low concentration.

The proposed areas for the repository are characterised by small scale topography with a mosaic of mature coniferous forest stands on well-drained elevated areas, and small patches of mixed/broadleaf forests and mires in the lower areas. It is important to consider the time scales of governing processes in such systems. The time scale for the nuclear waste in the repository is maybe 10^5 years. However, the problem may be reduced to about 10^2 if only considering the variation in time of hydrological and biological processes that govern the fate of radionuclides entering the terrestrial ecosystems. For example, a typical rotation time for managed forests in Sweden is about 60–120 years.

The main scenario of interest in the context of a nuclear waste repository is to understand the behaviour of radionuclides that reaches the biosphere at a slow rate from a shallow groundwater contamination. This report presents simulations of carbon and water fluxes for the main surface ecosystems in Formark and Oskarshamn as a basis for an extended sensitivity analysis of the radionuclide model. In addition, these results can contribute to the general site descriptions and will be further possible to test when new measurements will be made available in the two investigation areas.

1.2 Objectives

The objective for this study was to simulate near surface hydrology and carbon turnover of typical forest ecosystems in the Forsmark and Oskarshamn areas with the CoupModel. Specific objectives were to:

- Establish a 100 year dataset with climatic input data for the CoupModel
- Simulate water fluxes for typical mature coniferous forest stands in Forsmark with present day climate
- Simulate carbon and water fluxes for a 100-year period for forest ecosystems in Forsmark and Oskarshamn

2 Material and methods

2.1 Model description

The CoupModel is a one-dimensional model for simulation of fluxes of water, heat, carbon, and nitrogen in a soil-plant-atmosphere system, a type of model often referred to as SVAT (soil-vegetation-atmosphere-transfer) models. Fluxes of water heat and matter are calculated for a layered soil profile and one or several vegetation layers above with time series of meteorological data as the driving force. The model consists of one abiotic and one biotic part, which are described below as the water and heat model and the carbon and nitrogen model, respectively. The most important component for interaction between the biotic and the abiotic parts is the leaf area index (LAI), which is of highest importance for both interception of radiation and of precipitation. Both the losses by transpiration and the input of carbon to the system are strongly related to temperature and moisture of the soil. Radionuclides are simulated as conservative tracers following the carbon and water fluxes in the system with the recently implemented trace element submodule.

The technical description of the model /Jansson and Karlberg 2004/ can be downloaded from the Internet at ftp://www.lwr.kth.se/CoupModel/Coupmodel.pdf.

2.1.1 Water and heat model

The abiotic part of the model simulates the water and heat balance of a vertical soil profile discretized into horizontal layers. It was first published as the SOIL model /Jansson and Halldin 1979/. The core of the model is two coupled partial differential equations for the water and heat flows in the soil; the Richard's equation (water) and the Fourier law of diffusion (heat), respectively. The calculations are based on soil properties such as, the water retention curve, the unsaturated and saturated hydraulic conductivity, the heat capacity including the latent heat at thawing/melting, and thermal conductivity. Other important input data are boundary conditions for runoff, meteorological driving data and surface characteristics governing evapotranspiration and soil surface temperature.

Evapotranspiration

The upper boundary conditions – soil surface temperature, evaporation and infiltration – are based on an energy balance approach, i.e. the net radiation at the surface is partitioned into turbulent fluxes of latent and sensible heat and soil surface heat flux. The exchange with the atmosphere is calculated for three types of surface compartments, bare soil, snow, and one or several vegetation (canopy) layers. Evapotranspiration from the canopy layers includes transpiration and interception evaporation, and is calculated with the analytical approach suggested by /Penman 1953/ as modified by /Monteith 1965/, hereafter referred to as the 'Penman-Monteith' equation:

$$LE = \frac{\Delta(R_n - G) + \rho c_p \dfrac{\delta e}{r_a}}{\Delta + \gamma^*}$$

E evapotranspiration (mm/day)

L latent heat of vaporization (J kg^{-1})

R_n net radiation (J m^{-2} day^{-1})

G ground heat flux (J m^{-2} day^{-1})

δe vapor pressure deficit (Pa)

Δ slope of saturation pressure vs. temperature (Pa K^{-1})

ρ air density (kg m^{-3})
c_p specific heat of air (J kg^{-1} K^{-1})
r_a aerodynamic resistance (s m^{-1}),

where the parameter γ^* is equal to:

$$\gamma^* = \frac{\gamma(r_a + r_s)}{r_a}$$

γ psychrometric constant 66 (Pa K^{-1})

r_s surface resistance (s m^{-1}).

The aerodynamic resistance r_a is estimated from the logarithmic wind profile:

$$r_a = \log\left(\frac{z_{ref} - d}{z_0}\right)^2 \Big/ \left(k^2 u\right)$$

z_{ref} reference height (m) where the windspeed is measured
u windspeed (m/s)
d displacement height (m)
z_0 roughness length (m)
k Karman constant (0.4),

which may be further corrected for atmospheric stability according to Monin-Obukhov similarity theory, see for instance /Beljaars and Holtslag 1991/. The surface characteristics z_0 and d are estimated as a function of canopy height and leaf area index /Shaw and Perreira 1982/, and falls normally in the range of 1/10 and 2/3 of the canopy height, respectively.

For transpiration, the canopy surface resistance is calculated according to the Lohammar equation /Lindroth 1985/ as a function of global radiation R_{is} (J m^{-2} day^{-1}) and vapour pressure deficit δe (Pa):

$$(r_s)^{-1} = g_{\max} \frac{R_{is}}{R_{is} + g_{ris}} \frac{1}{1 + \delta e / g_{vpd}} LAI$$

g_{max}, g_{ris}, g_{vpd} empirical parameters
R_{is} global radiation (J m^{-2} day^{-1})
δe vapour pressure deficit (Pa)
LAI leaf area index (m^2 m^{-2}).

A constant, but considerably lower, surface resistance is normally used for interception evaporation, which represent an average resistance to the single source point from the different parts of the canopy. The Penman-Monteith equation tends to overestimate interception evaporation if the surface resistance is set to zero. This is probably because of the lack of feedback between the estimated evaporation and the vapour pressure in the canopy air space.

The difference between the original Penman and Penman-Monteith equations is the representation of atmospheric and canopy surface control on the evapotranspiration. These two control mechanisms are separated on r_a and r_s in the Penman-Monteith equation, whereas the Penman equation combines them into one single parameter that is called the wind function. Formally, the wind function corresponds to the aerodynamic resistance, and the Penman-Monteith equation is equal to the original Penman equation if r_s is set to zero and r_a is estimated as

$r_a = (\rho c_p)/(L\gamma 0.0026(1+0.54u))$.

Discharge

Several methods to estimate discharge and/or deep percolation are available in the CoupModel. In this study, a linear equation for discharge from saturated layers to drainage pipes or lower located boundary areas at a specified levels was used. The horizontal water flow is assumed to be proportional to the hydraulic gradient and to the thickness and saturated hydraulic conductivity of each layer:

$$q_{wp} = \int_{z_p}^{z_{sat}} k_s \frac{(z_{sat} - z_p)}{d_p} dz$$

q_{wp} horizontal water flow (mm/day)

z_p drainage level(m)

z_{sat} simulated depth of the ground water table (m)

d_p characteristic length (m).

No vertical groundwater flow from the bottom of the lowest soil layer was assumed. The simulated sites represented areas with a natural drainage basin with no ditches or artificial drainage. The z_p and the d_p values were defined after calibration with observed ground water tables.

2.1.2 Carbon and nitrogen model

The carbon and nitrogen part of the model simulates plant growth and carbon and nitrogen turnover in the soil based on three assumptions: 1) carbon input (photosynthesis) is driven by solar radiation /cf. de Wit 1965/ and 2) is limited by the nitrogen content in the leaves, and 3) photosynthesis governs the plant nitrogen demand. It is based on the SOILN model /Johnsson et al. 1987, Eckersten et al. 1998/. Organic matter is partitioned on several aboveground and belowground pools of carbon and nitrogen (Figure 2-1). The most important inputs to the model are characteristics governing the plant life-cycle such as allocation patterns of carbon and nitrogen, plant assimilation and respiration, nutrient uptake by plants, external nitrogen inputs to the soil, and finally decomposition and redistribution of different decomposition products in the soil profile.

The plant biomass is represented by three carbon and nitrogen pools, Stem, Leaves, and Roots, which are further partitioned on annual and perennial tissues (Figure 2-1). The stem compartment represents all woody material including stem, branches, and coarse roots. The root compartment represents only fine roots (approximately below 1 mm in diameter). Plant respiration is partitioned on growth and maintenance respiration from all three compartments, roots, stems and needles /Karlberg et al. 2006/.

Two or three pools of different turnover rate represent the organic material in the soil (Figure 2-1). One of these is named Litter and has a high turnover rate. It may be further divided into two pools of different turnover rates if necessary. The other one is Humus and represents a low turnover rate. These pools are represented in each soil horizon in the model, and should not be confused with the labelling of litter and humus layers in soil profile descriptions. Soil organisms, such as microorganisms, decompose the organic matter, and their activity is accounted for in the fluxes of carbon and nitrogen between different soil organic pools. Biomass of microorganisms can be considered explicitly, but this option was not used in this study.

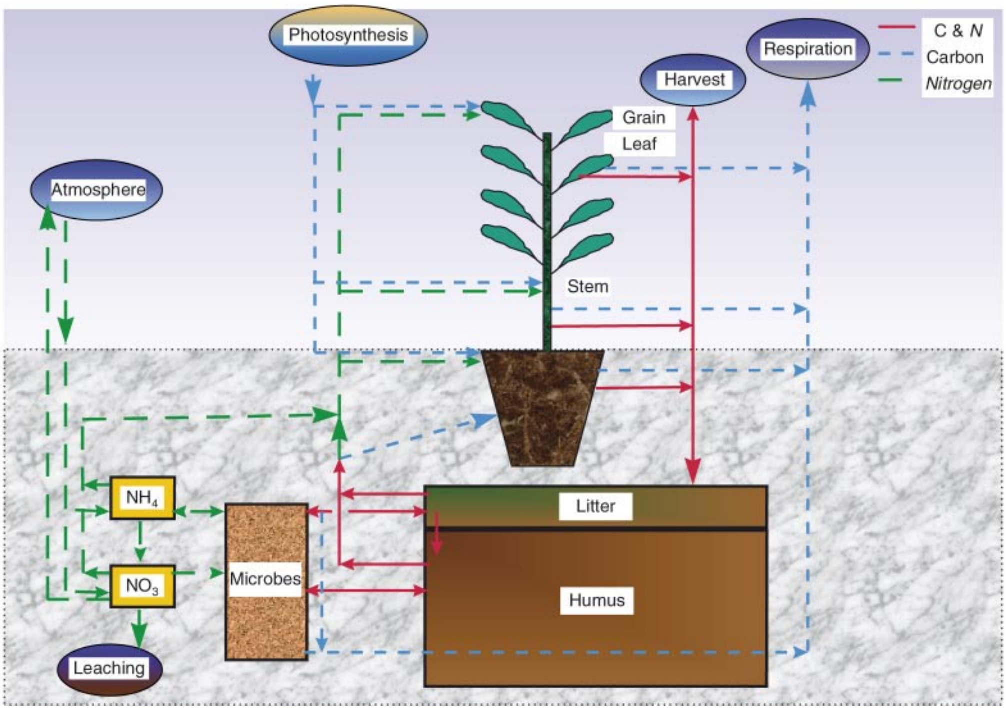

Figure 2-1. *Schematic scheme of carbon, nitrogen and biomass flows (in one dimension) and storages from /Eckersten et al. 1998/. The soil is further divided into layers and plant biomass is divided into pools of annual and perennial tissues.*

2.2 Data description

2.2.1 Meteorological input data

The necessary meteorological variables to run the CoupModel are: air temperature, wind speed, relative humidity, precipitation, global radiation, and cloudiness. Cloudiness is used together with global radiation to estimate net radiation, and can be exchanged by either measured net radiation or downward longwave radiation. However, only cloudiness were available for the Forsmark or Oskarshamn areas. Hourly or daily average variables are normally used, depending on the type of application. It was decided to use hourly values here, since most of the parameters were adopted from previous application of the CoupModel using hourly time resolution, see e.g. /Gustafsson et al. 2004/. The SOILN model was originally developed for daily average input of water and heat fluxes simulated with the SOIL model. However, the carbon and nitrogen model of the CoupModel have been used with an hourly time resolution sucessfully. It should be noted that some parameter values are dependent on the time resolution of the input, and cannot be used without conversion for other time resolutions.

