Modelling radiation use, water and nitrogen in willow forest

Henrik Eckersten, Angela Noronha-Sannervik,

Bengt Torssell, Per Nyman

Abstract

Modelling radiation use, water and nitrogen in willow forest

Henrik Eckersten, Angela Noronha-Sannervik, Bengt Torssell, Per Nyman

Department of Crop Production Ecology, Swedish University of Agricultural Sciences, P.O. Box 7043 UPPSALA, Sweden.

In this paper it was investigated to what extent it is necessary to include estimates of site nitrogen (N) conditions for prediction of biomass production of short rotation willow (Salix sp.) forests in Sweden. At the same time it was tested a growth model, that can be parameterised from a very limited amount of soil information of the site concerned and still is believed to mimic major effects of N dynamics on growth.

The willow growth model consists of three main modules: one for simulation of annual biomass production, one for daily water conditions and one for daily soil nitrogen conditions. Stem biomass production is predicted from the fraction of solar radiation intercepted, radiation use efficiency, shoot age and mortality and water and nitrogen availability. Nitrogen limitation to biomass production, was estimated as a seasonal N availability factor. This factor is estimated as the difference between seasonal plant N demand, and the seasonal net supply of N to the soil mineral N pool. The water and nitrogen modules were parameterised and calibrated for a clay soil and for a loamy sandy soil, as simulated by detailed soil heat, water, nitrogen and carbon models (SOIL and SOILN), that were tested elsewhere. Parameter values of other soil types were estimated with help of USDA soil classification.

The model was applied to 22 field experiments located at five different sites in southern Sweden. They differed in weather conditions, soil type and fertilisation level (N treatment). The model was able to explain 82 - 86 % of the observed variations in harvested biomass and 33 - 41 % of the variations in annual production. Taking into account the soil N conditions improved the model predictions of variations in harvested biomass as caused by N treatments, from 70 % to 82 %. Model predictions of the variations in annual production, or in harvest production of stands within the same N treatment, were not improved.

It is concluded, that for site conditions of willow forest plantations in Sweden, differences in N treatments are more important than differences in natural soil N availability between sites, and that differences in N availability between sites, due to fertilisation, are more important than differences in water availability or solar energy absorption, in determining variations in harvested biomass.

Sammanfattning

Modellering av strålningsutnyttjande, vatten och kväve i energiskogsbestånd

Henrik Eckersten, Angela Noronha-Sannervik, Bengt Torssell, Per Nyman

Department of Crop Production Ecology, Swedish University of Agricultural Sciences, P.O. Box 7043 UPPSALA, Sweden. E-mail:henrik.eckersten@vpe.slu.se

Hur stor betydelse har beräkningar av odlingsplatsens kväveförhållanden för förutsägelse av energiskogens (Salix) tillväxt? Det är denna fråga som besvarats i denna studie. Dessutom testades en tillväxtmodell som kan parameteriseras för växtplatser med en mycket begränsad mängd indata.

Modellen består av tre delmodeller. En simulerar årlig tillväxt, en simulerar vattenförhållanden dagligen och en simulerar kväveförhållanden, också dagligen. Tillväxten av stambiomassa beräknas utifrån den av lövverket uppfångade solinstrålningen, strålningsutnyttjandeeffektiviteten, skottålder och mortalitet samt vatten- och kväveförhållanden. Kväveunderskottseffekter på tillväxten beräknades på säsongsbasis som skillnaden mellan växtens ackumulerade efterfrågan på kväve under säsongen och nettotillförseln till markens mineralkvävepool. Delmodellerna för vatten och kväve baseras på de detaljerade modellerna SOIL och SOILN som testats i tidigare experiment. Delmodellerna parameteriserades för en lerjord och en sandjord. Parametervärden för andra markegenskaper beräknades m h a USDA markklassifiering.

Modellen tillämpades på 22 fältexperiment på fem olika lokaler i södra Sverige som representerade skillnader i främst väderförhållanden, markegenskaper och kvävegödslingsnivåer. Modellförutsägelserna förklarade 82 - 86% av den observerade variationen i biomassa vid skörd och 33 – 41% av variationen i årlig tillväxt. Beaktandet av kväveförhållandena förbättrade förutsägelserna av variationen i skördad biomassa från 70% till 82%. Förutsägelsernas förklaringsförmåga av den årliga variation förbättrades inte, liksom inte förklaringsförmågan av biomassan vid skörd inom en viss kvävetillförselnivå.

Slutsatser från denna studie är att skillnader i kväveförhållanden mellan marker där Salix odlats i Sverige bedöms ha mindre betydelse för variationen i tillväxt än skillnader i de kvävegödslingsnivåer som tillämpats. Också skillnader i tillgänglighet i vatten och solinstrålning har mindre betydelse än kvävegödslingsnivåerna.

Contents

Appendix

Appendix 1
Modelling processes

Appendix 2
Site description

Introduction

In Sweden, commercial plantations of willows (*Salix* sp.) have been established mainly on former farmland. These plantations are managed as short-rotation forestry for energy purposes. This implies that above-ground woody biomass is harvested at regular intervals, usually three to five years, (Ledin & Perttu, 1989). The yields required to obtain profitability are above eight tonnes per hectare and year (Rosenqvist, 1997).

However the production level of commercial plantations varies significantly from site to site and in many cases it does not reach $8 \, t \, ha^{-1} \, year^{-1}$ (see Jonsson, 1994). This may be due to both, differences in climatic conditions between the sites, and in part, as referred by Jonsson (1994), differences in site productivity and management. In particular the nutrient status of the soil has been considered to be very important in short-rotation forestry, since willow species grow rapidly and bind a great amount of nutrients in their biomass (Hytönen et al., 1995). The build up of large nutrient reserves (particularly nitrogen (N)), is considered fundamental for their resprouting potential (Bollmark et al., 1999) and for a high growth rate of regenerating shoots after harvest (Sennerby-Forsse & Zsuffa, 1995).

Fertilisation is a useful measure to improve crop yields (Ericsson, 1994), however, fertilisation implies costs and risk of N leaching, and it is important to account for the natural ability of the soil to supply the plants with N. This ability varies between soil types as the organic matter content and quality, as well as, the water conditions and biological activities vary.

Although the importance of N conditions on willow growth has been demonstrated in several experiments (e.g Ericsson, 1981; Alriksson, 1997; Weih & Nordh, 2002), it is still rare with successful quantitative predictions of the effect on willow production under field conditions (Kopp et al., 1996; Weih & Nordh, 2002). One reason for that is difficulties in distinguish the effects of N in relation to the other factors also affecting growth. Other reasons are problems in estimating the availability of N to plant, and that fertilisation may lead to that other factors might become limiting to growth, for instance by means of a reduction in soil pH and / or soil nutrient imbalance (Kopp et al., 1996).

There are several growth models that address the influence of soil N availability on plant growth (e.g. Ågren, 1989; Eckersten & Slapokas, 1990; Eckersten et al., 1995). The mechanistically based models are mostly used on field experiments with detailed observations and not used frequently on the many more field experiments with less data available, but comprising a larger range of site conditions. Instead models that are simplified, often on the expense of its mechanistic representation, are used to fulfil statistical requirements. However, still the mechanistic representation can be of central importance when considering the effect of site N conditions on production. This study addresses the benefit of including a more mechanistic approach when predicting the effect of N conditions on growth.

A detailed mechanistically based model for simulating willow growth (SOILN; Eckersten et al., 1998) was used as a base for developing a simplified model that was more easily applicable to the limited soil data information available for the different sites included in this study. The SOILN model was chosen because it has been used to evaluate the importance of different processes related to the N dynamics, both for agricultural (e.g. Blombäck et al., 1995) and for forest (e.g. Eckersten et al., 1995) systems in Sweden, with good results. In the new model development the requirement of input data was simplified in order to make the model applicable to the limited soil data information available for the different sites included in this paper.

The similar approach was used for water in a previous simulation study on grass ley by Eckersten et al. (2004). It was concluded that simulated site water availability did not contribute to explain variations in biomass production at different sites. However, there might be an effect of water on willow growth by means of its effect on nitrogen availability (Ögren, 1988; Weih, 2001).

The aim of this study is to determine to what extent the soil nitrogen conditions can contribute to explain the variations of biomass production of willow stands, growing under different fertilisation regimes and site conditions, in southern Sewden.

Material and methods

Experimental data

The model was developed and parameterised for Modellskogen, a willow stand growing on clay soil at Uppsala. The stand was planted in the summer of 1984 with a clone mixture of *Salix viminalis* L. cuttings and the data used in this study cover the period 1985-1994 including three harvests. The stand was fertilised and irrigated during the first eight years. The application rates varied considerably between years but were on average 105 kg N ha^{-1} y^{-1} and 100 mm y^{-1}, respectively. A more detailed description can be found in Verwijst (1991). A summarised description of the site and plantation characteristics and management is given in Table A1 (Appendix 2).

To test the model applicability, data from 22 different field fertilisation experiments, carried out on commercial willow coppice plantations, at five different locations in southern Sweden, were used. These sites, and plantations, with the exception of Gottsunda and Brunnby, have previously been described elsewhere (e.g. Alriksson, 1997; Noronha Sannervik, 2003). Here we present a summarised description of the site and plantation characteristics and management in Tables A1 and A2 (Appendix 2).

8

To investigate the influence of the N fertilisation rates on model predictability, model comparison was done for three groups of test data: 1) *All* – includes all the 22 test stands; 2) *Fertilised* – includes the 12 stands that, on average, received more than 75 kg N ha^{-1} y^{-1} (High and Moderate fertilisation in Table A1 in Appendix 2); and 3) *Unfertilised* - includes the 10 stands that, on average, received less than 65 kg N ha^{-1} y^{-1} (Low and No fertilisation in Table A2 in Appendix 2).

Model

The RUE-W-N model consists of three main modules: one for biomass, one for water availability and one for nitrogen availability (see Fig. 1). The biomass model (Biomass model, in Fig. 1) simulates stem production and mortality on annual bases. The growth depends on seasonal values for water and nitrogen availability that are estimated from daily simulations (Water model, and Nitrogen model in Fig. 1). The water and nitrogen simulations depend on the plant development in terms of leaf area, root depth, litter fall and plant nitrogen demand (Input to water model, and Input to nitrogen model in Fig. 1). These, daily values, are derived from the annually simulated stem production. The nitrogen simulations depend on daily inputs from the water simulations whereas the water simulations depend on the nitrogen simulations, only indirectly, by means of the annual stem production. The biomass and water models have been described in detail elsewhere (Noronha Sannervik, et al., 2005 and Eckersten et al., 2004) and are only described briefly below. The model is programmed in the Matlab (version 5.3) and Simulink (version 3.0) software environment (MathWork Ltd) allowing a clear representation of the different modules (see Fig. 1). A time step of one day and the Euler method of integration are used.