Forsmark

A 35-year dataset (1970–2004) with hourly values of air temperature, wind speed, relative humidity, precipitation, global radiation, and cloudiness was created based on the available data from a number of different stations in the region around Forsmark. This dataset was repeated three times to enable a 100-year period simulation.

The primary data sources were the SKB measurements of selected set of variables at Forsmark (Högmast and Storskäret) 2003–2004 and the SMHI (Swedish Meteorological and Hydrological Institute) station Örskär 1988 /Larsson-McCann et al. 2002a/ with a complete set of variables. Precipitation was corrected with 6% and 10% at air temperatures above and below +1°C, respectively, following the procedure used for the SMHI stations around Forsmark (P-O. Johansson, pers. comm.). All other variables were used without further corrections. Data from the two stations at Forsmark were averaged for each hourly observation.

Cloudiness was inferred from global radiation values. Secondary data sources for the meteorological driving data were observations of air temperature and precipitation from the SMHI stations Örskär, Östhammar, Lövsta, and Films Kyrkby 1994–2003. A complete set of meteorological data from Marsta Meteorological Observatory (Uppsala University) 1993–2000 and Uppsala airport (SMHI) 1970–1996 were used to extend the dataset to 1970–2004. Data from other stations than Forsmark were corrected to get the best possible representation of the local climatic conditions at Forsmark. Correction factors were derived from common time periods (see Appendix 1).

On average, precipitation in Forsmark was lower than at the inland stations in Uppsala. However, wintertime precipitation was generally higher (frequent snowstorms from the sea). These seasonal differences were accounted for in the correction of the Uppsala precipitation data. Precipitation from these stations were also as corrected with 6% and 10% at air temperatures above and below +1°C, respectively.

Oskarshamn

A one-year dataset with hourly values of air temperature, wind speed, relative humidity, precipitation, and global radiation was created based on the available data from Ölands norra udde 1981 /Larsson-McCann et al. 2002b/. Wind speed values were corrected with a factor of 0.4. The correction factor was derived by comparison of average and maximum wind speeds at Ölands norra udde and the available measurements at Äspö since 2003. Precipitaion was corrected with 6% and 10% at air temperatures above and below +1°C, respectively. The one-year of data was recycled for the long-term simulations.

2.2.2 Soil physical properties

Soil physical properties, or more specifically, functions for the water retention curve, the saturated and unsaturated hydraulic conductivity, and the thermal conductivity and heat capacity, were based on 1) grain size distributions from deep soil probe samples from Forsmark /Lundin et al. 2004/, and 2) a database of soil physical properties representing 260 soil profiles and 2,200 soil layers from different parts of Sweden. The database is distributed with the CoupModel, and is a compilation of investigations that goes back to 1950's performed by various soil scientists from the Swedish University of Agricultural Sciences, SLU. The data from Forsmark were divided into three layers. One layer for the uppermost meter below the soil surface, one layer for the last meter above the bedrock, and one layer inbetween for profiles deeper than 2 meters. Grain size distributions for these three layers were matched with grain size distribution of soil layers available in the CoupModel database. Water retention curves and functions for hydraulic condictivity were combined into profiles for each Forsmark profile (see Appendix 2). Finally, the uppermost meter of the soil profile was given a more realistic resolution by adopting parameters from Norunda /Stähli et al. 1995/ (Figure 2-2; Table A2-1). A combined Forsmark/Norunda profile of soil physical properties was used for all simulations in this report.

2.2.3 Groundwater levels

Groundwater levels were observed in a number of drilled wells in Forsmark. Four of them were selected for this study, representing three types of soil moisture conditions characterized as 'dry', 'wet' or 'fresh' (Table 2-1).

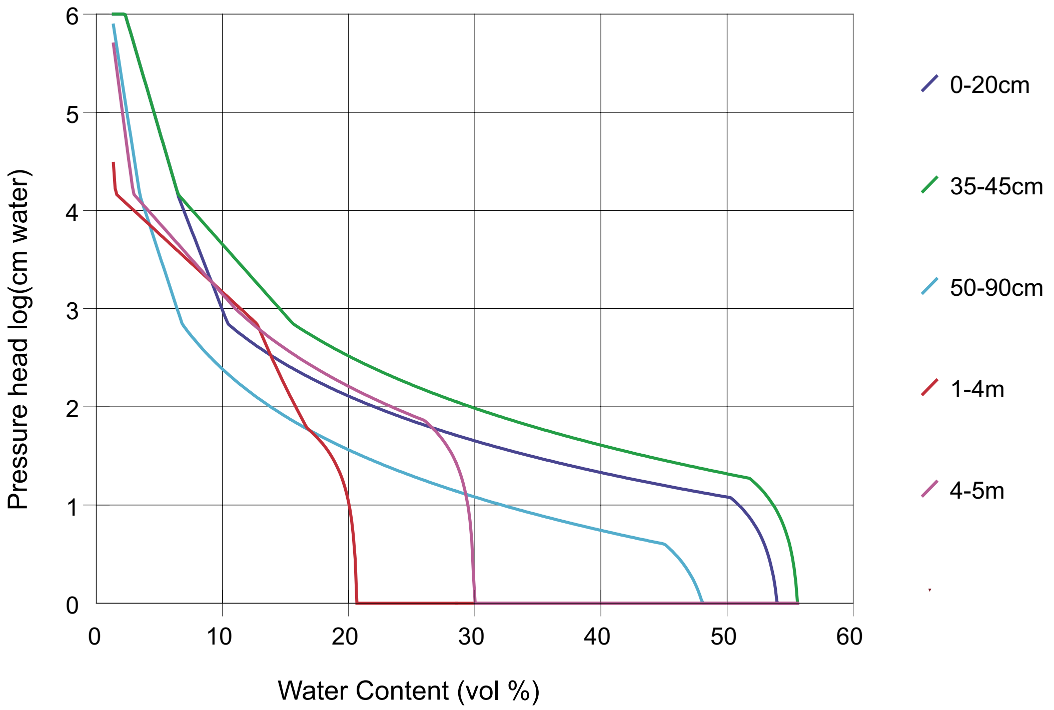

Figure 2-2. *Water retention curves used for the Forsmark simulations, derived from soil samples in Norunda (0–90 cm) /Stähli et al. 1995/ and Forsmark (1–5m) /Lundin et al. 2004/.*

Table 2-1. Groundwater tubes used to calibrate drainage levels for the simulations of Forsmark forest soils of different soil moisture conditions.

Moisture class	Groundwater tube	Level below ground (m)*
Wet	SFM0021	0.43
Fresh (slope)	SFM0004	0.50
Fresh (typical 'elevated' area)	SFM0005	1.04
Dry (local extreme)	SFM0008	2.87

* Average values for the period, 2003-08-01 to 2004-07-31.

2.2.4 Above and below ground carbon storages and fluxes

Forsmark and Oskarshamn data

The SKB site descriptions of Forsmark /Lundin et al. 2004, SKB 2005/ and Oskarshamn /SKB 2006/ presents data on carbon storages in soil and vegetation for a number of plots representing different vegetation and soil types These have been aggregated and summarized for three ecosystem types: forest, wetland, and arable land. The forest data were further aggregated into components that could be compared with the CoupModel simulations (see Table 2-2 and 2-3):

Table 2-2. Carbon pools in the tree layer of coniferous forest stands in Forsmark and Oskarshamn, based on Table 4-12, 4-13 in /SKB 2005/ and Table 3-28 and 3-29 in /SKB 2006/ respectively.

	Young coniferous (<30 y) Carbon pool ($gC\ m^{-2}$)	Annual increase ($gC\ m^{-2}\ y^{-1}$)	Old coniferous (>30 y) Carbon pool ($gC\ m^{-2}$)	Annual increase ($gC\ m^{-2}\ y^{-1}$)
Forsmark				
Leaf	93	25	399	58
Stem	1,072	52	5,649	120
Coarse roots*	186	52	967	120
Fine roots	128		665	
Total above ground	1,166	77	6,048	178
Total below ground	314	52	1,632	120
Total	**1,480**	**129**	**7,680**	**298**
Oskarshamn				
Leaf	136	33	356	54
Stem	1,340	69	5,332	111
Coarse roots*	221	69	853	110
Fine roots	118		455	
Total above ground	1,475	103	5,688	164
Total below ground	339	69	1,307	110
Total	**1,814**	**172**	**6,995**	**274**

* Annual increase represents the sum of coarse and fine roots.

Table 2-3. Carbon pools and annual change in forest soil and vegetation layers in Forsmark and Oskarshamn, based on Table 5-7 in /SKB 2005/ and 4-7 in /SKB 2006/ respectively.

	Forsmark Carbon pool ($gC\ m^{-2}$)	Annual increase ($gC\ m^{-2}\ y^{-1}$)	Oskarshamn Carbon pool ($gC\ m^{-2}$)	Annual increase ($gC\ m^{-2}\ y^{-1}$)
Tree layer				
Above ground	6,048	178	5,688	164
Below ground	1,632	120	1,307	110
Total	**7,680**	**298**	**6,995**	**274**
Field and ground layer				
Total above ground	**401**	**0**	**401**	**0**
*Soil organic carbon**				
Total	**9,551**	–	**9,551**	–
Ecosystem				
Above ground	6,449	178	6,089	164
Below ground	11,183	120	10,858	110
Total	**17,632**	**298**	**16,947**	**274**

* Sum of carbon in fungi, dead wood, litter layers, and soil organic carbon in humus layer, and below humus layer.

Fluxes affecting the soil and vegetation carbon pools were also estimated by SKB /SKB 2005, 2006/, that is net primary production NPP, and litterfall. Measurements of soil respiration and net ecosystem exchange of carbon are currently conducted at Forsmark and Oskarshamn but were not available for this investigation. The data currently available from Forsmark and Oskarshamn are presented in Table 2-4.

Long-term tree biomass development

Characteristic biomass development of pine forest stands in Uppland and Kalmar region were derived from standing stock volume data from the Swedish Forest Inventory NFI /Skogsdata 2003/. Standing stock volumes for different age classes were assumed to be representative for a forest stand development from 10 to 100 years of age. The standing stock volumes (m^3 ha^{-1}) were transformed into biomass (g dry weight) in different fractions of the tree using expansion factors adopted from Sweden's National Inventory Report (NIR) 2005 for anthropogenic emissions of direct greenhouse gases /Benediktson et al. 2005/. These expansion factors were based on the functions for standing stock volume used by NFI /Näslund 1947/ and the functions from /Marklund 1988/ for biomass per fractions (needles, branches, bark, stem and below ground parts) (Table 2-5). /Marklund 1988/ developed single-tree regression functions for biomass (dry weight at 105°C) per fractions for Scots pine, Norway spruce and Birch, which are well representative for Swedish conditions.

Marklunds function for below ground biomass does not include "fine roots" (because only woody roots was included in the sample procedure). We may thus understimate the total biomass of the tree. Roughly, the fine root biomass was approximated to be equal to 1/10 of the stump and coarse root biomass estimated with the Marklund functions or derived from the standing stock using the expansion factors.

Table 2-4. Net Primary production and litterfall in Forest ecosystem in Forsmark and Oskarshamn, based on Tables 4-15 and 5-9 in /SKB 2005/ and Tables 3-30 and 4-9 in /SKB 2006/ respectively.

NPP and litterfall	Forsmark ($gC\ m^{-2}\ y^{-1}$)	Oskarshamn ($gC\ m^{-2}\ y^{-1}$)
NPP		
Tree layer*	1,091	982
Field and ground layer	34	34
Mycelia production	137	137
Total	**1,262**	**1,153**
Litter fall (above ground)		
Tree layer	128	253
Field layer	–	–
Total	**128**	**253**
Root Litter (below ground)		
Tree layer	665	455
Field layer	–	–
Mycelia litter	137	137
Total	**802**	**592**

* The NPP estimates for the tree layer, equal to the sum of net annual increase of carbon and litterfall above and below ground, is assumed to exclude the assimilates consumed by the mycelia through mycorrhiza symbiosis. Therefore, and since mycelia is represented by the fine roots in the CoupModel, the estimated mycelia production was included in the total NPP and in the total below ground litterfall.

The estimated development of tree biomass fractions for Uppland and Kalmar regions are presented in Tables 2-6, 2-7, 2-8, and 2-9.

Table 2-5. Expansion factors from Standing stock (m^3 sk ha^{-1}) to Biomass (dwg m^{-2}) derived from /Benediktson et al. 2005/.

	Stem	Branches	Stump	Total
Pine	41	11	16	67
Spruce	41	20	17	78
Broad-leaved	50	14	19	83
Dead trees	43	15	17	75
All	42	15	17	75

Table 2-6. Standing stock volume (m^3 sk ha^{-1}) and corresponding carbon storages (g C m^{-2}) for different tree age classes in the Uppsala region, based on /Skogsdata 2003/ and the expansion factors in 2–5, assuming a mixture of spruce and pine.

Age class (yr)	Standing stock volume (m^3 sk ha^{-1})	Biomass (g C m^{-2}) Stem	Branch	Stump	Fine roots	Total
3–11	18	354	134	143	14	641
11–21	28	551	208	222	22	997
21–31	79	1,555	588	626	63	2,812
31–41	142	2,795	1,056	1,125	112	5,054
41–61	200	3,936	1,488	1,584	158	7,118
61–81	242	4,763	1,800	1,917	192	8,613
81–101	274	5,392	2,039	2,170	217	9,752
101–121	312	6,140	2,321	2,471	247	11,105

Table 2-7. Standing stock (m^3 sk ha^{-1}) and corresponding carbon storages (g C m^{-2}) for different tree age classes in the Kalmar region, based on /Skogsdata 2003/ and the expansion factors in 2–5, assuming a mixture of spruce and pine.

Age class (yr)	Standing stock volume (m^3 sk ha^{-1})	Biomass (g C m^{-2}) Stem	Branch	Stump	Fine roots	Total
3–11	18	354	134	143	14	641
11–21	37	728	275	293	29	1,317
21–31	99	1,948	737	784	78	3,524
31–41	159	3,129	1,183	1,259	126	5,659
41–61	210	4,133	1,562	1,663	166	7,474
61–81	251	4,940	1,867	1,988	199	8,934
81–101	275	5,412	2,046	2,178	218	9,788
101–121	258	5,077	1,920	2,043	204	9,183

Table 2-8. Average annual increase in forest carbon storages (g C m^{-2} $year^{-1}$) for different tree age classes in the Uppsala region, based on /Skogsdata 2003/ and the expansion factors in Table 2-5, assuming a mixture of spruce and pine.

Age classes (yr)	Annual increase of carbon (g C m^{-2} $year^{-1}$) Stem	Branch	Stump	Fine roots	Total
3–21	22	8	9	1	40
11–31	100	38	40	4	182
21–41	124	47	50	5	224
31–61	76	29	31	3	138
41–81	41	16	17	2	75
61–101	31	12	13	1	57
81–121	37	14	15	2	68

Table 2-9. Average annual increase in forest carbon storages (g C m^{-2} $year^{-1}$) for different tree age classes in the Kalmar region, based on /Skogsdata 2003/ and the expansion factors in Table 2-5, assuming a mixture of spruce and pine.

Age classes (yr)	Annual increase of carbon (g C m^{-2} $year^{-1}$) Stem	Branch	Stump	Fine roots	Total
3–21	42	16	17	2	75
11–31	122	46	49	5	221
21–41	118	45	48	5	214
31–61	67	25	27	3	121
41–81	40	15	16	2	73
61–101	24	9	10	1	43
81–121	–17	–6	–7	–1	–30

2.3 Forsmark and Oskarshamn models

2.3.1 Water and heat processes

Water and heat processes (i.e. transpiration, interception, snow melt, soil heat and water flows) were parameterised based on an earlier application to a mature pine/spruce forest in Norunda, Uppland, Sweden /Gustafsson et al. 2004/. Two canopy layers of different height and structures were used to represent tree and field layer. LAI, canopy height, and degree of surface cover were simulated by using carbon as an independent variable to estimate the respectively variable of the two canopy layers. For the hydrological simulations without simulated carbon and nitrogen processes, LAI was prescribed to be 4.5 for the tree layer and 0.5 for the field layer.

The parameter for drainage level was found by calibrating the model using the observed ground water levels for the three hydrological regimes, dry, fresh and wet.

2.3.2 Carbon and nitrogen processes

The carbon and nitrogen model was parameterized using a multi-criteria approach based on the need to meet both short-term (one or several years) and long-term (life-cycle of ~10^2 years) behaviors of the soil organic pools and the plant biomass. Parameter values that could not be assigned from independent measurements were allowed to be changed in order to meet the tree layer biomass development derived from NFI /Skogsdata 2003/ and a number of criteria for acceptance based on literature values summarized in Table 2-10.

A minimum of parameters were used in the calibration process, whereas a majority was taken from previous applications of SOILN and CoupModel to a number of Swedish forest sites, i.e. Skogaby, Halland /Eckersten and Beier 1998, Gärdenäs et al. 2003/, Asa, Småland /Svensson 2004/, Jädraås /Gärdenäs et al. 2003/, and Knottåsen /Svensson 2004/ in Hälsingland.

The starting point for the parameterization was the mineralization rates for soil organic matter, and the initial distribution of soil organic carbon and nitrogen derived from the LUSTRA project site descriptions /Berggren et al. 2004/.

Secondly, we adopted the parameterization of tree biomass development originating from Skogaby /Eckersten and Beier 1998/, with the extension of the recently implemented partitioning of plant respiration on roots, stems and needles, including both growth and maintenance respiration /Karlberg et al. 2006/.

Thirdly, we introduced a secondary plant layer that was assigned different properties compared to the tree layer in the following respects:

- much lower canopy height, i.e. below 0.2 m compared to a maximum tree height of 30 m,
- two times higher specific leaf area (leaf area per leaf mass),
- shorter maximum leaf life time (1 year versus 5 years for trees),
- different carbon allocation pattern (less carbon to stem, and more to leaf), and
- higher N demand in relation to carbon uptake.

Allocation patterns, plant respiration rates, and nitrogen availability through organic uptake from the litter pool were the main parameters that were changed in the calibration process. Specific parameter values are given in Appendix 2.

Table 2-10. Diagnostic output variables used in the parameterization of the carbon and nitrogen model.

Variables	Range			Unit	Source
Biomass production					
NPP/GPP	0.25–0.60 (mean value 0.46)			–	/Waring and Running 1998/ [1]
Distribution of NPP in trees at different age:	<u>*sapling stand*</u>	<u>*pole stage stand*</u>	<u>*mature stand*</u>		
NPP leaf	15	12	14	% of NPP	
NPP stem	39	26	18		/Helmisaari et al. 2002/ [2]
NPP coarse roots	3	3	8		
NPP fine roots	43	59	60		
Respiration					
Plant respiration/ total respiration	>0.70			–	/Waring and Running 1998/ [3]
Heterotrof respiration/ total soil respiration	0.15–0.70			–	/Ryan et al. 1997/ [4]
Litterfall, trees					
Ratio leaves/needles	~0.70			–	/Waring and Running 1998/
Above ground litterfall	50–100			$gC\ m^{-2}\ y^{-1}$	LUSTRA (M. Svensson, pers. comm.) [5]
Below ground litterfall	45–60			$gC\ m^{-2}\ y^{-1}$	
Maximum C/N ratios, trees					
Trees, stem	700–1,500			$gC\ gN^{-1}$	
Trees, needles	80–100			$gC\ gN^{-1}$	

[1] Lower values for boreal forests /Ryan et al. 1997/, [2] Scots pine in eastern Finland, [3] during vegetation period, [4] annual average for young pine forest, [5] average 2001–2004.

3 Results

3.1 Hydrology

3.1.1 Forsmark

Simulations of the water balance without the interaction of the carbon and nitrogen model using constant leaf area index and vegetation heights were used represent a mature forest stands. Simulations were run for the period 2003-08-01 to 2004-07-31 using climate input data from the local measurements at Forsmark (average values of observations at the two stations Högmast and Storskäret).

Accumulated precipitation was 645 mm, partitioned on about 410 mm (64%) evapotranspiration and 235 mm (36%) runoff in the simulations characterized as 'Fresh' and 'Dry' (Table 3-1). Transpiration and thus also total evapotranspiration was about 100 mm lower in the 'Wet' simulation than in the 'Fresh' and 'Dry'. However, the reduction of transpiration due to decreased root water uptake from saturated soil layers may be somewhat exaggerated in the present simulations (Tables 3-2). The same root depth (0.7 m) was used in all simulations. It is probably more realistic to assume that plants adapt their root distribution to the prevailing soil moisture conditions. The relation between evapotranspiration components (Table 3-2) showed that transpiration was about half of the total evapotranspiration in the fresh and dry simulations. Interception evaporation and soil evaporation was thus about 30% and 20% of the total evapotranspiration, respectively.

The simulated evapotranspiration was about 70% of the 'potential evapotranspiration' calculated with the original Penman equation /Penman 1953/ (Table 3-3). However, simulated winter evapotranspiration was higher than predicted by the Penman equation and it followed a different seasonal pattern due to a considerable amount of interception evaporation (see also Figure 3-1).

Table 3-1. Simulated water balance for the Forsmark forest 2003-04 with the CoupModel.

Water balance Component	(mm) Wet	Fresh	Dry	(% of precipitation) Wet	Fresh	Dry
Precipitation	645	645	645	100	100	100
Evapotranspiration	329	415	407	51	64	63
Runoff	316	230	239	49	36	37

Table 3-2. Simulated evaporation components for the three Forsmark forest area, accumulated fluxes 2003-04.

Evaporation Component	(mm) Wet	Fresh	Dry	(% of evapotranspiration) Wet	Fresh	Dry
Interception evaporation	133	132	133	40	32	33
Transpiration	100	196	193	31	47	47
Soil evaporation	93	84	78	28	20	19
Snow evaporation	3	3	3	1	1	1

Table 3-3. Simulated monthly sums (mm) of precipitation, runoff and evaporation components for the 'wet/fresh' simulation, and 'potential evaporation' from a short crop calculated with the Penman equation /Penman 1953/.

Month	Precipitation	Runoff	Evapo-transpiration	Interception	Transpiration	Soil+Snow	Potential evaporation
Jan	42	23	4	3	0	1	–1
Feb	15	33	6	4	1	1	6
Mar	25	56	12	7	2	3	24
Apr	30	15	31	5	15	11	61
May	42	8	56	13	30	12	102
Jun	45	5	73	11	45	17	131
Jul	84	5	77	25	38	13	108
Aug	110	4	77	28	36	14	95
Sep	49	7	41	8	23	10	46
Oct	74	8	17	9	5	3	9
Nov	58	25	7	7	0	1	–1
Dec	71	40	13	12	0	1	3
Sum	645	230	415	132	196	87	585

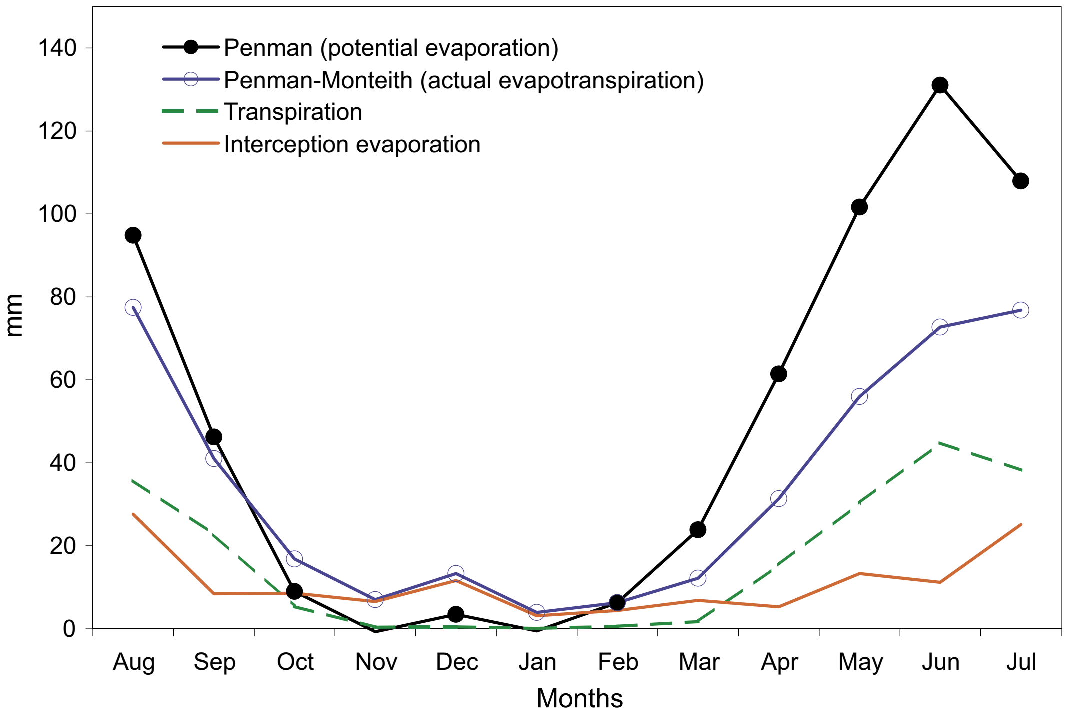

Figure 3-1. Monthly sums of 'potential evapotranspiration' estimated with the Penman equation for a short crop, compared to total evapotranspiration, transpiration, and interception evaporation simulated with the CoupModel for a forest stand in Forsmark, simulation period 2003-08-01 to 2004-07-31.