Biomass model

The biomass model is based on the radiation use efficiency concept (Monteith, 1977). Stem growth is simulated on an annual basis as proportional (ε) to the radiation intercepted during the vegetation period (R_{Int}). Both ε and R_{Int} depend on shoot age (t_{Age}). The increase in growth is counteracted by a fraction (m) lost by mortality. At harvest biomass is removed ($W_{Harvest}$). The annual stem biomass balance is:

$$\Delta W = \varepsilon(t_{Age})\ R_{Abs}(t_{Age})\ f_W\ f_N\ (1\text{-}m) - m\ W - W_{Harvest} \qquad (1)$$

where f_W and f_N are reduction factors, ranging between 0 and 1, that relate growth to water and nitrogen availability on an annual basis.
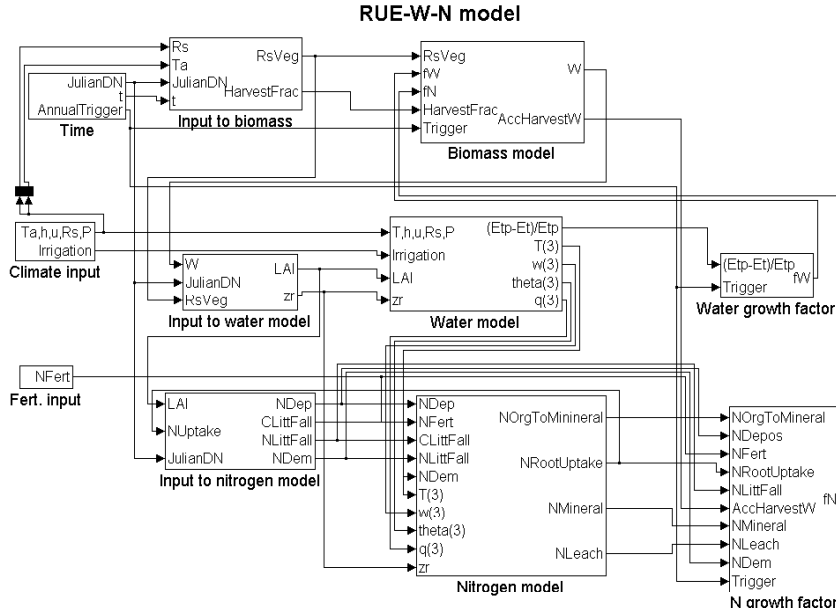
Fig. 1. The RUE-W-N model is programmed in Matlab/Simulink program environment. Symbols are: Ta and T are air temperature, Rs is global radiation, RsVeg is accumulated Rs during vegetation period, h is air humidity, u is wind speed, P is precipitation, zr is root depth, w is soil water content, theta is soil relative water content (θ), q is soil water flow, NOrgToMineral is $\Sigma N_{Org \rightarrow Mineral}$, JulianDN is daynumber from January 1, and Annual Trigger activates annual calculations. Explanation of other symbols are found in the text.

Water availability is simulated daily by the water model and used to estimate an annual water factor (f_W) that influences growth, expressed as the reduced annual actual transpiration (ΣE_t) relative to the annual potential transpiration (ΣE_{tp}).

$$f_W = a_W (1 - (\Sigma E_{tp} - \Sigma E_t) / \Sigma E_{tp}) \qquad 0 \leq f_W \leq 1 \qquad (2)$$

The parameter a_W is larger than one, and makes growth not sensitive to transpiration reductions close to potential transpiration conditions.

The growth reduction factor (f_N) due to nitrogen deficit is expressed as the difference between annual N demand and annual N availability ($N_{Deficit}$) in relation to the annual demand (ΣN_{Dem}).

$$f_N = 1 - b_N N_{Deficit} / (a_N \Sigma N_{Dem}) \qquad 0 \leq f_N \leq 1 \qquad (3)$$

The parameter a_N is the fraction of the plant demand for N uptake that is needed for maximal growth rate. The parameter b_N is the relative decrease of f_N caused by an increased N deficit.

The N deficit is calculated on an annual basis and is the difference between annual plant N demand for maximal growth and annual N availability. The N availability

is the net of input flows, annual net mineralisation ($\Sigma N_{Org \to Mineral}$), deposition ($\Sigma N_{Dep}$) and fertilisation ($\Sigma N_{Fert}$), and output flow, annual leaching (ΣN_{Leach}), to the soil mineral N pool, added by the amount available at the beginning of the year ($N_{Mineral}$) and an internal supply of N ($N_{Internal}$) from the plant itself.

$$N_{Deficit} = a_N \, \Sigma N_{Dem} - (\Sigma N_{Org \to Mineral} + \Sigma N_{Dep} + \Sigma N_{Fert} - \Sigma N_{Leach} + N_{Mineral} + N_{Internal}) \geq 0 \qquad (4)$$

The annual sums are calculated from simulated daily values. The internal supply is estimated to increase continuously by a fraction (β) of the accumulated root uptake reduced by N lost by litter fall ($N_{LittFall}$) or taken away at harvest (assuming the N concentration of stem to be 0.5 %).

$$N_{Internal} = \beta \, (\Sigma N_{RootUptake} - \Sigma N_{LittFall} - 0.005 \, \Sigma W_{Harvest}) \qquad (5)$$

In eq. 5 the symbol Σ stands for the accumulated sum during the whole simulation period.

Water model

The water model, described by Eckersten et al. (2004), is based on processes for throughfall, evaporation of intercepted water, soil evaporation, transpiration, root water uptake, infiltration, soil water storage, capillary rise, and run off. The model simulates water dynamics on a daily basis in the vertical dimension, disregarding horizontal water flows into the soil column. Soil heat storage is not considered. The model is basically similar to the water part of the SOIL (Jansson, 1991; Jansson & Halldin, 1979) and COUP (Jansson & Karlberg, 2001) models, except that only three layers are used to represent the soil profile (Eckersten, 1995). In the surface layer, infiltration and soil evaporation are the dominant processes. In the root zone, root water uptake (transpiration) is most important, and in the zone below the root zone, capillary rise and run off are the main processes.

Nitrogen model

The soil nitrogen model is based on processes for decomposition of dead organic matter, including mineralisation or immobilisation of N, nitrification, nitrate transport, and root N uptake. The model, is as concerns the processes, to a large extent similar to the SOILN model (Eckersten et al., 1998; Johnson et al., 1987). The present model is simplified as concerns the soil layer representation. The same three layers as for the water model are included. All processes act in all layers except root N uptake that does not occur in the layer below root zone. In the surface layer a large proportion of the organic matter originates from litter fall, and soil moisture conditions often become dry. In the root zone, root N uptake is usually the most important process, and in the layer below the root zone, moisture is normally high and N can be leached out of the profile. N mineralisation varies between layers because of different inputs of litter and different moisture conditions.

<u>Input from biomass model</u>

The soil nitrogen model needs input of daily values on plant N demand and litter fall (Input to nitrogen model, in Fig. 1), that are estimated from the leaf area, which in turn is estimated from the standing stem biomass at start of the growing season, see further Appendix 1.

The N demand function was derived from values simulated by the SOILN model for Modellskogen (Eckersten, 1994), and is proportional (k_{Max}) to the LAI development (cf. model by Sinclair & Muchow, 1995). This proportionality is modified so that, when LAI increases, the N demand increases strongly at low LAI ($k = 0.2$), whereas for decreasing LAI, it decreases strongly at high LAI ($k = 2$).

$$N_{demand} = k_{Max} \, (f_{LAI})^k \qquad\qquad \begin{array}{l} k = 0.2 \text{ if } \delta LAI/\delta t > 0 \\ k = 2 \quad \text{if } \delta LAI/\delta t \leq 0 \end{array} \qquad (6)$$

where f_{LAI} is LAI normalised to the seasonal maximal value (see Appendix 1). The daily litter fall function was determined to increase proportionally to LAI, representing mainly root turnover. The contribution from leaf senescence to litter fall is estimated to be proportional to the decrease rate of LAI ($-\delta LAI/\delta t$).

$$C_{LittFall} = k_{Li1} \, LAI + k_{Li2} \, (-\delta LAI/\delta t) \qquad\qquad \delta LAI/\delta t \leq 0 \qquad (7)$$

The nitrogen litter fall equals the carbon litter fall divided by the predefined C/N ratio of litter ($CN_{RatioLitt}$).

$$N_{LittFall} = C_{LitterFall} \, / \, CN_{RatioLitt} \qquad\qquad\qquad (8)$$

<u>Input from the water model</u>

Microbial processes and nitrate transport depend on the soil water content (w), the relative soil water content (θ) and water flows between layers (q), as simulated by the water model. These data are daily input to the nitrogen model (see Fig. 1).

<u>Carbon and nitrogen balance</u>

A total soil depth (z_{Soil}) defines the soil volume of nitrogen potentially available for the plant. This volume is divided into three layers in accordance to the water model (Eckersten et al., 2004). The surface layer is set to a constant depth of a few cm, the layer of the root zone varies in depth depending on root depth, and the depth of the layer below that, varies in accordance to the root zone layer and z_{Soil}. In each layer there are carbon pools for microbial biomass, litter and humus (fast and slow decomposable dead organic matter), and similar pools for nitrogen. There are also pools for ammonium N and nitrate N, respectively.

Separate from the soil layers, input of above ground litter and fertiliser are on a daily basis put into non active pools ($C_{LittAbove}$, $N_{LittAbove}$, $N_{FertAbove}$), from which material is transferred to the active pools of the soil layers at relative rates of k.

12

$$\delta C_{LittAbove} = 0.5\ C_{LittFall} - k_{Active}\ C_{LittAbove}(t\text{-}1) \tag{9}$$

$$\delta N_{LittAbove} = 0.5\ N_{LittFall} - k_{Active}\ N_{LittAbove}(t\text{-}1) \tag{10}$$

$$\delta N_{FertAbove} = N_{Fert} - k_{DisolvFert}\ N_{FertAbove}(t\text{-}1) \tag{11}$$

The above ground litter is assumed to be 50 % of the total litter fall ($C_{LittFall}$ and $N_{LittFall}$; see further Appendix 1).