3.1.2 Oskarshamn

Accumulated annual precipitation in the simulation was 495 mm, partitioned on 376 mm evapotranspiration, and 122 mm runoff (Table 3-4). Similar to the Forsmark simulations, transpiration was somewhat less than half (44%) of the total evapotranspiration (44%). Interception evaporation and soil evaporation were about one fourth each (28% and 26%, respectively).

Table 3-4. Annual water balance for the forest simulated with the CoupModel.

	mm	% of precipitation
Precipitation	495	–
Evapotranspiration	376	75
Runoff	122	25

Table 3-5. Annual Evaporation components.

	mm	% of evapotranspiration
Transpiration	167	44
Interception evaporation	106	28
Soil evaporation	98	26
Snow evaporation	5	1

3.2 Carbon and nitrogen simulation

3.2.1 Forsmark

A 100-year development of a spruce/pine forest was simulated with a full coupling between the water and heat part and the nitrogen and carbon part of the model. Two vegetation layers were simulated to represent tree and field layer. Initial values of carbon contents in the vegetation layers were chosen to represent small tree seedlings and a fully developed field layer. Three consecutive 100-year cycles were simulated with harvest of the tree layer stem biomass at the end of each cycle. Such long simulation cycles are necessary for a proper initialization of the soil organic pools of carbon and nitrogen in the model. Climate data from 1970-08-01 to 2004-07-31 was repeated three times for each 100-year cycle as input to the model

Forest stand development

The simulation was compared to the tree layer stem biomass of an approximate stand development and annual growth derived from the NFI data (Figure 3-2 and 3-3).

Tree growth and increase of soil organic carbon was overestimated during the first two 100-year rotations, as a part of the iterative initialization of the model. The model results were more stable and in better agreement with the reference data after 200 years.

Results from the last 100 years were selected for the carbon budget analysis presented below. It is worth noting the considerable inter-annual variation in net tree layer growth, derived as NPP-litterfall (Figure 3-3).

Leaf area index is one of the most important interactions between the carbon and nitrogen model and the water and heat model. The simulated LAI for the tree layer was between 4 and 5 m^2 m^{-2} at simulated stand age 30 years or older (Figure 3-4).

Carbon budget

Average annual carbon pools and carbon fluxes were calculated for periods roughly corresponding to the classification in the SKB site investigations: 0–30 years, 30–100 years, and 0–100 years. These are presented in the tables below and compared to the available site-specific estimates from the Forsmark area.

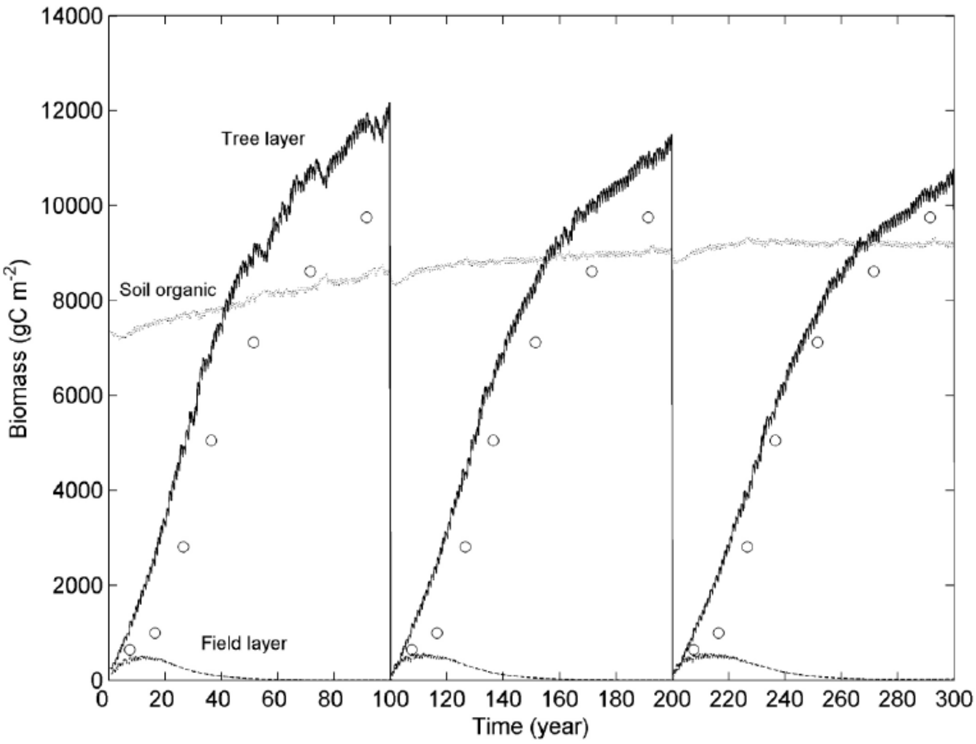

Figure 3-2. *Simulated carbon storage (top) in the tree layer (solid line) and field layer vegetation (dashed line), and in the soil organic pools (dotted line) during three consequtive 100-year rotation periods, compared to approximate stand development derived from tree volume of different age classes from the Uppsala region /Skogsdata 2003/ and transformations according to the biomass functions from /Marklund 1988/.*

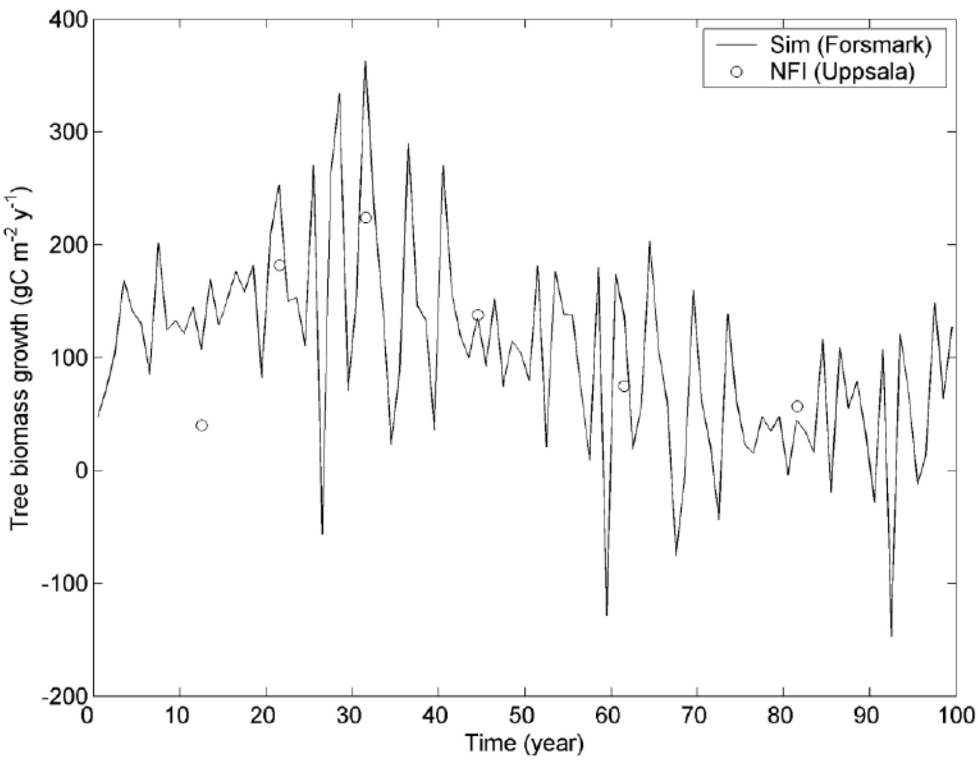

Figure 3-3. *Simulated annual tree layer growth (NPP-litterfall) (solid line) compared to growth data derived from tree volume of different age classes from the Uppsala region /Skogsdata 2003/ and transformations according to /Marklund 1988/.*

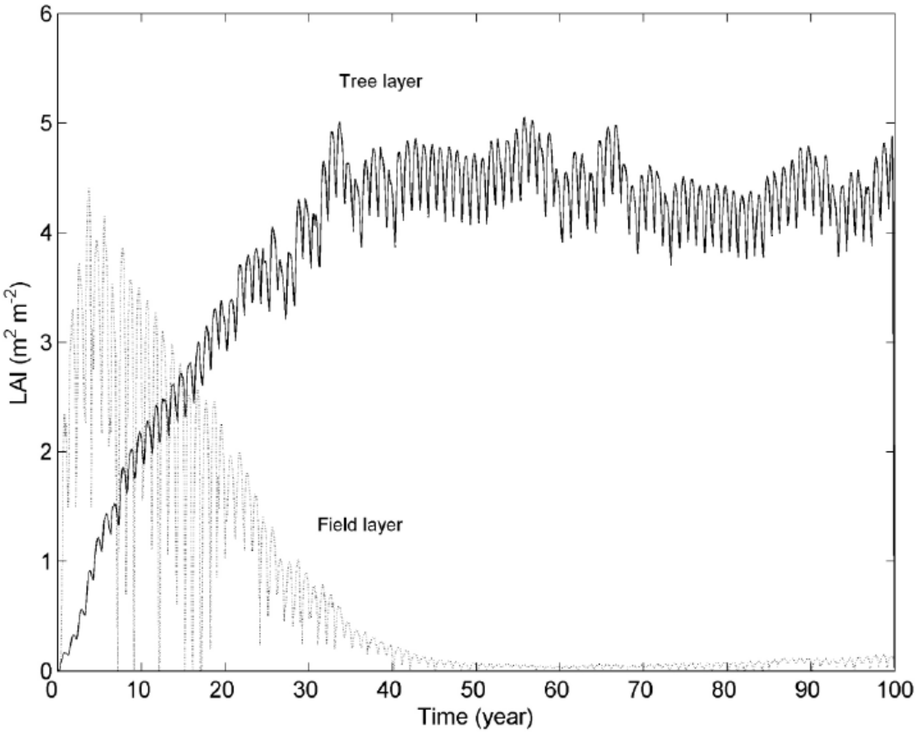

Figure 3-4. *Simulated leaf area index for the tree layer (solid line) and field layer vegetation (dashed line) during the third 100-year-period.*

The overall carbon budgets for the forest ecosystem, including GPP, plant respiration, heterotrophic soil respiration, and the internal carbon flow between the living biomass and the soil organic pool (litterfall) are presented in Tables 3-6, 3-7, and 3-8. A net annual carbon balance of +107 gC m^{-2} $year^{-1}$ was simulated for the entire 100-year period. The relation between the carbon balance and the input (GPP) and output fluxes (total respiration) is about 1:10, which means that a small change in any of these large fluxes may change the system from net accumulation to net loss of carbon.

Carbon pools in vegetation and soil, and the average annual increase for stand ages 0–30 years, 30–100 years, and 0–100 years are presented in Table 3-9. Fluxes affecting the carbon pools, i.e. primary production, respiration, and litterfall are presented in Table 3-10, 3-11, and 3-12.

C/N ratios in vegetation and soil organic matter are presented in Table 3-13. C/N ratios in the vegetation were within the acceptable ranges (Table 2-10). On the other hand, the C/N ratio of the different soil organic pools were generally too high compared to what have been observed at other sites /Berggren et al. 2004/.

Table 3-6. Average annual carbon budget for the entire 100-year-period, simulated for a coniferous forest stand in Forsmark.

	Input (gC m^{-2} y^{-1})		Output (gC m^{-2} y^{-1})			Balance
	GPP	Litterfall	Respiration	Litterfall	Leaching	(gC m^{-2} y^{-1})
Tree layer	888	–	589	195	–	104
Field layer	81	–	44	37	–	0
Soil organic matter	–	232	228	–	< 1	3
Total	**969**	**–**	**861**	**–**	**< 1**	**107**

The ratio between the simulated carbon content in the tree and the field layer was approximately 36:1 averaged over the entire period (Table 3-14), and the corresponding ratio for nitrogen was 8:1. In other words, relatively more nitrogen compared to carbon was stored in the field layer. Naturally, and despite the uptake of organic nitrogen, the largest part of the nitrogen (around 90%) resided in the soil organic pools.

Additional details on the simulated carbon storages and fluxes are given in Appendix 3.

Table 3-7. Average annual carbon budget for stand age 0–30 years, simulated for a coniferous forest stand in Forsmark.

	Input (gC m^{-2} y^{-1}) GPP	Litterfall	Output (gC m^{-2} y^{-1}) Respiration	Litterfall	Leaching	Balance (gC m^{-2} y^{-1})
Tree layer	637	–	374	117	–	146
Field layer	241	–	129	102	–	10
Soil organic matter		219	208	–	< 1	11
Total	**878**	**–**	**711**	**–**	**< 1**	**167**

Table 3-8. Average annual carbon budget for stand age 30–100 years, simulated for a coniferous forest stand in Forsmark.

	Input (gC m^{-2} y^{-1}) GPP	Litterfall	Output (gC m^{-2} y^{-1}) Respiration	Litterfall	Leaching	Balance (gC m^{-2} y^{-1})
Tree layer	995	–	681	228	–	85
Field layer	13	–	8	9	–	–4
Soil organic matter	–	238	237	–	< 1	0
Total	**1,008**	**–**	**926**	**–**	**< 1**	**81**

Table 3-9. Carbon pools C (gC m^{-2}) and annual change ΔC (gC m^{-2} year^{-1}) in vegetation and soil; CoupModel simulations of a 100 years development of a coniferous forest stand in Forsmark area, averaged for stand ages 0–30 years and 30–100 years, compared with site specific estimates from Forsmark /SKB 2005/.

Stand age	Simulated 0–30 y gC m^{-2}	gC m^{-2} y^{-1}	Forsmark <30 y gC m^{-2}	gC m^{-2} y^{-1}	Simulated 30–100 y gC m^{-2}	gC m^{-2} y^{-1}	Forsmark >30 y gC m^{-2}	gC m^{-2} y^{-1}
Tree layer								
Leaf	243	13	93	25	442	0	399	58
Stem*	1,739	128	1,072	52	7,834	85	5,649	121
Coarse roots	–	–	186	52	–	–	967	120
Fine roots	118	5	128	0	188	0	665	
Total	**2,104**	**146**	**1,480**	**129**	**8,470**	**85**	**7,680**	**298**
Field layer								
Total	**433**	**10**	**–**	**–**	**76**	**–4**	**401**	**–**
Soil organic matter								
Total	**9,093**	**11**	**–**	**–**	**9,206**	**1**	**9,551****	**–**
Ecosystem								
Above ground	2,371	151	–	–	6,556	102	6,449	–
Below ground	9,243	15	–	–	9,349	5	11,183	–
Total	**11,614**	**167**	**–**	**–**	**15,905**	**107**	**17,632**	**–**

* All woody material including coarse roots, ** including litter, humus, mycelia, and dead wood.

Table 3-10. Primary production (gC m^{-2} y^{-1}) in the tree and field layer, annual mean, max, min, and standard deviation (std), compared with the site estimates from Forsmark /SKB 2005/, where numbers in brackets includes mycelia production.

	Simulated 0–30 y		Simulated 30–100 y		Forsmark >30 y
	GPP	NPP	GPP	NPP	NPP
Tree Layer					
Mean	637	263	995	314	1,091
Max	1,165	513	1,284	548	
Min	88	48	682	110	
Std	251	100	120	78	
Field Layer					
Mean	241	111	13	5	34
Max	467	227	74	32	
Min	69	24	4	1	
Std	108	57	14	6	
Ecosystem					
Mean	878	374	1,008	318	1,262
Max	1,260	556	1,358	580	
Min	450	162	686	114	
Std	179	79	124	81	

Table 3-11. Respiration in vegetation and in soil organic matter, simulated for a forest stand in Forsmark.

	Respiration (gC m^{-2} $year^{-1}$)		
Stand age	**0–30 year**	**30–100 year**	**0–100 year**
Tree layer			
Leaf	94	162	141
Stem	93	226	186
Fine roots	186	294	262
Total	**374**	**682**	**589**
Field layer			
Leaf	60	3	20
Stem	16	2	6
Fine roots	53	3	18
Total	**129**	**8**	**44**
Soil respiration			
Heterotrof Humus	45	54	51
Heterotrof Litter	163	183	177
Total	**208**	**237**	**228**
Autotrof (roots)	239	297	280
Ecosystem			
Above ground	264	392	354
Below ground	447	534	508
Total	**711**	**926**	**861**

Table 3-12. Litterfall from tree layer and field layer, annual average values for different age classes, simulated values compared with data from the Forsmark area /SKB 2005/.

	Simulated litterfall (gC m^{-2} year^{-1})			Forsmark data /SKB 2005/
	0–30 years	**30–100 years**	**0–100 years**	
Tree layer				
Leaf	20	37	32	128
Stem	11	51	39	
Fine roots	86	141	124	665
Total	**117**	**228**	**195**	**793**
Field layer				
Leaf	59	4	20	
Stem	18	4	8	
Fine roots	25	1	8	
Total	**102**	**9**	**37**	
Ecosystem				
Above ground litter	108	95	99	128
Root litter	111	142	133	665
Mycelia litter	–	–	–	137
Total*	**219**	**238**	**232**	**930**

* Mycelia is implicitly represented by the fine roots in the CoupModel, and thus simulated root litter should be compared with the sum of observed root and mycelia litter.

Table 3-13. C/N ratios in the soil and vegetation, simulated for a coniferous forest stand in Forsmark, annual average values for different stand ages.

	C/N ratio (gC gN^{-1})		
	0–30 year	**30–100 year**	**0–100 year**
Tree layer			
Leaf	50	53	52
Stem	945	1,008	1,002
Root	24	26	26
Field layer			
Leaf	36	14	31
Stem	270	153	212
Root	18	17	18
Soil organic matter			
Humus	32	32	32
Litter	24	25	25
Litter surface	44	65	–

Table 3-14. Simulated carbon and nitrogen content in the tree layer, field layer and soil organic pools for a coniferous forest stand in Forsmark, and the ratio between amounts in tree and field layer and soil and vegetation layers, respectively.

Simulation period	0–30 years	30–100 years	0–100 years
Carbon (gC m^{-2})			
tree layer carbon (TC)	2,100	8,464	6,555
field layer carbon (FC)	423	76	180
TC/FC	5	112	36
soil organic carbon (SOC)	9,091	9,204	9,170
SOC/(TC+FC)	4	1	1
Nitrogen (gN m^{-2})			
tree layer nitrogen (TN)	12	23	20
field layer nitrogen (FN)	6	1	2
TN/FN	2	24	8
Soil organic nitrogen (SON)	292	292	292
SON/(TN+FN)	17	12	13

3.2.2 Oskarshamn

The parameterization of the Forsmark forest was applied to Oskarshamn without further calibration. The one-year climate series derived from Ölands N Udde (1981) was used repeatedly for the 3 consecutive 100-year periods. The simulated stand development during the last 100-year period was compared to the data derived from NFI representing the Kalmar region (Figure 3-5). Similar to the Forsmark simulations, the simulated tree growth was too large during the first 30 years compared to the NFI data, whereas the simulated tree growth during the last 70 years was almost identical to the NFI data (Figure 3-6). A better fit of the tree layer biomass for the entire 100-year period could be achieved by reducing the nitrogen uptake from the slowly decomposing soil organic pool with 50%. However, this procedure had a bad influence on the annual growth rates for the 30 to 70-year period and did not improve the overestimated growth rates forthe younger trees significantly. Thus, for the analysis of the carbon fluxes it was preferred to keep the parameterization identical between the two sites and just change the climate. Tables of average carbon pools and fluxes and comparison with the data from SKB estimates for Oskarshamn are presented in Appendix 3.

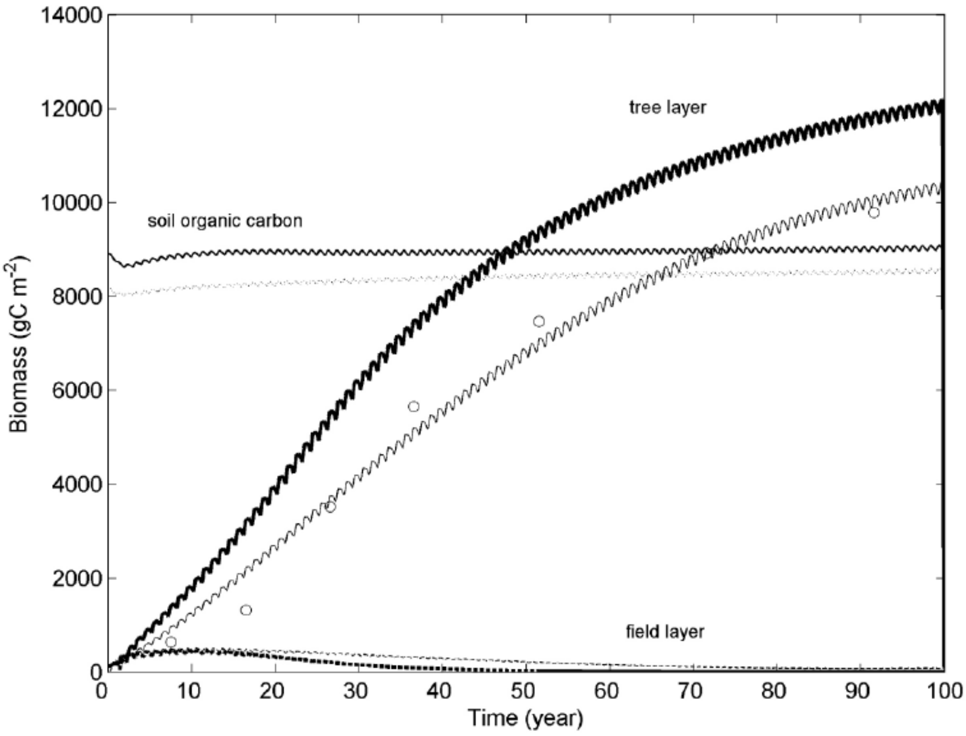

Figure 3-5. Simulated carbon storage (top) in the tree layer (solid lines), field layer vegetation, (dashed lines), and in the soil organic pools (dotted line) during a 100-year rotation period, compared to approximate stand development derived from tree volume of different age classes from the Kalmar region /Skogsdata 2003/ and transformations according to the biomass functions from /Marklund 1988/. Simulations with the Forsmark parameterization are presented with fat lines, and simulations with reduced organic nitrogen uptake.

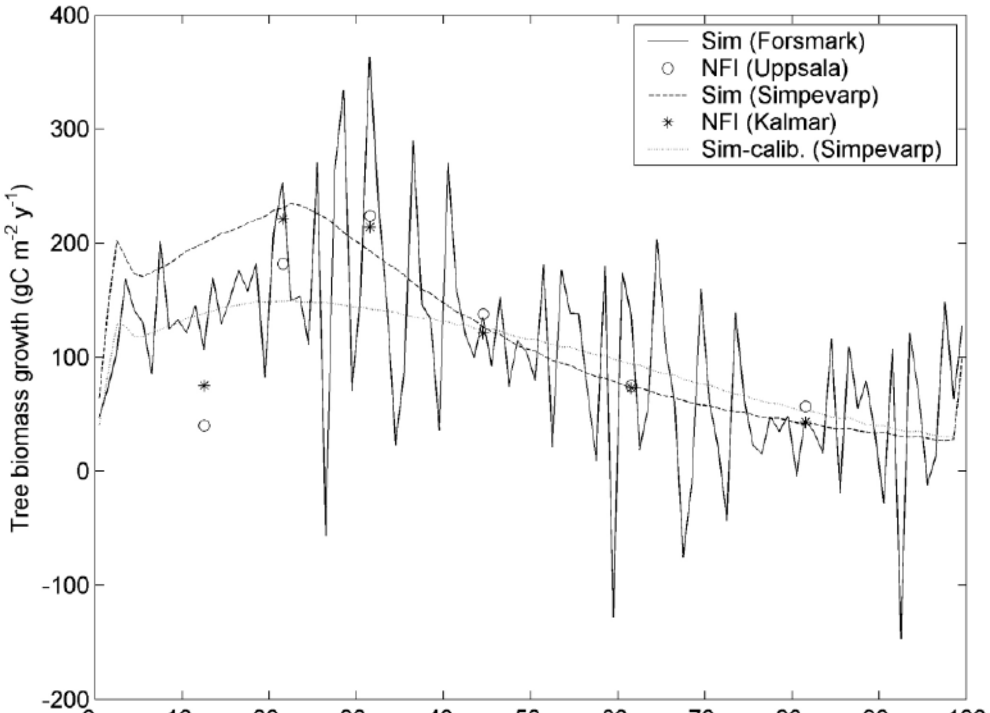

Figure 3-6. Annual tree layer growth (NPP-litterfall), simulations for Forsmark (solid line), Oskarshamn with the Forsmark parameterization (fat dashed line), Oskarshamn with reduced organic N uptake (thin dashed line), and data derived from NFI for the region of Uppsala (circles) and Kalmar (stars).