In the surface layer there are C and N pools for microbes and dead organic matter, respectively, and mineral N pools. The total daily carbon balance of the surface layer (δC_{Surf}) is the difference between the input from litter and the loss by decomposition ($C_{MicSurf \to Atm}$), eq. 12. Nitrogen is mineralised, nitrified and transported with water flow to the root zone ($N_{Surf \to RZ}$). Daily N deposition (N_{Dep}) is set constant and is a direct input to the soil surface mineral N pools.

$$\delta C_{Surf} = k_{Active}\ C_{LittAbove} - C_{MicSurf \to Atm} \tag{12}$$

$$\delta N_{Surf} = k_{Active}\ N_{LittAbove} + k_{DisolvFert}\ N_{FertAbove} + N_{Dep} - N_{Surf \to RZ} \tag{13}$$

In the root zone the daily carbon balance (δC_{RZ}) is determined by root litter fall, assumed to be 50 % of total litter fall, reduced by the decomposition of organic matter ($C_{MicRZ \to Atm}$), eq. 14. For nitrogen (δN_{RZ}) there is a corresponding input of litter but also an input by nitrate N flow from above ($N_{Surf \to RZ}$) reduced by nitrate N flow to the layer below the root zone ($N_{RZ \to Below}$). A large term of this balance is the root N uptake (N_{Uptake}).

$$\delta C_{RZ} = 0.5\ C_{LittFall} - C_{MicRZ \to Atm} + \delta C_{RootDepth} \tag{14}$$

$$\delta N_{RZ} = 0.5\ N_{LittFall} - N_{Uptake} + N_{Surf \to RZ} - N_{RZ \to Below} + \delta N_{RootDepth} \tag{15}$$

The C and N balances of the root zone are also influenced by the change in root depth. Increasing root depth results in a part of the nitrogen and carbon in the layer below, being defined as belonging to the root zone ($\delta C_{RootDepth}$, $\delta N_{RootDepth}$).

Below the root zone carbon is lost to the atmosphere by decomposition ($C_{MicBelow \to Atm}$). Nitrogen is linked to layers above by means of nitrate N transport ($N_{RZ \to Below}$). N is lost from the soil profile by leaching (N_{Leach}). In addition the varying root depth influence the balances in analogy to the balances of the root zone.

$$\delta C_{Below} = -\ C_{MicBelow \to Atm} - \delta C_{RootDepth} \tag{16}$$

$$\delta N_{Below} = N_{RZ \to Below} - N_{Leach} - \delta N_{RootDepth} \tag{17}$$

Due to that the root depth and the depth of organic matter are not the same, the latter depth is defined separately. Inputs for densities of soil organic matter are given in accordance to the depth of the organic matter (z_{Org}). The densities of the root zone and the layer below are then calculated in accordance to the actual root depth. The soil mineral N is handled similarly, and the depth is given by z_{Min}.

<u>Soil processes</u>

These processes are formulated in a similar way as in the SOIL and SOILN models (Eckersten et al., 1998; Johnsson et al., 1987). A summarised description can be found in the Appendix 1. However, one correction factor is introduced in the RUE-W-N model to compensate for systematic differences in simulated average N leaching, compared to the more detailed SOIL-SOILN models. Nitrate-N is transported between layers and leach out of the deepest layer in relation to the net downward water flow and the nitrate-N concentration of the source layer. Between the surface layer and the root zone, for instance, the transport is:

$$N_{Surf \to RZ} = q_{Surf \to RZ} \; N_{NO3Surf} \; / \; w_{Surf} \qquad \text{if } q_{Surf \to RZ} \geq 0 \qquad (18)$$

$$= 0 \qquad \text{if } q_{Surf \to RZ} < 0 \qquad (19)$$

where $q_{Surf \to RZ}$ is the water flow from the surface layer to the root zone. w_{Surf} and $N_{NO3Surf}$ are the amount of water and nitrate N in the surface layer, respectively. For the lowest layer, below root zone, there is a correction factor (k_{Corr}) multiplied to eq. 18 that accounts for effects of the simplified layer representation in comparison with more detailed soil models. The correction factor is larger at soil relative water contents (θ) close to saturation (θ_{Poro}), i.e. $k_{Corr} = 1.3 \; \theta/\theta_{Poro}$. Upward transport of nitrate is assumed negligible, and ammonium is assumed immobile. The N transport between the root zone and the layer below the root zone, and the outflow from that layer, are simulated in the same way.

Model parameterisation

Parameterisation strategy

The parameterisation adopts a multi parameter model to site conditions with a very limited amount of information. We reduced the number of parameters to be set at each site by introducing soil types with specified parameter values. We tried to follow a straightforward parameterisation procedure that is related to the physical meaning of the parameters.

First, the biomass model (Biomass model in Fig. 1) and water model (Input to water model, Water model and Water growth factor in Fig. 1) were parameterised by taking values from earlier studies. Second, soil N parameters were set (Nitrogen model in Fig. 1). Values of parameters of process intrinsic character, were taken from earlier applications of the SOILN model to a clay soil, whereas, to account for the simplified structure of the RUE-W-N soil model, a number of soil N parameters were adjusted by calibration to a SOILN soil simulation of the Modellskogen forest. Third, the functions for plant litter fall and plant N demand (Input to nitrogen model in Fig. 1), that are estimated from biomass production, were calibrated against the SOILN simulation for Modellskogen.

Thereafter, the overall performance of the model, for both plant and soil, was adjusted by introducing the clay parameterisation and then calibrate the model to give the similar results as for the SOILN simulation of Modellskogen. The adjustment of biomass predictions for different N treatments was achieved by calibration of parameters for the relative response of plant growth to N availability. For this one of the fertilisation experiments was used (N growth factor in Fig. 1).

Finally, to make the soil model applicable to different soil types the nitrogen model was parameterised for four different soil types: clay, clay loam, sandy loam and loamy sand. Differences in parameterisation between soil types were identified by calibration against two winter wheat applications of the SOIL-SOILN models to a clay soil and a loamy sand, respectively. For the intermediate soil types, clay loam and sandy loam, intermediate values were used for some of the parameters that differed between clay and loamy sand (Table 4).

Water model

The soil water model was parameterised to the Modellskogen forest separately in an earlier study (Noronha Sannervik, 2003; see also Eckersten et al., 2004) by calibration to simulation results of a detailed soil water and heat model (SOIL; Persson and Jansson, 1989) (Table 1). Saturated conditions were assumed at start of the simulation.

Table 1. *Parameterisation of the water model for a willow forest on a clay soil (Modellskogen). Values are the same as used by Noronha Sannervik (2003).*

Parameter	Symbol	Value	Unit
Total soil depth	$z_{SoilDepth}$	2	m
Maximum root depth	z_{RDmax}	1.5	m
Surface layer thickness	z_{Surf}	0.04	m
Porosity	θ_{Poro}	0.475	$m^3\ m^{-3}$
pF soil type		clay	-
Coefficient for soil surface resistance as f(water potential)	c_{rss2}	75	MPa^{-1}
Saturated hydraulic conductivity	k_{Sat}	1	$m\ d^{-1}$
Lowest soil water potential for maximum root uptake	ψ_{Crit}	-0.01	MPa
Coefficient for reduction of water uptake as function of potential transpiration	c_t	0.04	$d\ mm^{-1}$
Maximum stomata conductance per leaf area in Lohammar eq.	c_{Max}	0.008	$m\ s^{-1}$
Input to water model			
Root depth coefficient	k_{zRD}	0.046	m^{-2}
Maximum LAI	LAI_{Max}	6	
Minimum stem biomass for development of leaf area	W_{sMin}	21	$g\ m^{-2}$

Nitrogen and water model

The nitrogen model was linked to the water model, as calibrated above. The combined model (Water model and Nitrogen model alone in Fig. 1) was calibrated by comparison with SOILN simulation outputs of the Modellskogen willow forest (Eckersten, 1994). Initial states were set similar to that of the SOILN simulation. Parameters for uptake of mineral N (c_{Up}) and C/N ratio of microbes ($CN_{RatioMic}$)

15

were set independently according to previous applications of the SOILN model (Eckersten et al., 2001). In addition, depths of the organic matter (z_{Org}) and mineral N (z_{Min}) were set to get the similar initial pools as for the SOILN simulation of Modellskogen .

In the calibration to the SOILN simulation, first the microbial responses to temperature and moisture were adjusted (Q_{10}, θ_0 and θ_1; see Table 2). Second, the microbial growth efficiency parameters (f_l and f_h) were set to fit the C/N ratio of total soil organic matter. Third, the specific decomposition rates of litter and humus (k_l and k_h) were adjusted to fit changes of total soil organic C and N pools over time. Fourth, the correction factor for vertical nitrate flow (k_{Corr}) was adjusted to fit accumulated N leaching. Finally, steps 2, 3 and 4 were repeated to fit all the three target variables simultaneously.

The fit to the SOILN model simulation was on average good for N mineralisation and N storage (Fig. 2). However, for N leaching the differences were substantial. This might be explained by the soil layer representation, that is simplified compared to the SOILN model, and that air temperature is used to substitute soil temperature.
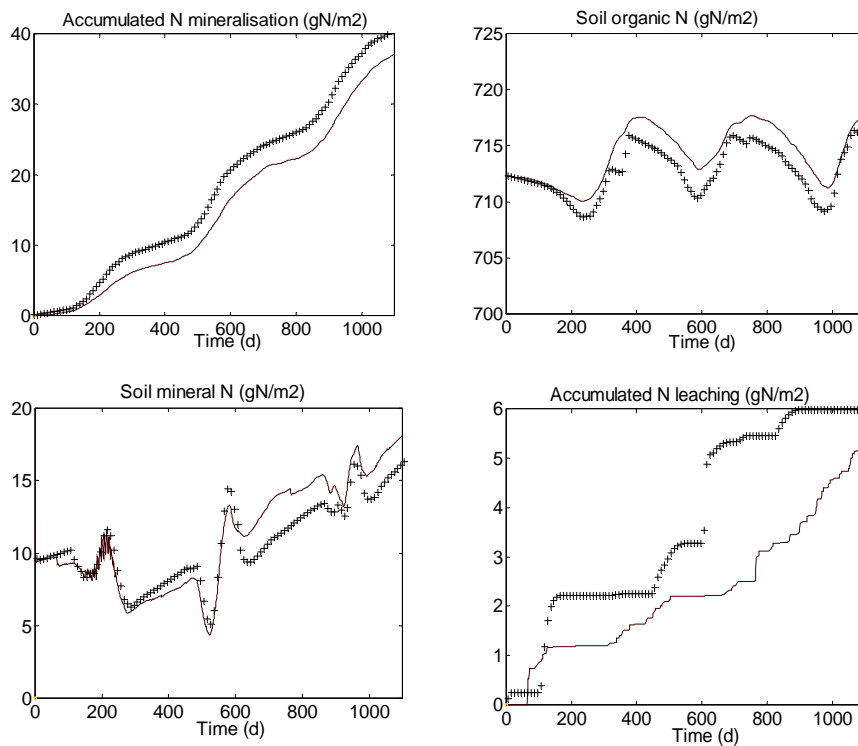

Fig. 2. Comparison between variables simulated with the soil nitrogen and water models (line) and the SOIL-SOILN model (marks) for total soil profile. x-axies is number of days since start of simulation 19850101.

The parameters related to the input functions of the nitrogen model (plant N demand and litter input; Fig. 1) were calibrated to get the best on average fit to values simulated by the SOILN model for Modellskogen. The plant N demand was calibrated against the actual N uptake, assuming that the N uptake of the fertilised willow forest was close to plant maximum demand (see Table 2).

Table 2. *Parameterisation of the nitrogen model for a willow forest on a fertilised clay soil.*

Parameter	Symbol	Value	Unit	Reference
Initial soil C and N				
Root depth	$z_r(t_o)$	0.26	m	From SOILN sim. [a]
Soil organic N density in layers: surface, root zone, below	$N_{Org}(t_o)$	2500 1800 20	gN m^{-3}	From SOILN simulation [b]
Soil organic C/N ratio in layers: surface, root zone, below	$C_{Org}/$ $N_{Org}(t_o)$	11.0 10.5 10.5	gC m^{-3}	From SOILN simulation [b]
Soil mineral N density in layers: surface, root zone, below	$N_{Min}(t_o)$	1.5 5.5 4.7	gN m^{-3}	From SOILN simulation [d]
Nitrogen model				
Depth of soil organic matter	z_{Org}	1.2	m	From SOILN sim. [b]
Depth of soil mineral N	z_{Min}	1.5	m	From SOILN sim. [b]
Fractional uptake of soil mineral N	c_{Up}	0.1	d^{-1}	Eckersten et al., 2001; eq. A18
C/N ratio of microbes	$CN_{RatioMi}$	10	gC gN^{-1}	Eckersten et al., 2001; eq. A15
Microbial temperature response	Q_{10} [c]	2.75	-	Cal. vs temp. response [a]; eq. A7
Microbial moisture response	θ_0, θ_1	θ_{Poro}–0.325 θ_{Poro}–0.025	m^3 m^{-3}	Cal. vs moist response [a]; eq. A8
Microbial efficiency of litter	f_l	0.4	-	Cal. vs C/N ratio [c]; eq. A9
Microbial efficiency of humus	f_h	0.2	-	Cal. vs C/N ratio [c]; eq. A9
Litter specific decomposition rate	k_l	0.02	d^{-1}	Cal. vs soil C and N [a]; eq. A5
Humus specific decomposition rate	k_h	2.5 e-5	d^{-1}	Cal. vs soil C and N [a]; eq. A6
Correction of N flow	k_{Corr}	1.3 θ/θ_{Poro}	-	Cal. vs acc. N leaching [a]
Input to nitrogen model				
N demand at maximum LAI	k_{Max}	0.25	gN m^{-2} d^{-1}	Cal. vs acc. N uptake [a]
Litter fall coef.	k_{Li1}	0.23	gC m^{-2} d^{-1}	Cal. vs acc. litter fall [a]
Litter fall coef.	k_{Li2}	35	gC m^{-2}	Cal. vs acc. litter fall [a]
C/N ratio of litter fall	$CN_{RatioLitt}$	20	gC gN^{-1}	Cal. vs acc. N litter fall [a]

a) SOILN model simulation of Modellskogen, Uppsala 1985-88 (Eckersten, 1994)
b) SOILN simulation of Sänkan clay soil (Eckersten et al., 2001)
c) SOILN simulation of Sänkan clay soil and Mellby loamy sand (Eckersten et al., 2001)
d) Profile distribution from Sänkan simulation[b] but total profile from Modellskogen simulation [a]

Application to a standard clay soil

For the application of the model to different soil types, the Sänkan soil (Kätterer et al., 1997) was chosen to represent clay. This soil type was introduced in the Modellskogen application above. The application was then recalibrated. First the depth of organic matter and mineral N were given (z_{Org} and z_{Min}). Then, to keep the same levels of accumulated N mineralisation and N leaching, the decomposition rate of litter and humus (k_1, k_h) and the leaching correction factor (k_{Corr}) were modified. Further, the initial values of the organic pools (given as g m^{-3} bulk soil) were adjusted by making a pre-simulation of one year to avoid, strong initial effects of the pool sizes at start of simulation not being in balance with transfer rates. The final parameterisation is regarded to represent a willow forest on a clay soil fertilised by about 105 kg N ha^{-1} y^{-1} (Table 2). The fit to the observed standing stem biomass was good (Fig. 3)
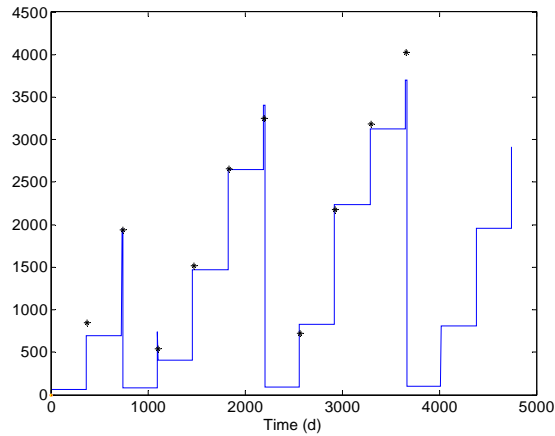

Fig. 3. Comparison between simulated (line) and measured (marks) standing stem biomass. x-axes is number of days since start of simulation (19850101). y-axes is in units of g d.w. m^{-2}.

Biomass, water and nitrogen model

Parameters for absorption of solar radiation and shoot mortality used in the biomass model (Fig. 3) were taken from previous applications of the model (Noronha Sannervik 2003; Noronha Sannervik & Kowalik, 2003; Noronha Sannervik et al., 2005). The response of biomass predictions of the whole RUE-W-N model to N conditions was adjusted using one of the N fertilisation trials (Korrvike; see Tables A1 and A2 in Appendix 2) to calibrate the response of the nitrogen growth factor (f_N; eq. 3) to nitrogen availability. First the N demand reduction factor (a_N) was estimated so as to achieve no nitrogen stress for the highest N addition rate (12 g N m^{-2} y^{-1}). Second, the N deficit response parameter (b_N) was calibrated to fit the decrease in production for the non fertilised stand, compared to the highest N addition rate (Table 3).

18

Table 3. *Parameterisation of the biomass model for a willow forest.*

Parameter	Value	Source
Coefficient for ratio between N demands for optimal growth and N uptake (a_N; -)	0.8	Calibration vs production of high N addition[b]
Relative decrease of growth due to increased N deficit (b_N; -)	0.7	Calibration vs production of high and low N addition[b]
Fraction of plant internal N available for new growth (β; -)	0.05	arbitrarily
Maximum radiation use efficiency (ε_{Max}; g d.w. MJ^{-1})	0.80	a)
Relative scaling of radiation use efficiency ($f(t_{Age})$; -) for shoot age 1, 2, 3, 4	0.91, 1.00, 0.83, 0.69	a)
Fraction of radiation absorbed ($\alpha(t_{Age})$; -) for shoot age 1, 2, 3, 4	0.59, 0.73, 0.76, 0.74	a)
Mortality fraction (m)	0.10	a)

a) From Noronha Sannervik (2003) and Noronha Sannervik et al. (2005)
b) Experimental data of Korrvike

Application to different soil types

To apply the model to different soil types, two approaches were combined. First, the response to two different soil types was identified. The RUE-W-N model was applied to both a clay and a loamy sand, cultivated with winter wheat and compared with corresponding SOIL-SOILN simulations (Eckersten et al. 2001; Kätterer & Andrén, 1996; Blombäck et al., 1995). It was found that the initial states of organic matter and mineral N, and the specific decomposition rates were the main soil characteristics determining the difference in dynamics between soil types (Table 4). Secondly, two more soil types, clay loam and sandy loam, were characterised as concern C and N, based on the clay and loamy sand. Clay loam was set similar to clay except for the depth of organic matter that was changed from 1.2 m to 1 m (see for instance Kirchmann & Eriksson, 1993). Sandy loam was set similar to loamy sand, except that the depth of organic matter was increased from 0.5 m to 0.7 m (see Table 4). Also here a pre-simulation of one year was made to avoid strong effects of initial organic pool values. The initial mineral N densities were adjusted for each site to the value achieved after three years of simulation without fertilisation.