4 Discussion

4.1 Water balance simulations

Simulated water balances, more specifically the relation between evapotranspiration, runoff, and precipitation, generally agreed well with measurements and simulation studies on similar forest areas in Sweden, e.g. /Grelle et al. 1997/ and /Gustafsson et al. 2004/, as well as simulations of the Forsmark and Oskarshamn sites using the distributed hydrological model MIKE SHE /SKB 2006/. The largest difference between the three simulation types, 'Dry', 'Fresh', and 'Wet', was the reduction of transpiration in the 'Wet' simulations (Tables 3-2). However, the decreased root water uptake from saturated soil layers may be somewhat exaggerated in this case, since the same root depth (0.7 m) was used in all simulations. It is probably more realistic to assume that plants adapt their root distribution to the prevailing soil moisture conditions.

A large difference in terms of absolute values of evapotranspiration and runoff for the Oskarshamn area can be noted between this study and the results presented in /SKB 2006/. However, these discrepancies were mainly a result of different methods to correct the measured input precipitation. The total annual precipitation 1981 was only 495 mm based on the correction used in this study (6% for rain and 10% for snow applied on observed precipitation per 12 hours), compared to the 576 mm that was achieved using the monthly correction factors derived by /Larsson-McCann et al. 2002/. However, the distribution on 75% evapotranspiration and 25% runoff corresponded well to the estimates with MIKE SHE model for the area /SKB 2006/.

One useful indicator of a successful water balance simulation may be the partitioning of the different evaporation components, averaged over the year as well as within the course of a typical year. In this respect, the relation between evapotranspiration components achieved in this study (Table 3-2 and Table 3-4) was similar to the results of /Gustafsson et al. 2004/. The interception evaporation was about 30% of the total evapotranspiration or 20% of the precipitation calculated as annual averages, but it may be even more important during wintertime. Many studies have stressed the importance of snow interception evaporation from boreal forests, for instance /Harding and Pomeroy 1996/ or /Essery et al. 2003/, and it has been found that about 30% of the wintertime precipitation may be lost by interception evaporation /Lundberg and Kovusalo 2003/. Verification of the partitioning between soil evaporation and transpiration is difficult without measurements of either one of these components or soil water content in the root zone.

The comparison of the simulations to calculations with the original Penman equation /Penman 1953/ showed that the simulated evapotranspiration was about 70% of the potential, much in line with the analysis by /Grelle et al. 1999/ based on measurements from a similar forest site in Norunda. The main reason for the difference compared to the Penman equation is related to the difference between a forest and an open grassland area. First of all, the aerodynamic resistance is about one order of magnitude lower for a rough forest surface compared to a short crop. This explains the large amount of interception evaporation in the CoupModel calculations, especially during winter as was also discussed above. On the other hand, the stomatal control of canopy transpiration is much higher and more sensitive to atmospheric conditions for a forest than for a crop or grassland. The surface resistance in the Penman-Monteith equation can be modelled in various ways; in this case as a function of global radiation and vapour pressure deficit. Typically, the annual sum of evapotranspiration is rather similar for a forest and an agricultural crop, but the seasonal patterns differ due to the difference in seasonal variations of surface and aerodynamic resistances, see for instance /Gustafsson et al. 2004/.

4.2 Carbon and nitrogen simulations

The simulated development of carbon in the tree layer and in the soil organic pools generally agreed well with the reference data both for the Forsmark and the Oskarshamn areas, even though the net tree growth was somewhat overestimated in the latter case. In fact, the net tree growth was overestimated at both sites over the entire 100-year period, but mainly due to an overestimated growth during the initial 30 years. The simulated tree growth during the last 70 years was almost identical to the NFI data. The tree growth estimated from the NFI data indicated lower growth rates for the younger trees, which obviously was not been considered properly in the simulations. There are several possible explanations: effects of management (thinning), underestimated competition from field and bush layer (the field layer canopy height was lower than 0.2 m), age dependent allocation patterns. This has been pointed out also by /Gärdenäs et al. 2003/, who implemented both management procedures in the simulations and different parameter values for different stand ages to fit the net growth of tree layer biomass for an entire rotation period. In this study, a common parameterisation for the entire rotation period and correct annual growth rates for the 30 to 70-year period was preferred. Thus, the results for the 0 to 30 year period should be used with caution.

The simulated net carbon balances (net ecosystem production) for the Forsmark (107 g C m^{-2} $year^{-1}$) and Oskarshamn (204 g C m^{-2} $year^{-1}$) areas were within plausible ranges compared to other studies considering location and forest stand ages. For instance, /Medlyn et al. 2005/ reported –50 gC m^{-2} $year^{-1}$ for a 40 year Norway spruce site in northern Sweden, 590 gC m^{-2} $year^{-1}$ for a 20 year old Sitka spruce forest in Scotland, and 575 gC m^{-2} $year^{-1}$ for a 30 year maritime pine forest in France. In a simulation study comparing nine different models /Amthor et al. 2001/ found net ecosystem production between –11 g C m^{-2} $year^{-1}$ to 85 g C m^{-2} $year^{-1}$ for a 150 year Black spruce forest in central Canada.

It should also be noted that the partitioning of the carbon fluxes between the tree and field layer is probably more realistic for the 30–100 year period than for the 0–30 year period, since the net tree growth was largely overestimated for the inital 30 years compared to the NFI data. This is also evident from the comparison with the corresponding estimates in the SKB site description of the Forsmark area /SKB 2005/ (Tables 3-9, 3-10, and 3-12). Obviously, the simulated competition of resources between the field layer and the tree layer vegetation could be further improved. On the other hand, the general picture of two or more vegetation layers that plays different roles in the transition from clear-cut to mature forest is what could be expected. For the 30–100 year period the simulated results were in better agreement with the site description estimates. Still, two major discrepancies were noted also for this period: 1) the simulated net primary production (NPP), and the net tree layer growth (NPP-litterfall) was lower much than the SKB estimates, and 2) the field layer vegetation was much too small in the simulations.

The large discrepancy between the simulated net tree layer growth and the site description estimates was clearly related to NPP, especially if the mycelia production was included in the tree layer NPP (see Table 3-10). On the other hand, the maximum simulated annual NPP actually was equal to the SKB estimate excluding the mycelia production. Thus, inter-annual variations in the climatic conditions could also be part of the explanation. On the other hand, there was a good agreement between simulated and estimated tree layer litterfall. Further more, the simulated results of both GPP and NPP/GPP were well within the given ranges for acceptance even though the simulated GPP was quite low (Table 3-10).

It should also be noted that the fine root compartment in the Coupmodel simulations represents roots of approximately 0–2 mm diameter, whereas the site description estimates refers to data for roots of 0–5 mm in diameter /Berggren et al. 2004/. Coarse roots were not explicitly treated in the version of the CoupModel use in this study, but it have been implemented in later versions, see for instance report by /Karlberg et al. 2006/, who have made improved simulations of the Oskarshamn area. The root dynamics have been further improved also with respect to nitrogen. In the present simulations, the C/N ratios in vegetation were within the acceptable ranges, whereas the C/N ratios in the soil organic pools were much too high compared to what have been observed /Berggren et al. 2004/ The relation between the C/N ration in the surface litter pool and the soil organic pools was acceptable, with higher C/N ratio in the surface litter and lower in the soil. In other words, the nitrogen concentration in the soil organic matter increased as could be expected as a result of respiration of the soil organic carbon. However, we do not expect a higher C/N ration in the slowly decomposing humus fraction compared to the faster litter pool. The present results indicate that the simulated plant uptake of organic carbon from the slowly decomposing humus pool was too high or that a related increase of soil respiration due to organic nitrogen uptake was missing in the model. On the other hand, the model did not consider any increase of the soil respiration as a consequence of the organic uptake, which is expected and could reduce this particular problem /Näsholm et al. 1998/.

More reasonable were the partitioning of carbon and nitrogen between vegetation layers and the soil organic pools, especially the relationships between the tree layer and the field layer vegetation with regard to carbon and nitrogen content. The ratio between the simulated carbon content in the tree and the field layer was approximately 36:1 averaged over the entire period (Table 3-14), and the corresponding ratio for nitrogen was 8:1. In other words, relatively more nitrogen compared to carbon was stored in the field layer /Waring and Running 1998/. Naturally, and despite the uptake of organic nitrogen, the largest part of the nitrogen (around 90%) resided in the soil organic pools.

The results show that the current simulations present a reasonable model of the long-term carbon and nitrogen turnover in the Forsmark forest, and might be used for the sensitivity analysis of the radionuclide model. However, the model do not account for any changes in allocation patterns with stand age. For instance, the net annual growth seems to be exaggerated in the early stages of tree development compared to the available reference data. This might be a result of for instance changed allocation patterns and plant morphology with age, but also responses to changed environmental conditions. It should be noted that the reference data used here also is a result of the forest management in the area. More detailed models of allocation pattern and morphology as function of age and environmental conditions are available in the literature and could be included in the model. However, the final 'steady-state' carbon budget will depend more on the nitrogen deposition (and fixation which is not represented in the model explicitly) and the average net growth (assimilation-respiration) than the distribution of carbon flows within the rotation time and between plant compartments.

Finally, even though the carbon balance results for Oskarshamn and Forsmark were plausible, results have to be used with care. No efforts were made in this study to quantify the uncertainties of the simulated results and the used parameter values. The method to select the parameter values was mainly by trial and error, even though the NFI data and the additional criteria of model acceptance were used in the process. This study was only a first step towards the multiple-criteria parameterization approach presented by /Karlberg et al. 2006/. In future studies, calibration procedures and uncertainty estimates will be even further improved by using methods presented by for instance /Yapo et al. 1998/ and /Barrett 2002/.

5 Conclusions

We have delivered a number of results for the future research;

1) a meteorological driving data set for Forsmark 1970–2004, suitable for simulations of a 100-year period representing the present day climate,
2) a hydrological parameterization of the CoupModel for simulations of the forest ecosystems in the Forsmark and Oskarshamn areas,
3) an estimation of the the evapotranspiration fluxes with partioning between the most important components of forest ecosystems in Forsmark and Oskarshamn,
4) simulated carbon budgets and process descriptions for Forsmark that correspond to a possible steady state of the soil storage of the forest ecosystem,
5) a platform based on SKB data for further use of process oriented model like CoupModel to study the fate of radionuclides,
6) the simulated ecosystem fluxes of water and carbon to allow for an independent test against the new micrometeorological measurements that are presently conducted in the two study areas.

We have identified the crucial role of some key processes that need to be carefully considered when transient long-term development of ecosystem is to be described. For time scales up to 100 years, nitrogen transformations and nitrogen uptake have been demonstrated as very crucial and also complicated to parameterize. We believe that the present model is well adapted to represent time-scales of about 100 years. However, to enable a realistic representation for time scales of 1,000 years or longer, we suggest model developments that take into account soil formation processes, feedback between soil organic storage and physical properties of the soils, and transitions between different plant species.

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Appendix 1

Meteorological driving data Forsmark 1970–2004

A continuous time series of meteorological driving data representative for Forsmark was established for a 35 year period 1970–2004. The basis for the dataset was the SKB measurements at Forsmark (Högmast and Storskäret), and the data from SMHI stations at Örskär, Films Kyrkby, Östhammar, and Lövsta. Gaps were filled with data from two stations in Uppsala: Marsta Meteorological Observatory and Uppsala Airport. All data from stations other than Forsmark were corrected based on linear regressions using data from overlaping time periods. Details are given in the tables below. The final data set consisted of hourly values of air temperature (°C), wind speed (m/s), relative humidity (%), global radiation (W/m^2), cloudiness (–), corrected precipitation (mm/d). Monthly averages with minimum, maximum, and standard deviation are also presented in tables.

Air temperature

Table A1-1. Meteorological stations with air temperature. The shaded areas indicate time period when data was available from the different stations. Gaps in the time-series from Forsmark were filled with corrected data from the other stations in the order of the list from top to bottom. Corrections were based on linear regression functions using data from overlapping time periods.

Years Station	1970– 1987	1988	1989– 1993	1994– 1996	1997– 2000	2001	2002	2003	2004
Forsmark (Högmast)								■	■
Forsmark (Storskäret)								■	■
Örskär		■		■	■	■	■	■	
Films				■	■	■	■	■	
Marsta (Uppsala)				■	■				
Uppsala airport	■	■	■	■					

Table A1-2. Air temperature (°C), monthly averages, standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	–2.1	3.1	2.7	–11.3
Feb	–2.4	3.3	3.9	–11.3
Mar	0.3	1.9	4.0	–4.0
Apr	4.1	1.1	6.3	2.1
May	9.6	1.4	12.1	6.4
Jun	13.5	1.3	15.6	11.0
Jul	15.9	1.7	19.5	13.0
Aug	14.8	1.6	18.8	11.2
Sep	10.5	1.4	14.2	7.9
Oct	6.2	1.4	9.3	3.3
Nov	2.0	1.7	5.8	–1.3
Dec	–1.1	2.4	3.5	–7.6

Wind speed, relative humidity, and global radiation/cloudiness

Table A1-3. As Table A2-1 for wind speed, relative humidity, and global radiation and cloudiness.