Table 4. *Soil model parameters that differ between the experimental sites. For explanation of water symbols see Table 1, and for nitrogen symbols see Table 2.*

Site	Modellskogen	Gottsunda	Grimstad	Korrvike	Bännebo	Logården	Borgeby	Brunnby
Parameter								
USDA soil type	Clay	Clay loam	Loamy sand	Clay	Clay	Clay loam	Sandy loam	Clay
z_{RDmax}[b] (m)	1.5	1.5	0.6	1.5	1.5	1.5	1.0	1.5
Water model								
c_{rss2}[b] (MPa^{-1})	75	75	225	75	75	75	225	75
k_{Sat}[b] (m d^{-1})	1	4	100	1	1	4	40	1
θ_{Poro}[b] (-)	0.475	0.46	0.435	0.475	0.475	0.46	0.45	0.475
pF soil type[b] (USDA)	1	2	4	1	1	2	3	1
ψ_{Crit}[b] (MPa)	-0.01	-0.0075	-0.002	-0.01	-0.01	-0.0075	-0.002	-0.01
Nitrogen model								
Initial soil organic N in	2100[c]	2100[e]	2300[d]	2100[e]	2100[e]	2100[e]	2300[f]	2100[e]
layers: surface, root zone,	1500[c]	1500[e]	1500[d]	1500[e]	1500[e]	1500[e]	1500[f]	1500[e]
below (g m^{-3})[j]	1000[c]	870[e,g]	240[d]	1000[e]	1000[e]	870[e,g]	415[f,g]	1000[e]
Initial C/N ratio in layers:	11.5[c]	11.5[e]	15.5[d]	11.5[e]	11.5[e]	11.5[e]	15.5[f]	11.5[e]
surface, root zone, below	10.5[c]	10.5[e]	15.5[d]	10.5[e]	10.5[e]	10.5[e]	15.5[f]	10.5[e]
(gC gN^{-1})	10.5[c]	10.5[e]	15.5[d]	10.5[e]	10.5[e]	10.5[e]	15.5[f]	10.5[e]
Initial soil mineral N in	1.5[c]	1.5[e]	5.5[d]	1.5[e]	1.5[e]	1.5[e]	5.5[f]	1.5[e]
layers: surface, root zone,	5.5[c]	5.5[e]	5.5[d]	5.5[e]	5.5[e]	5.5[e]	5.5[f]	5.5[e]
below (g m^{-3})[j]	4.7[c]	4.5[h]	3.0[d]	4.7[e]	4.7[e]	4.5[h]	3.0[f]	4.7[e]
z_{Org} (m)	1.2[c]	1.0[i]	0.5[d]	1.2[e]	1.2[e]	1.0[h]	0.7[a]	1.2[e]
z_{Min} (m)	1.5[c]	1.5[e]	1.0[d]	1.5[e]	1.5[e]	1.5[e]	1.0[f]	1.5[e]
k_l (d^{-1})	0.006[c]	0.006[e]	0.015[d]	0.006[e]	0.006[e]	0.006[e]	0.015[f]	0.006[e]
k_h (d^{-1})	4.5 10^{-5} [c]	4.5 10^{-5} [e]	6.0 10^{-5} [d]	4.5 10^{-5} [e]	4.5 10^{-5} [e]	4.5 10^{-5} [e]	6.0 10^{-5} [f]	4.5 10^{-5} [e]

a) arbitrarily, b) From application of the RUE-W model by Noronha Sannervik (2003), c) From Modellskogen and Sänkan clay soil, d) From calibration to a SOILN simulation for sandy loam (Uppsala 1980-86 in Eckersten et al., 2001), e) The same as for Modellskogen clay soil, f) The same as for Grimstad loamy sand, g) Estimated in relation to z_{Org}, h) Estimated in relation to z_{Min}, i) Kirchmann & Eriksson (1993), j) Initial root depth is 0.26 m.

Results

Sensitivity test

A sensitivity test was done to investigate differences, in the growth N response factor (f_N; eq. 3) and N leaching, between the different soil types. The test was conducted by simulating growth on different soil types under different fertilisation scenarios, using weather and harvest conditions of the Modellskogen forest. The growth N response factor is highest for clay and lowest for loamy sand (Figs. 4 and 5). The difference between the soil types is small during fertilisation and high already a few years after fertilisation has stopped. For non fertilised stands, the growth N response factor is also highest for clay, but essentially lower than for fertilised stands, and decreasing over time (i.e f_N is lower after 13 than after 5 years; Fig. 4). The difference between soil types is high, although not as high as for the transient case after fertilisation had stopped.

The N leaching is essentially lower for the non fertilised stands (Fig. 5). For clay, it is about one third of the fertilised stand, and for loamy sand, one fifth. The differences between soil types, in N leaching of fertilised stands, follow the same pattern as differences in run off (Fig. 5).
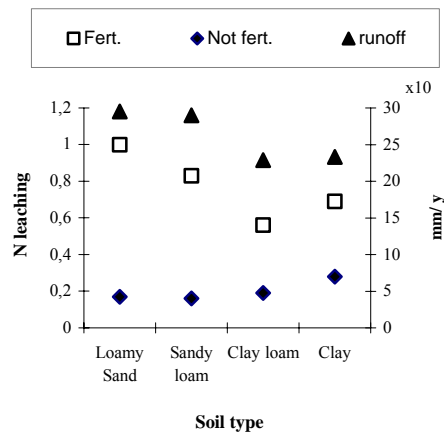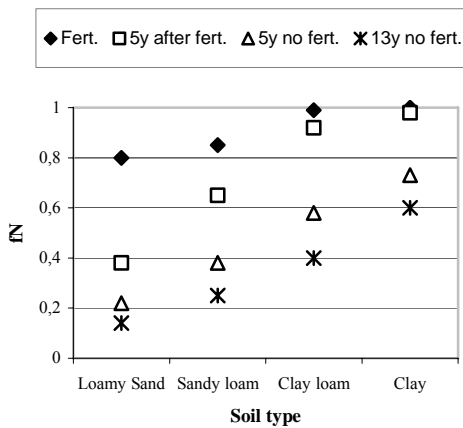
Fig 4. Growth N response factor (f_N; dimensionless) obtained for Modellskogen growing under different soil types and fertilisation regimes. Points represent: fertilised stands (♦); 5 years after fertilisation stopped (□); not fertilised stand, after 5 years (Δ) and; not fertilised stand after 13 years (*).

Fig 5. Accumulated N leaching (-) over a 13 year period in relation to that of a fertilised willow stand on a loamy sand (uppermost left □). Triangles represent, absolute values of average annual run off (mm y^{-1}) of the fertilised stands.

Nitrogen effect on test sites

The growth N response factor (f_N) obtained in the applications to the experimental sites varies from 0.42 for an unfertilised stand on loamy sand to 1 for a fertilised stand on clay (Fig. 6). The range of variation of f_N, is larger between fertilisation levels than between soil types. At each fertilisation level, the lowest f_N values are obtained for the loamy sand soil type, while the f_N values for the other soil types are rather similar (Fig. 6).
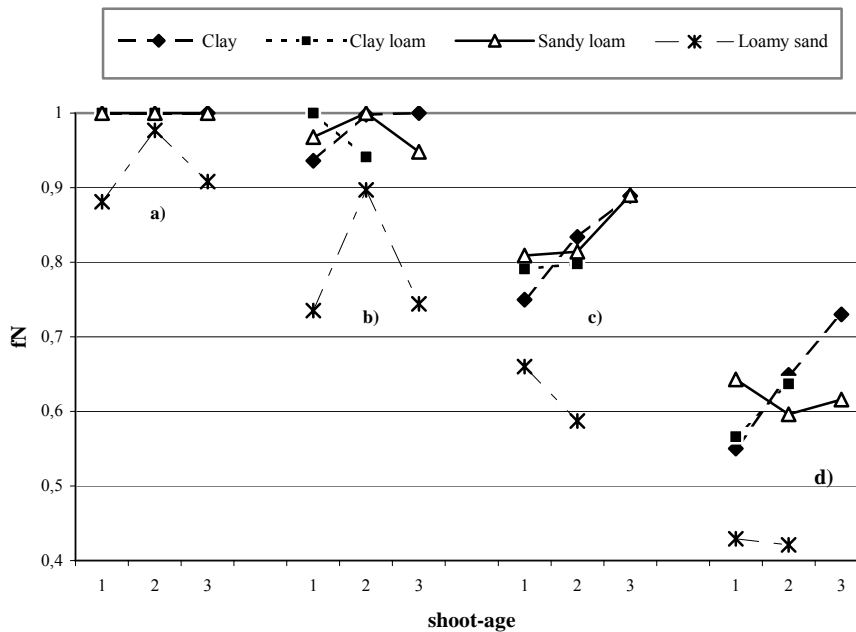

Fig. 6. Values of the growth N response factor (f_N) obtained for the test stands growing under different fertilisation levels and on different soil types. The fertilisation levels, in kg N ha^{-1} y^{-1}, are: a) high fertilisation - 150 year 1, 180 year 2 and 150 year 3; b) moderate fertilisation - 90 year 1, 150 year 2 and 90 year 3, except for clay loam where fertilisation was 150 year 1 and 90 year 2; c) low fertilisation - 45 year 1, 75 year 2 and 45 year 3 for clay, 75 year 1 and 45 year 2 for clay loam and loamy sand and 45 year 1, 75 year 2 and 75 year 3 for sandy loam; d) no fertilisation.

With the high fertilisation level there is no limitation to growth, due to N availability ($f_N = 1$), for all soil types except loamy sand, where there is still some deficit on N availability ($f_N \leq 0.98$; a) in Fig. 6). This is in line with general agricultural knowledge that it is for this type of soil that fertilisation most improves N availability.

The variations in f_N between years are mainly related to the actual N application at each year (see legend of Fig. 6). Exceptions are the stands on clay soil, where f_N increases from year to year independently of the actual N application.

Predictability

Harvest

The simulated biomass production at harvest (after 3 years) shows an acceptable fit to measured data independently of whether the stands are fertilised or not. The RUE-W-N model was able to explain 82 to 86 % of the observed variations in yield at harvest (Fig. 7). However, the RUE model alone, gave a slightly better prediction of the **Fertilised** stands production than the RUE-W-N model (Table 5), i.e., the inclusion of soil N availability did not improve predictability for stands with N supply higher than 75 kg N ha^{-1}. The same was almost true for **Unfertilised** stands where the RUE-W-N model explains only 2 % more of the variability than the RUE model (Table 5). Consequently, the inclusion of soil type effects on N availability only slightly improved the predictability for stands with low or no N fertilisation.

Fig. 7. Comparison between simulated (x) and observed (y) yield at harvest predicted with the RUE-W-N model for:
a) All stands; b) Fertilised stands and c) Unfertilised stands. Regression lines are for:
a) y = 1.227 x – 218 (R^2 = 0.82); n = 19
b) y = 1.197 x – 223 (R^2 = 0.83); n = 11
c) y = 1.876 x – 1271 (R^2 = 0.86); n = 8
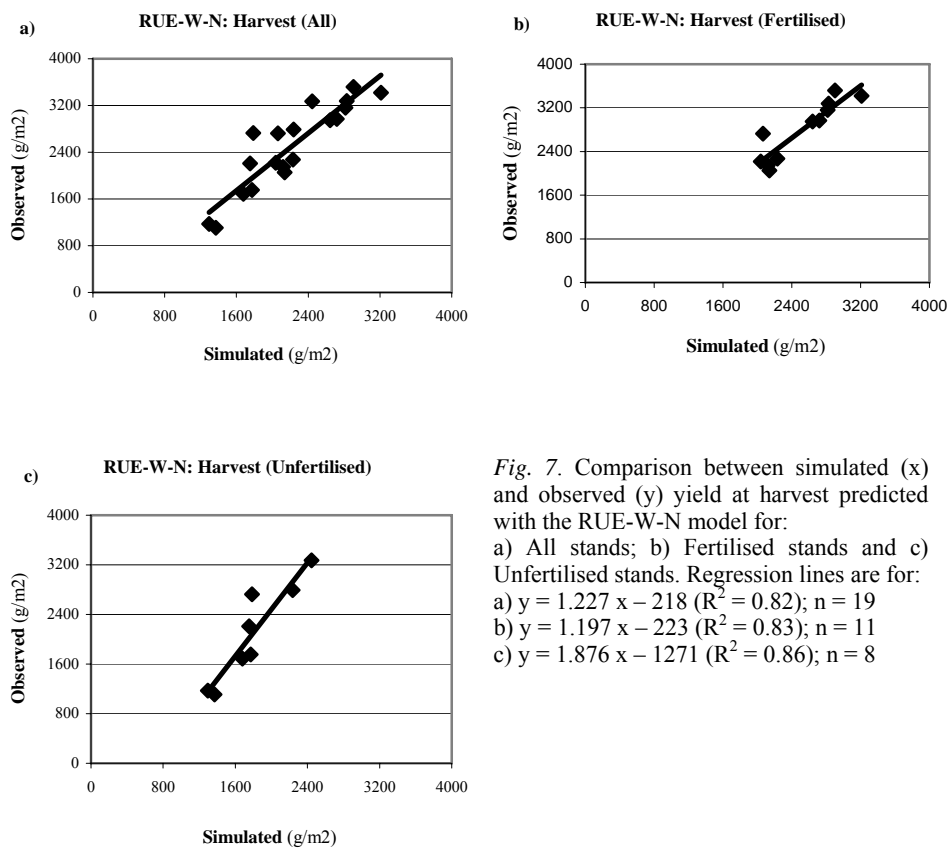
Considering **All** stands together, 82 % of the variability, in harvest production, between stands can be explained by the RUE-W-N model while the RUE model

explains 70% (Table 5). This indicates that the inclusion of simulated soil nitrogen availability improves the predictability of willow growth when growing under different N fertilisation regimes.

Annual

The model ability to reproduce variations in annual stem biomass production is low for all cases (Fig. 8). The observed annual stem biomass production shows a much larger variability than is estimated by model simulations. For example, the observed production for year two varies between ca. 400 and ca. 1600 g m^{-2}, while the simulated production varies between ca. 700 and ca. 1300 g m^{-2} (see Fig. 8). Further, stem biomass production of year one is generally overestimated (especially for **Fertilised** stands) while biomass production of year three is underestimated (Fig. 8).
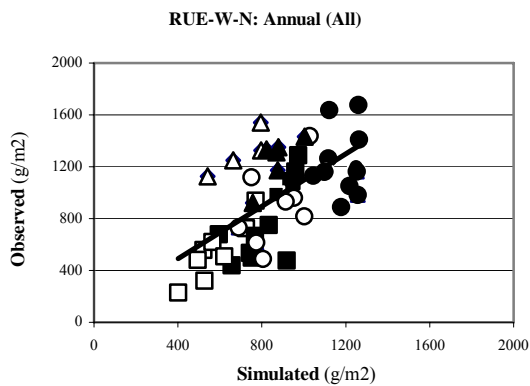

RUE-W-N: Annual (All)

Fig. 8. Comparison between simulated (x) and observed (y) annual stem biomass predicted with the RUE-W-N model for:
a) **All** stands; b) **Fertilised** stands and c) **Unfertilised** stands. Regression line is:
$y = 1.013 x + 85$ ($R^2 = 0.41$); n = 51
Squares (■) represent year 1, circles (●)year 2, triangles (▲)year 3, and the lozenge (♦) year 4. Dark symbols represent values from **Fertilised** stands and light symbols values from **Unfertilised** stands.

As for production at harvest, only when **All** stands are considered a slight improvement, in predicting willow annual production, is acquired by using the RUE-W-N model instead of the RUE model alone (Table 5).

Model comparisons

Independently of which of the three models is used, prediction of yield at harvest is always better than prediction of annual biomass production (Table 5). These results indicate that other factors than those considered in the model, for example weed competition or browsing, may significantly influence the growth for particular years, causing variations in production not simulated by the model. Further, predictions, tend to be better for the first year of the cutting cycle than for the second or third years (Table 5). This might be, as referred in previous studies (Noronha Sannervik et al., 2005), due to the fact that annual simulations are not independent from the previous year. The initial biomass of each year, except the first, is simulated by the model, and not adjusted to the observed value. An error in

estimated biomass production of one year will then introduce an error in the simulation of the following year.

The annual productions are worst estimated for the **Unfertilised** stands (see Annual in Table 5). In contrast, the best predictions of the first year's production are obtained for this group of stands (see Year 1 in Table 5). It should be noted, however, that the number of samples in the regressions are sometimes few, which might make the R^2-value sensitive to the ommision or inclusion of single values.

For **Unfertilised** stands, best predictions of production are achieved with the RUE-W-N model, both at harvest and annualy, except for Year 2, (see Unfert. Table 5). However, the improvement in model fit (R^2) is small except for Year 3 (Table 5).

For **Fertilised** stands, the best predictions of production are obtained with the RUE model except for year 3 (see Fert. Table 5). For Year 3, the best predictions, are achieved by the inclusion of the soil water availability simulations, and the effect of including N availability simulations can actually be seen as negative also here.

For **All** stands, the best predictions are obtained with the RUE-W-N model, except for Years 1 and 3 (see All in Table 5).

Table 5. *Coefficient of determination (R^2) values of the regression lines between observed and simulated values obtained with the different models. The n is the number of data points used in the regression analysis. Figures in bold denotes the model that gives the highest R^2 value for each situation.*

Stands	Model	Harvest	Annual (all years)	Year 1	Year 2	Year 3
All	RUE	R2 = 0.70; n=19	R2 = 0.38; n=51	**R2 = 0.72; n=20**	R2 = 0.14; n=20	R2 = 0.00; n=10
	RUE-W	R2 = 0.69; n=19	R2 = 0.20; n=51	R2 = 0.68; n=20	R2 = 0.01; n=20	**R2 = 0.47; n=10**
	RUE-W-N	**R2 = 0.82; n=19**	**R2 = 0.41; n=51**	R2 = 0.63; n=20	**R2 = 0.38; n=20**	R2 = 0.21; n=10
Fert.	RUE	**R2 = 0.85; n=11**	**R2 = 0.48; n=31**	**R2 = 0.74; n=12**	**R2 = 0.04; n=12**	R2 = 0.09; n=6
	RUE-W	R2 = 0.77; n=11	R2 = 0.34; n=31	R2 = 0.68; n=12	R2 = 0.00; n=12	**R2 = 0.77; n=6**
	RUE-W-N	R2 = 0.83; n=11	R2 = 0.40; n=31	R2 = 0.52; n=12	R2 = 0.01; n=12	R2 = 0.61; n=6
Unfert.	RUE	R2 = 0.84; n=8	**R2 = 0.32; n=20**	R2 = 0.76; n=8	**R2 = 0.49; n=8**	R2 = 0.31; n=4
	RUE-W	R2 = 0.83; n=8	R2 = 0.08; n=20	R2 = 0.76; n=8	R2 = 0.08; n=8	R2 = 0.31; n=4
	RUE-W-N	**R2 = 0.86; n=8**	**R2 = 0.32; n=20**	**R2 = 0.80; n=8**	R2 = 0.28; n=8	**R2 = 0.74; n=4**

Discussion

Incorporating simulations of soil N availability, did not affect model predictability of stem biomass production, significantly. For **Fertilised** stands (>75 kg N ha^{-1} year^{-1}) the predictability decreased slightly which could be explained by only a little limitation on growth, due to N deficies, and that more complex estimates introduce new sources for errors. For **Unfertilised** stands the predictability increased only slightly, and not significantly. This was less expected since variations in soil N availability are common, and it was expected that variations in productivity were related to variations in N availability.

If the model correctly mimics the N availability and its effect on growth, the conclusion would be that differences in natural N availability between the sites hardly influence willow production. However, are the model simulations realistic? Does the model simulate the effect of N availability on production (f_N in eq. 3) in a realistic way? From pot experiments by Weih & Nordh (2002) it can be estimated that a decrease in N supply from 120 to 20 kg N ha^{-1} y^{-1} corresponded to a decreased production by 61-73%. This could be expressed as a relative decrease of N supply by about 1.25% corresponding to a relative decrease of production by 1% (1.25:1). Aronsson & Bergström (2001) reported a similar response to reduction in N supply for well watered willows growing as vegetation filters (about 1.2:1). We can not mimic those experiments in detail with the RUE-W-N model since we do not know the soil N fluxes of those experiments. However, the model showed similar relative response to reductions in N supply for the Modellskogen forest (about 1.25:1), as in those experiments (Fig. 4).

Hence, it seems that the behavior of the growth factor (f_N), simulated under different fertilisation and soil type scenarios, is in accordance with what could be expected from experimental results (Fig. 4). For the fertilised scenarios in Fig. 6 the differences in f_N between soil types are small (f_N was 1, except for loamy sand where it was 0.9), while for non fertilised stands the differences are high (f_N ranged between 0.4 and 0.7).

What about the simulations of N availability, are they realistic? The model simulations were calibrated against the SOILN model simulations that were tested against two experimental sites (a clay soil and a loamy sand) with detailed measurements on N dynamics. The simulated N mineralisation of our study ranged between 40 kg N ha^{-1} y^{-1} for loamy sand to about 120 kg N ha^{-1} y^{-1} for clay, which are in similar range as mineralisation rates between 35 and 121 kg N ha^{-1} y^{-1} estimated for agricultural soils by Kätterer et al. (1999). N leaching ranged between 5 and 30 kg N ha^{-1} y^{-1}, which also are resonable values for agricultural soils (Kätterer et al., 1999). However, short term dynamics of N leaching were poorly simulated (Fig. 2) and might have introduced an error on estimated N availability to plant. As the leaching was about 15 - 25% of N mineralistion, an error of, lets say, 50% in N leaching estimates would give an error of less than 10 - 15% of the estimated N availability.