Years Station	1970– 1987	1988	1989– 1993	1994– 1996	1997– 2000	2001	2002*	2003	2004
Forsmark (Högmast)								■	■
Forsmark (Storskäret)								■	■
Örskär		■					■	■	
Marsta (Uppsala)				■	■				
Uppsala airport	■	■	■	■					

* Only wind speed available 2002.

Table A1-4. Wind speed (m s^{-1}), monthly averages with standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	2.0	0.2	2.6	1.6
Feb	1.9	0.2	2.3	1.5
Mar	1.9	0.2	2.5	1.6
Apr	1.9	0.2	2.2	1.4
May	1.9	0.2	2.2	1.4
Jun	1.8	0.1	2.0	1.4
Jul	1.7	0.2	1.9	1.3
Aug	1.7	0.2	2.0	1.3
Sep	1.8	0.1	2.1	1.5
Oct	1.9	0.1	2.3	1.5
Nov	1.9	0.2	2.6	1.6
Dec	2.0	0.3	2.7	1.4

Table A1-5. Relative humidity (%), monthly averages with standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	90.5	2.0	94.0	84.6
Feb	85.7	3.4	91.7	80.3
Mar	86.6	3.5	92.2	76.8
Apr	77.7	2.8	83.1	70.0
May	76.0	3.2	82.0	70.2
Jun	76.2	3.3	84.4	69.0
Jul	73.6	4.8	82.7	63.9
Aug	80.1	2.4	84.0	72.9
Sep	80.6	2.3	86.0	75.6
Oct	78.3	3.0	87.3	73.9
Nov	81.4	3.4	93.5	76.2
Dec	85.3	3.1	90.6	75.3

Table A1-6. Global radiation (W m^{-2}), monthly averages with standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	11.8	2.9	18.3	6.1
Feb	33.5	5.9	43.2	23.7
Mar	74.4	9.2	94.6	61.5
Apr	130.3	15.6	161.3	103.3
May	196.3	19.9	236.0	160.9
Jun	214.6	23.6	253.2	155.0
Jul	202.0	28.4	277.4	150.7
Aug	151.3	18.0	188.0	117.3
Sep	91.5	10.4	114.6	71.2
Oct	41.8	4.1	52.9	31.1
Nov	14.8	3.0	20.5	8.3
Dec	7.4	1.9	10.3	3.9

Table A1-7. Cloud cover fraction, monthly averages with standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	0.7	0.1	0.9	0.5
Feb	0.7	0.1	0.9	0.4
Mar	0.7	0.1	0.8	0.5
Apr	0.6	0.1	0.8	0.5
May	0.5	0.1	0.7	0.4
Jun	0.6	0.1	0.8	0.4
Jul	0.6	0.1	0.7	0.3
Aug	0.6	0.1	0.7	0.4
Sep	0.6	0.1	0.8	0.5
Oct	0.7	0.1	0.9	0.5
Nov	0.7	0.1	0.9	0.6
Dec	0.7	0.1	1.0	0.4

Precipitation

Table A1-8. As Table A1-1 for precipitation.

Years Station	1970– 1987	1988	1989– 1993	1994– 1996	1997– 2000	2001	2002*	2003
Forsmark (Högmast)							■	■
Forsmark (Storskäret)							■	■
Örskär		■		■	■	■	■	
Östhammar				■	■	■	■	
Lövsta				■	■	■	■	
Marsta (Uppsala)				■	■			
Uppsala airport	■	■	■	■				

Table A1-9. Precipitation (corrected) (mm), monthly averages with standard deviation, minimum, and maximum in the meteorological driving data set constructed for Forsmark 1970–2004.

Month	Ave	Std	Max	Min
Jan	41.5	19.7	76.8	6.1
Feb	25.5	17.7	62.5	2.5
Mar	46.7	24.3	98.8	0.1
Apr	46.5	28.4	121.8	5.2
May	30.3	17.8	75.7	4.8
Jun	50.8	27.4	118.5	8.4
Jul	66.3	35.9	136.7	7.2
Aug	49.4	32.4	134.6	8.7
Sep	52.8	31.8	150.1	10.1
Oct	44.8	24.2	107.0	6.6
Nov	58.2	28.7	130.5	0.0
Dec	47.7	24.6	99.6	8.4

Potential evapotranspiration

Table A1-10. Potential evapotranspiration, monthly averages with standard deviation, minimum, and maximum, calculated with the meteorological driving data set constructed for Forsmark 1970–2004 using the original Penman equation /Penman 1953/ assuming albedo=20%.

Month	Ave	Std	Max	Min
Jan	–8.1	4.4	–0.8	–21.1
Feb	–0.1	3.3	5.9	–7.8
Mar	13.2	2.4	19.7	8.3
Apr	41.4	5.4	53.1	33.3
May	79.8	9.5	101.6	57.9
Jun	98.9	11.5	119.5	68.7
Jul	103.4	16.8	146.7	74.5
Aug	68.5	8.9	83.9	50.7
Sep	30.1	4.3	40.8	23.2
Oct	10.1	3.1	15.4	4.6
Nov	–1.2	3.4	5.9	–10.1
Dec	–7.3	4.6	3.3	–16.9

Appendix 2

Parameter lists

Table A2-1. Model soil profile layers and depths in (m).

Layer #	Depths Upper	Lower	Thickness
1	0.00	0.05	0.05
2	0.05	0.15	0.10
3	0.15	0.25	0.10
4	0.25	0.35	0.10
5	0.35	0.50	0.15
6	0.50	0.70	0.20
7	0.70	0.90	0.20
8	0.90	1.20	0.30
9	1.20	1.50	0.30
10	1.50	2.10	0.60
11	2.10	2.70	0.60
12	2.70	3.30	0.60
13	3.30	4.30	1.00
14	4.30	5.30	1.00
15	5.30	6.30	1.00

Table A2-2. Soil hydraulic properties, parameter values for Brooks-Corey water retention function.

Layer depths (m) Upper	Lower	λ (–)	h_a (cm)	θ_s (vol%)	θ_p (vol%)	θ_r (vol%)	θ_{macro} (vol%)
0.00	0.2	0.389	9.731	54.3	6.4	0.170	4
0.20	0.25	0.382	8.592	55.5	6.4	0.169	4
0.25	0.35	0.334	14.943	55.8	6.4	0.218	4
0.35	0.45	0.355	6.124	48.4	5.4	0.138	4
0.45	0.55	0.156	6.841	45.3	3.4	0.258	4
0.55	0.91	0.368	3.166	49.1	3.4	0.104	4
0.91	4.00	0.112	8.805	20.7	1.5	0.127	4
4.00	5.00	0.330	47.000	30.0	2.9	0.136	4

λ = pore size distribution index, h_a = air entry pressure, θ_s = porosity, θ_r = residual water content, θ_{macro} = macro pore volume.

Table A2-3. Soil hydraulic properties, parameters for hydraulic conductivity.

Layer depths (m) Upper	Lower	k_s (mm day^{-1})	$n_{Tortuosity}$ (–)	n_{SatRel} (–)	$n_{SatEffective}$ (–)
0	0.2	1,037	1	8.141	8.141
0.2	0.25	10,800	1	8.236	8.236
0.25	0.35	281	1	8.989	8.989
0.35	0.45	430	1	8.641	8.641
0.45	0.55	430	1	15.825	15.825
0.55	0.91	430	1	8.428	8.428
0.91	4.00	833	1	8.428	8.428
4.00	5.00	5	1	8.428	8.428

k_s = saturated hydraulic conductivity, $n_{Tortuosity}$, n_{SatRel}, and $n_{SatEffective}$ = parameters in

Table A2-4. Plant properties.

	Unit	Tree layer	Field layer
Max Height	m	30	0.2
Root Lowest Depth	m	–0.7	–0.7
Albedo	%	8	9
Specific Leaf Area	gC m^{-2}	100	50
Maximum Leaf Lifetime	year	5	1

Table A2-5. Plant growth.

	Unit	Tree layer	Field layer	Comments
Allocation parameters				
Mobile Allo Coef	–	0.5	0.5	
Shoot Coef	–	1.0	1.0	
Leaf c1	–	0.2	0.5	
Root CN c1	–	0.5	0.2	
Root CN c2	–	–0.1	–0.1	
Litter fall Above Ground				
Leaf	day^{-1}	0.0027	0.0027	
Stem	day^{-1}	0.000018	0.00018	
Litter fall Below Ground				
Root	day^{-1}	0.0054	0.0054	
Minimum CN Ratios of plants				
Leaf	gC gN^{-1}	25	25	
Stem	gC gN^{-1}	533	300	
Root	gC gN^{-1}	40	40	
Photosynthesis				Carbon assimulation is reduced from the optimum as a function of the C/N ratio of the leaves. The scaling function varies linearly from 1 at a C/N ration equal to the optimum value to 0 at the threshold value.
RadEfficiency	gDw MJ^{-1}	2	2	
Optimum C/N ratio leaf	gC gN^{-1}	25	25	
Threshold C/N ratio leaf	gC gN^{-1}	100	100	

	Unit	Tree layer	Field layer	Comments
Respiration of plants				
Growth	day^{-1}	0.28	0.28	
Leaf-maintainance	day^{-1}	0.0015	0.0015	
Stem-maintainance	day^{-1}	0.0001	0.0001	
Root-maintainance	day^{-1}	0.006	0.006	

Table A2-6. Soil organic processes.

	Unit	Value	Comment
CN Ratio Microbe	$gC\ gN^{-1}$	20	High value used to avoid immobilisation phenomenas
RateCoefHumus	day^{-1}	0.0002	Corresponds to about 50 year of turnover time
RateCoefLitter	day^{-1}	0.01	Corresponds to about 1 year of turnover time
Upt OrgRateCoef H	day^{-1}	0.0002	High value to avoid N stress
Upt OrgRateCoef L	day^{-1}	0.001	

Table A2-7. Soil Mineral Processes.

	Unit	Value	Comment
DenitTemQ10	–	3	
DenitThetaPowerC2	–	2	
DenitThetaRange	vol %	17	
NUptFlexibilityDeg	–	0.9	High value to allow flexibility to uptake in the entire root zone
NUptMaxAvailFrac	–	0.2	
NitrateAmmRatio	–	0.25	
NitriTemQ10	–	3	

Table A2-8. Nitrogen deposition.

	Unit	Value	Comment
Dep N DryRate	$g\ m^{-2}\ day^{-1}$	0.0005	The values for dry and wet deposition corresponds to the average annual deposition reported by IVL when using the average annual precipitation for Forsmark.
Dep N WetConc	$mgN\ l^{-1}$	0.05	

Table A2-9. Transpiration and Interception.

	Unit	Tree	Field	Comment
Interception				
WaterCapacityPerLAI	$mm\ m^{-2}$	0.3	0.3	These parameters are common for all plant layers in the model.
SnowCapacityPerLAI	$mm\ m^{-2}$	4.2	4.2	
WithinCanopyRes	$s\ m^{-1}$	10	10	
Transpiration				
Conduct Max	$m\ s^{-1}$	0.005	0.02	The tree layer values corresponds to Norunda, Uppland /Gustafsson et al. 2004/. The field layer was assigned parameter values corresponding to lower minimum canopy resistance, and lower sensitivity to radiation and vapour pressure deficit than the tree layer.
Conduct Ris	$J\ m^{-2}\ day^{-1}$	1.123E+07	1.180E+06	
Conduct VPD	Pa	359	2,000	
CritThresholdDry	cm water	150	150	
FlexibilityDegree	–	0.7	0.7	

Appendix 3

Additional tables of simulated carbon pools and fluxes

Forsmark

Table A3-1. Carbon storage and annual change in soil and vegetation pools, simulated for a 100 year development of a coniferous forest stand in the Forsmark area, average for stand age periods 0–30, 30–100, and 0–100 years.