Concerning long term effects on N availability, the return of nutrients to the soil is important. Theoreticaly a coppice culture may improve soil fertility as it allowes a large amount of litter to be returned to the soil (Ceulemans, 1990). For clay soils, the model response to fertilisation is in line with this idea, in terms of that f_N increases with time independently of fertilisation. For sandy soils, however, f_N follows the variations in fertilisation from year to year (see Fig. 6). One possible reason is that, in sandy soils, more of the N supplied by the litter is leached, due to a higher run off, than in clay soils. The model simulations also give an indication that the influence of soil related factors may become more important for willow growth with time. The variations on biomass production of Year 3 were indicated to be better simulated by the RUE-W or RUE-W-N models than by the RUE model alone (Table 5). The contrary is almost true for Year 1 where the RUE model (that does not consider differences in soil types) gives better predictions, except for **Unfertilised** stands. However, no conclusion on long term effects could be made from simulations because there were too few samples to obtain significant results.

When the results considering all stands are analysed together, more of the variability in production at harvest and annual production, can be explained by using the RUE-W-N model than the RUE. This is particularly evident for production at harvest where additionally 12 % of the variability in production could be explained by incorporating simulations of soil N availability (Table 5).

These results indicate that the fertilisation level is more valuable to describe the variations in biomass production, of the willow test stands, than the ability of the different soil types to supply N to plant growth.

In comparison with other studies, focusing or touching on the evaluation of the effects of different environmental or management factors on willow growth, our study give both comparable and contradictory results. Alriksson (1997) found that willow productivity had a stronger relationship to soil texture (clay content), especially after normalising for differences in precipitation, than to the amount of N applied. Alriksson (1997) speculates "that the site properties related to clay content have been more important than N-fertilisation". The results of our study indicate rather the opposite conclusion: N-fertilisation is more important, in explaining variations in willow productivity, than soil type. However, Alriksson says that "the importance of soil texture tends to increase with time", and shows results for the fifth and six growing season. The production data used in our studies covers (with one exception) the three first growing seasons and it is possible that a positive effect of clay soils is more pronouced after five or six growing seasons than after three.
Another study by Tahvanainen & Rytkönen (1999), investigating biomass production of *Salix viminalis* in southern Finland, obtained results showing that climatic conditions had a stronger influence, on biomass production than soil properties. Their results were obtained for biomass production after three growing seasons. Therefore they are rather comparable to the test stands used here and supports the idea that during the first years, the influence of soil properties on N

28

availability for plant growth might not be high enough to produce significant variations in productivity.

Both the simulations of N availability and its effect on growth seems realistic from the point of view of the processes included. Then, which mechanisms, that were not considered in the model, can cause that the soil's natural N availability only has a very small effect on willow stem production? Young trees (Rytter, 1997) and trees growing on poor N environments (Cannel & Dewar, 1994) tend to allocate a higher fraction of growth to roots. The effect of small (young) trees is included in the model, however, an increased allocation to roots due to poor N status of the plant is not explicitly included. This would have increased the N availability for the willow stands on the poor sites, and decrease the differences between sites, compared to what was simulated. Another factor that also could decrease the differences in N availability between sites, and that was not included in the model, is that the N poor sites could have had an increased uptake by mycorrhiza than the fertile sites. Wallander (1995) refers to several tree experiments that indicate that fungal growth is reduced with increased N availability. The uptake of organic N in low fertile forest soils are known to be important and has been modelled for old spruce stands on sandy soils in Denmark to range, from about 40 % of total tree N demand for non fertilised stands to about 15 % for stands fertilised by 34 kg N ha^{-1} y^{-1} (Beier & Eckersten 1998). The contribution of organic N to total plant N uptake is unknown for the current agricultural soils, but might have been of importance in the unfertilised sandy soils, as the mineralisation rates in those were fairly low (below 50 kg N ha^{-1} y^{-1}).

Conclusions

Explicit simulation of the soil N availability improves model predictability to forecast the production of stands growing under different fertilisation regimes. For stands subject to a similar level of fertilisation, predictability is slightly improved if low or no fertilisation is applied and it becomes worse if high levels of fertilisation are applied. This suggests that variations in productivity of **Fertilised** stands and of **Unfertilised** stands, respectively, are to a large extent (> 80%) dependent on the absorbed solar radiation, mortality and shoot-age. Yield variations of **Fertilised** and **Unfertilised** stands, together, depend on the level of fertilisation and soil N availability.

The improvments obtained in predictability for **Unfertilised** stands are rather low and may not justify the use of the RUE-W-N model, instead of the RUE model alone. As stated by Loague & Green (1991), "if model performance improvments are not great or if data requirements are too expensive then simpler models are justified".

References

Ågren, G. 1989. Willow stand growth and seasonal nitrogen turnover. In K. Perttu and P. Kowalik, (Eds). Modelling of energy forestry: growth, water relations and economics. Pudoc, Wageningen, Netherland. *Simulation Monographs* 30**,** 19-23.

Alriksson, B. 1997. Influence of site factors on *Salix* growth with emphasis on nitrogen response under different soil conditions. *Doctoral thesis. Dep. of Short Rotation Forestry. Swedish University of Agricultural Sciences*, Uppsala, Sweden, Silvestria 46.

Aronsson, P.G. & Bergström, L.F. 2001. Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type. *Biomass and Bioenergy* 21, 155-164.

Beier, C. & Eckersten, H. 1998. Modelling the effects of nitrogen addition on soil nitrogen status and nitrogen uptake in Norway spruce. *Environmental Pollution* 102, S1 409-414.

Blombäck, K., Stähli, M. & Eckersten, H. 1995. Simulation and water and nitrogen flows and plant growth for a winter wheat stand in central Germany. *Ecological Modelling* 81, 157-167.

Bollmark, L., Sennerby-Forsee, L. & Ericsson, T. 1999. Seasonal dynamics and effects of nitrogen supply rate and nitrogen and carbohydrate reserves in cutting-derived *Salix viminalis* plants. *Canadian Journal of Forest Research* 29, 85-94.

Cannel, M.G.R. & Dewar, R.C. 1994. Carbon allocation in trees: a review of concepts for modelling. *Advances in Ecological Research* 25, 59-104.

Ceulemans, R. 1990. Genetic variation in functional and structural productivity determinants in poplar. *Amsterdam Thesis Publishers*, Amsterdam.

Eckersten, H. 1994. Modelling daily growth and nitrogen turnover for a short-rotation forest over several years. *Forest Ecology and Management* 69, 57-72.

Eckersten, H., 1995. Simulation of water flow in plant communities - SPAC model description, excercises and user's manual, SPAC version 5.0. Division of Hydrotechnics, Communications 95:7, Department of Soil Sciences, *Swedish University of Agricultural Sciences*, Uppsala, ISRN SLU-HY-AVDM--95/7--SE. 49 pp.

Eckersten, H., Beier, C., Holmberg, M, Gundersen, P., Lepistö, A., Persson, T., 1999. Application of nitrogen model to forested land. In: Jansson P-E., Persson T, Kätterer T (Eds.), 1999. Nitrogen processes in arable and forest soils in the Nordic countries – Field scale modelling and experiments. *Nordic Councils of ministers*. TemaNord 1999:560. p 99-129

Eckersten, H., Blombäck, K., Kätterer, T. & Nyman, P. 2001. Modelling C, N, water and heat dynamics in winter wheat under climate change in southern Sweden. *Agriculture Ecosystems and Environment* 86, 221-235.

Eckersten, H., Gärdnäs, A. & Jansson, P-E. 1995. Modelling seasonal nitrogen, carbon, water and heat dynamics of the Solling spruce stand. *Ecological Modelling* 83, 119-129.

Eckersten, H. & Jansson P-E., 1991. Modelling water flow, nitrogen uptake and production for wheat. *Fertilization Research* 27:313-329.

Eckersten, H., Jansson, P-E. & Johnsson, H. 1998. SOILN model, ver. 9.2, User's, manual. *Division of Hydrotechnics, Communications 98:6, Dep. of Soil Sciences, Swedish Univeristy of Agricultural Sciences*, Uppsala, 113 pp.

Eckersten, H. & Slapokas, T. 1990. Modelling nitrogen turnover and production in an irrigated short-rotation forest. *Agr. For. Met.* 50, 99-123.

Eckersten, H., Torssell, B., Korhner, A., Nyman, P., 2004. Modelling radiation use and regrowth in grass and red clover swards: Method of calibration. *Ecology and Crop Production Science. Report 5. Swedish University of Agricultural Sciences.* 50 pp.

Ericsson, T. 1981. Growth and nutrition of three *Salix* clonesin low conductivity solutions. *Physiol. Plant.* 52, 239-244.

Ericsson, T. 1994. Nutrient cycling in energy forest plantations. *Biomass and Bioenergy* 6, 115-121.

Hytönen, J. Saarsalmi, A. & Rossi, P., 1995. Biomass production and nutrient uptake of short-rotation plantations. Silvia Fennica 29 (2): 117-139.

Jansson, P.E. 1991. Simulation Model for Soil Water and Heat Conditions. Description of the SOIL model. *Report 165, Division of Agricultural Hydrotechnics, Dep. of Soil Sciences, Swedish University of Agricultural Sciences*, Uppsala, Sweden.

Jansson, P.E. & Halldin, S., 1979. Model for annual water and energy flow in layered soil. In: Halldin (ed.) Comparison of forest water and energy exchange models. *Int. Soc. Ecol. Modellin* (Copenhagen) pp. 145-163.

Jansson, P.E. & Karlberg, L., 2001. Coupled heat and mass transfer model for soil-plant-atmosphere systems. *Royal Institute of Technolgy, Dept of Civl and Environmental Engineering*, Stockholm 325 pp.

Johnsson, H., Bergström, L. & Jansson, P-E., 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agriculture, Ecosystems and Environment* 18, 333-356.

Jonsson, H., 1994. Sammanfattande utvärdering av svenska försökodlingar med *Salix* 1986-1991. Ramprogram Energiskog, NUTEK 1994: 24.