Stand age	0–30 years			30–100 years			0–100 years		
	gC m^{-2}	gC m^{-2} y^{-1}	–	gC m^{-2}	gC m^{-2} y^{-1}	–	gC m^{-2}	gC m^{-2} y^{-1}	–
Tree layer									
Leaf	243	13	0.12	442	0.5	0.05	382	4.3	0.07
Stem	1,739	128	0.83	7,834	85	0.92	6,006	98	0.90
Fine roots	118	5	0.06	188	–0.5	0.02	167	1.1	0.03
Total	**2,104**	**146**	**1.00**	**8,470**	**85**	**1.00**	**6,560**	**103**	**1.00**
Field layer									
Leaf	109	1	0.25	6	–0.5	0.08	37	–0.1	0.13
Stem	281	9	0.65	68	–3.6	0.89	132	0.1	0.81
Fine roots	34	0	0.08	2	–0.1	0.02	11	–0.1	0.04
Total	**433**	**10**	**1.00**	**76**	**–4.3**	**1.00**	**183**	**–0.1**	
Soil organic matter									
Humus	8,447	4	0.93	8,609	0.7	0.94	8,560	2	0.93
Litter	644	7	0.07	595	0.2	0.06	610	2	0.07
Total	**9,093**	**11**	**1.00**	**9,206**	**0.9**	**1.00**	**9,172**	**4**	**1.00**
Ecosystem									
Above ground	2,371	151	0.20	8,350	81	0.47	6,556	102	0.41
Below ground	9,243	15	0.80	9,394	0.3	0.53	9,349	5	0.59
Total	**11,614**	**167**	**1.00**	**17,744**	**82**	**1.00**	**15,905**	**107**	**1.00**

Table A3-2. Primary production in the tree and field layer, simulated for a coniferous forest stand in the Forsmark area.

Carbon fluxes	0–30 years			30–100 years			0–100 years		
(gC m^{-2} y^{-1})	GPP	NPP	GPP/NPP	GPP	NPP	GPP/NPP	GPP	NPP	GPP/NPP
Tree layer									
Leaf	127	33	0.26	199	37	0.19	178	36	0.21
Stem	232	139	0.60	361	136	0.38	323	137	0.44
Fine roots	277	91	0.33	435	140	0.32	387	125	0.32
Total	637	**263**	0.41	995	**314**	0.32	888	**298**	0.34
Field layer									
Leaf	120	60	0.50	6	3	0.48	41	20	0.48
Stem	43	26	0.62	3	1	0.30	15	8	0.39
Fine roots	78	25	0.32	4	1	0.31	26	8	0.32
Total	241	**111**	0.46	13	**5**	0.39	81	**37**	0.41
Field+Tree layer									
Total	878	**374**	0.43	1,008	**318**	0.32	969	**335**	0.35

Table A3-3. Respiration in vegetation and in soil organic matter, simulation of coniferous forest stand Forsmark area.

Stand age	0–30 year Respiration ($gC\ m^{-2}\ y^{-1}$)			Fraction (–)	30–100 year Respiration ($gC\ m^{-2}\ y^{-1}$)			Fraction (–)	0–100 year Respiration ($gC\ m^{-2}\ y^{-1}$)			Fraction (–)
	G*	**M***	**T***		**G**	**M**	**T**		**G**	**M**	**T**	
Tree layer												
Leaf	36	59	94	0.25	56	106	162	0.24	50	92	141	0.24
Stem	65	28	93	0.25	101	124	226	0.33	90	96	186	0.32
Fine roots	78	109	186	0.50	122	173	294	0.43	108	153	262	0.44
Total	**178**	**195**	**374**	**1.00**	**279**	**403**	**682**	**1.00**	**249**	**341**	**589**	**1.00**
Field layer												
Leaf	34	27	60	0.47	2	2	3	0.43	11	9	20	0.44
Stem	12	4	16	0.13	1	1	2	0.23	4	2	6	0.20
Fine roots	22	31	53	0.41	1	2	3	0.34	7	10	18	0.36
Total	**67**	**62**	**129**	**1.00**	**4**	**4**	**8**	**1.00**	**23**	**22**	**44**	**1.00**
Soil respiration												
Heterotrof Humus			45				54				51	
Heterotrof Litter			163				183				177	
Total			**208**				**237**				**228**	
Autotrof (roots)			239				297				280	
Ecosystem												
Above ground			264	0.37			392	0.42			354	0.41
Below ground			447	0.63			534	0.58			508	0.59
Total			**711**	**1.00**			**926**	**1.00**			**861**	**1.00**

* G = growth respiration, M = maintainance respiration, T = total, F = Fraction of total (–).

Oskarshamn

Table A3-4. Average annual carbon budget, CoupModel simulations, coniferous forest stand Oskarshamn 0–100 years development.

	Input ($gC\ m^{-2}\ y^{-1}$)		Output ($gC\ m^{-2}\ y^{-1}$)			Balance
	GPP	**Litterfall**	**Respiration**	**Litterfall**	**Leaching**	($gC\ m^{-2}\ y^{-1}$)
Tree layer	1,064		726	219		118
Field layer	52		29	23		0
Soil organic matter		242	240		0	3
Total	**1,116**		**996**		**0**	**120**

Table A3-5. Average annual carbon budget, CoupModel simulations, coniferous forest stand Oskarshamn 0–30 years development.

	Input ($gC\ m^{-2}\ y^{-1}$)		Output ($gC\ m^{-2}\ y^{-1}$)			Balance
	GPP	Litterfall	Respiration	Litterfall	Leaching	($gC\ m^{-2}\ y^{-1}$)
Tree layer	870		526	146		199
Field layer	170		95	71		5
Soil organic matter		216	217		0	0
Total	**1,041**		**837**		**0**	**204**

Table A3-6. Average annual carbon budget, CoupModel simulations, coniferous forest stand Oskarshamn 30–100 years development.

	Input ($gC\ m^{-2}\ y^{-1}$)		Output ($gC\ m^{-2}\ y^{-1}$)			Balance
	GPP	Litterfall	Respiration	Litterfall	Leaching	($gC\ m^{-2}\ y^{-1}$)
Tree layer	1,147		813	251		83
Field layer	1		1	2		–2
Soil organic matter		253	250		0	3
Total	1,148		1,064		**0**	**84**

Table A3-7. Carbon storage ($gC\ m^{-2}$) and annual change of carbon ($gC\ m^{-2}\ year^{-1}$) in soil and vegetation layers, simulated for a 100 year development of a coniferous forest stand in Oskarshamn area, average of stand age 0–30 and 30–100 years, compared with site specific estimates from Oskarshamn /SKB 2006/.

	Simulated 0–30 y		Oskarshamn data		Simulated 30–100 y		Oskarshamn data	
	$gC\ m^{-2}$	$gC\ m^{-2}\ y^{-1}$	$gC\ m^{-2}$	$gC\ m^{-2}\ y^{-1}$	$gC\ m^{-2}$	$gC\ m^{-2}\ y^{-1}$	$gC\ m^{-2}$	$gC\ m^{-2}\ y^{-1}$
Tree layer								
Leaf	322	17	136	33	494	–1	356	53
Stem	2,417	176	1,340	69	9,336	85	5,332	111
Coarse roots			221	69			853	110
Fine roots	153	7	118	0	210	–1	455	
Total	**2,897**	**199**	**1,814**	**172**	**10,048**	**83**	**6,995**	**274**
Field layer								
Total	**322**	**5**			**29**	**–2**	**401**	
Soil organic matter								
Total	**8,890**	**0**			**8,972**	**3**	**9,551**	
Ecosystem								
Above ground	3,031	198			7,811	117	6,089	
Below ground	9,064	6			9,145	3	10,858	
Total	**12,095**	**204**			**16,956**	**120**	**16,947**	

Table A3-8. Primary production in the tree and field layer, annual mean, max, min, and standard deviation (std), compared with the site estimates from Oskarshamn /SKB 2006/, where numbers in brackets includes mycelia production.

Carbon fluxes	Simulated 0–30 y		Simulated 30–100 y		Oskarshamn >30 y
(gC m⁻² y⁻¹)	GPP	NPP	GPP	NPP	NPP
Tree Layer					
Mean	870	345	1,147	334	982
Max	1,207	440	1,210	428	
Min	115	64	1,106	291	
Std	291	92	29	40	
Field Layer					
Mean	170	76	1	0	34
Max	472	260	9	1	
Min	11	2	1	0	
Std	139	68	1	0	
Mycelia					
mycelia NPP					137
Ecosystem					
Mean	1,041	421	1,148	334	1,153
Max	1,220	466	1,218	429	
Min	136	77	1,107	291	
Std	209	66	30	40	

Table A3-9. Primary production in the tree and field layer, simulated for a coniferous forest stand in the Oskarshamn area.

Carbon flux	0–30 years			30–100 years			0–100 years		
(gC m^{-2} y^{-1})	GPP	NPP	GPP/NPP	GPP	NPP	GPP/NPP	GPP	NPP	GPP/NPP
Tree layer									
Leaf	174	43	0.25	229	41	0.18	213	41	0.20
Stem	322	191	0.59	417	145	0.35	389	159	0.42
Fine roots	374	111	0.30	500	148	0.30	462	137	0.30
Total	**870**	**345**	**0.40**	**1,147**	**334**	**0.29**	**1,064**	**337**	**0.32**
Field layer									
Leaf	85	41	0.49	0.6	0.3	0.45	26	13	0.46
Stem	31	18	0.60	0.0	0.0	0.50	9	6	0.53
Fine roots	55	16	0.29	0.4	0.1	0.29	17	5	0.29
Total	170	76	0.44	1.3	0.1	0.09	52	23	0.20
Tree+field layer									
Total	**1,041**	**421**	**0.40**	**1,148**	**334**	**0.29**	**1,116**	**360**	**0.32**

Table A3-10. Respiration in vegetation and in soil organic matter, simulation of coniferous forest stand Oskarshamn area.

Respiration (gC m⁻² y⁻¹)	0–30 year G*	M*	T*	F*	30–100 year G	M	T	F	0–100 year G	M	T	F
Tree layer												
Leaf	49	82	131	0.25	64	125	189	0.23	60	112	171	0.24
Stem	90	41	131	0.25	117	155	272	0.33	109	121	230	0.32
Fine roots	105	159	263	0.50	140	212	352	0.43	129	196	325	0.45
Total	**244**	**282**	**526**	**1.00**	**321**	**491**	**813**	**1.00**	**298**	**429**	**726**	**1.00**
Field layer												
Leaf	24	20	44	0.46	0.2	0.2	0.3	0.30	7	6	13	0.35
Stem	9	4	12	0.13	0.0	0.5	0.5	0.46	3	1	4	0.36
Fine roots	15	23	39	0.41	0.1	0.2	0.3	0.23	5	7	12	0.29
Total	**48**	**47**	**95**	**1.00**	**0.4**	**0.8**	**1.1**	**1.00**	**15**	**15**	**29**	**1.00**
Soil respiration												
Heterotrof Humus			50				57				55	
Heterotrof Litter			166				194				185	
Total			217				250				240	
Autotrof (roots)			302				352				337	
Ecosystem												
Above ground			318	0.38			462	0.43			419	0.42
Below ground			519	0.62			602	0.57			577	0.58
Total			**837**	**1.00**			1,064	1.00			996	1.00

* G = growth respiration, M = maintainance respiration, T = total, F = Fraction of total (–).

Table A3-11. Litterfall from tree layer and field layer, simulated for a coniferous forest stand in Oskarshamn, compared to the site specific estimates /SKB 2006/.

	Simulated 0–30 y gC m⁻² y⁻¹	–	Simulated 30–100 y gC m⁻² y⁻¹	–	Simulated 0–100 y gC m⁻² y⁻¹	–	Oskarshamn data gC m⁻² y⁻¹
Tree layer							
Leaf	26	0.18	41	0.16	37	0.17	253
Stem	15	0.10	60	0.24	47	0.20	
Fine roots	104	0.71	149	0.60	136	0.63	455
Total	**146**	**1.00**	**251**	**1.00**	**219**	**1.00**	**708**
Field layer							
Leaf	41	0.58	0.4	0.16	13	0.29	
Stem	14	0.19	1.8	0.78	5	0.60	
Fine roots	16	0.22	0.1	0.06	5	0.11	
Total	**71**	**1.00**	**2.3**	**1.00**	**23**	**1.00**	
Ecosystem							
Above ground litter	97	0.45	104	0.41	102	0.42	253
Root litter	120	0.55	150	0.59	141	0.58	455
Mycelia litter	–	–	–	–	–	–	137
Total	**216**		**253**		**242**		**845**

* Mycelia is implicitly represented by the fine roots in the CoupModel, and thus simulated root litter should be compared with the sum of observed root and mycelia litter.

Table 3-12. C/N ratios in the soil and vegetation, simulated for a coniferous forest stand in Oskarshamn.

	0–30 year gC gN^{-1}	30–100 year gC gN^{-1}
Tree layer		
Leaf	46	52
Stem	966	971
Root	24	26
Field layer		
Leaf	28	14
Stem	263	82
Root	17	19
Soil organic matter		
Humus	32	31
Litter	23	25
Litter surface	54	71