Kätterer, T. & Andrén, O. 1996. Measured and simulated nitrogen dynamics in winter wheat and a clay soil subjected to drought stress or daily irrigation and fertilisation

Kätterer, T., Eckersten, H., Andrén, O. & Pettersson, R. 1997. Winter wheat biomass and nitrogen dynamics under different fertilisation and water regimes: application of a crop growth model. *Ecological modelling* 102, 301-314.

Kätterer, T., Eckersten, H., Heidmann, T., Borg, G., Sippola, J., Breland, T.A., Vold, A., Haugen, L-E., Thomsen, A., Blombäck, K. & Bakken, L. 1999. Application of the nitrogen model to agricultural land. In: Jansson, P-E., Persson, T. & Kätterer, T. (Eds.) *Nitrogen processes in arable and forest soils in the nordic countries. Field-scale modelling and experiments.* TemaNord 1999:560. Nordic Council of Ministers, Copenhagen. ISBN 92-893-0350-6, 83-98.

Kirchmann, H. & Eriksson, J. 1993. Properties and classification of soils of the Swedish log term fertility experiment. II Sites at Örja and Torup. Acta Agriculturae Scandinavica Section B, Soil and Plant Vol. 43, 193-205.

Kopp, R.F., Abrahamson, L.P., White, E.H., Nowak, C.A., Zsuffa, L. & Burns, K.F. 1996. Woodgrass spacing and fertilization effects on wood biomass production by a willow clone. *Biomass an Bioenergy* 11, 451-457.

Ledin, S. and Perttu, K. 1989. Climatic, edaphic and management requirements for energy forestry. K. Perttu and P. Kowalik, (Eds). *Modelling of energy forestry: growth, water relations and economics.* Pudoc, Wageningen, Netherland. Simulation Monographs **30,** 3-11.

Loague, K. & Green, R-E. 1991. Statistical and graphical methods for evaluating solute transport models. Overview and application. *J. Contam. Hydro.* 7, 51-73.

Molina, J.A.E., Clapp, C.E., Shaffer, M.J., Chichester, F.W., Larson, W.E., 1983. NCSOIL, A model of nitrogen and carbon transformations in soil: description, calibration and behaviour. *Soil Sciences Soc. American J.* 47:85-91

Monteith, J.L., 1977. Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London.* B281, 277-294.

Noronha Sannervik, A., 2003. Modelling productivity of willow stands in Sweden – Evaluation of concepts for radiation use efficiency and soil water and nitrogen availability. Diss. Silvestria 26. *Acta Universtatis agriculturae Sueciae. Swedish University of Agricultural Sciences.* 31pp.

Noronha Sannervik, A., Eckersten H., Verwijst T., Kowalik, P., Nordh N-E. 2005. Simulation of willow productivity based on radiation use efficiency, shoot mortality and shoot age. *European Journal of Agronomy.* (accepted for publication 2005-07-08).

Noronha Sannervik, A., Kowalik, P., 2003. Annual variations in the solar energy conversion efficiency in a willow coppice stand. *Biomass and Bioenergy* 25, 227-233.

Ögren, E. 1988. Suboptimal nitrogen status sensitizes the photosynthetic apparatus in willow leaves to long term but not short term water stress. *Photosynthesis Research* 18, 263-275.

Persson, G. and Jansson, P-E., 1989. Simulated water balance of a willow stand on clay soil. In Perttu and Kowalik Eds. Modelling of energy forestry: growth, water relations and economics. ISBN 90-220-0947-5. Pudoc Wageningen, Netherlands.

Rosenqvist, H. 1997. Salix – Kalkylmetoder och lönsamhet. *Swedish Univ. Agricult. Sci.* Silvestria 24, ISBN 91-576-5308-9.

Rytter, R-M. 1997. Fine root production and carbon and nitrogen allocation in basket willows. *Doctoral thesis. Dep. of Short Rotation Forestry. Swedish University of Agricultural Sciences*, Uppsala, Sweden, Silvestria 39.

Sennerby-Forsse, L. & Zsuffa, L. 1995. Bud structure and resprouting in coppiced stools of *Salix viminalis* L., *S. eriocephala* Michx., and *S. amygdaloides* Anders. *Trees* 9, 224-234.

Sinclair, T.R. & Muchow, R.C. 1995. Effect of nitrogen supply on maize yield. I. Modeling physiological responses. *Agronomy Journal* 87, 632-641.

Tahvanainen, L. & Rytkönen, V-M. 1999. Biomass production of *Salix viminalis* in southern Finland and the effect of soil properties and climate conditions on its production and survival. *Biomass and Bioenergy* 16: 103-117.

Verwijst T. 1991. Shoot mortality and dynamics of live and dead biomass in a stand of *Salix viminalis. Biomass and Bioenergy* 1: 35-39.

Wallander, H. 1995. A new hypothesis to explain allocation of dry matter between mycorrhizal fungi and pine seedlings in relation to nutrient supply. *Plant and Soil* 168-169, 243-248.

Weih, M. 2001. Evidence for increased sensitivity to nutrient and water stress in a fast-growing hybrid willow compared with a natural willow clone. *Tree Physilogy* 21, 1141-1148.

Weih, M. & Nordh, N-E. 2002. Characterising willows for biomass and phytoremediation: growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes. *Biomass & Bioenergy* 23, 397-413.

Modelling processes

Short description of processes of the RUE-W-N model that have been described elsewhere (Eckersten et al., 1998, 1999; Eckersten and Jansson, 1991; Johnsson et al., 1987; Noronha Sannervik, 2003).

Leaf area

Leaf area is estimated from the standing stem biomass at start of the growing season ($W(t_o)$).

$$LAI = f_{Ws} \, LAI_{Max} \, f_{LAI} \qquad \qquad (A1)$$

where

$$f_{Ws} = 1 - W_{Min}/W(t_o) \qquad \qquad 0 \le f_{Ws} \le 1 \qquad (A2)$$

f_{LAI} is a Julian daynumber function for relative values of LAI ranging between 0 and 1. LAI_{Max} is the maximum possible LAI and scales f_{LAI} to actual LAI values. At standing biomass levels below W_{Min} no leaf area emerges.

Dissolve litter and fertiliser

The rates of transfer, from the non active litter or fertiliser pools above soil surface, to the soil surface layer, are assumed to decrease at low relative soil water content (θ). This response is set similar to that of microbial activity. At optimal water conditions the transfer rate is 0.05 d^{-1} for litter, whereas for fertilisers it depends on the type of fertiliser. For "Modellskogen" $k_{Fert} = 0.99$, for the other sites $k_{Fert} = 0.15$.

$$k_{Active} = 0.05 \, (\theta - 0.1)/0.3 \qquad \qquad 0 \le k_{Active} \le 1 \qquad (A3)$$

$$k_{DisolvFert} = k_{Fert} \, (\theta - 0.1)/0.3 \qquad \qquad 0 \le k_{DisolvFert} \le 1 \qquad (A4)$$

Decomposition

The decomposition of organic matter depends on the specific assimilation rate of litter and humus by microbes (k_l and k_h), and the response functions for soil moisture and temperature conditions (e_θ and e_t). Microbes assimilate litter and humus in a similar way. Only the specific rates of gross assimilation and utilisation efficiency differ. The flows of carbon from litter (C_{Litter}) to microbes (C_{Mic}) and from humus (C_{Humus}) to microbes are assumed to be substrate limited (Johnsson et al., 1987):

$$C_{Litter \rightarrow Mic} = k_l \, e_T \, e_\theta \, C_{Litter} \qquad \qquad (A5)$$

$$C_{Humus \rightarrow Mic} = k_h \, e_T \, e_\theta \, C_{Humus} \qquad \qquad (A6)$$

where, e_T and e_θ are response functions to temperature and soil water content, respectively, taken from Johnsson et al. (1987). The air temperature is used instead of soil temperature, which might result in systematic error of the annual decomposition rates (this is compensated for by calibration of the specific decomposition rates).

$$e_T = Q_{10} \ e^{((T - 20)/10)} \tag{A7}$$

$$e_\theta = (\theta - \theta_0)/(\theta_1 - \theta_0) \qquad\qquad 0 \le e_\theta \le 1 \tag{A8}$$

A fraction (f_l for litter and f_h for humus) of the carbon consumed by microbes is lost to the atmosphere by growth respiration (Johnsson et al., 1987).

$$C_{Mic \to Atm} = f_l \ C_{Litter \to Mic} + f_h \ C_{Humus \to Mic} \tag{A9}$$

Carbon balances

Mortality of microbes is regulated by the assumption that the microbial C is 3 % of the total organic C. The dead microbes are transferred to litter.

$$C_{Mic \to Litter} = C_{Mic} - 0.03 \ (C_{Humus} + C_{Litter} + C_{Mic}) \qquad \ge 0 \tag{A10}$$

The litter carbon balance is the input by litter fall ($C_{LittFall}$) and microbial mortality reduced by the amounts assimilated by microbes (Eckersten et al., 1998, 1999).

$$\Delta C_{Litter} = C_{LittFall} + C_{Mic \to Litter} - C_{Litter \to Mic} \tag{A11}$$

The carbon balance of humus is the amount humified reduced by the amount assimilated by microbes (Eckersten et al., 1998, 1999).

$$\Delta C_{Humus} = C_{Mic \to Humus} - C_{Humus \to Mic} \tag{A12}$$

The carbon balance of microbes is then:

$$\Delta C_{Mic} = C_{Litter \to Mic} + C_{Humus \to Mic} - C_{Mic \to Atm} - C_{Mic \to Litter} \tag{A13}$$

N mineralisation

Nitrogen dynamics of the organic matter is governed by the C flows related to growth of microbes. N flow is the C flow multiplied by the N/C ratio of the source (Eckersten et al., 1998).

$$\Delta N_{Mic} = (N/C)_{Litter} \ C_{Litter \to Mic} + (N/C)_{Humus} \ C_{Humus \to Mic} - \tag{A14}$$
$$(N/C)_{Mic} \ C_{Mic \to Litter} - N_{Org \to Mineral}$$

Whether N is mineralised or immobilised ($N_{Org \to Mineral}$), depends on whether the N/C ratio of the microbes is lower or higher than their demand, determined by a constant N/C ratio ($CN_{RatioMic}$). If it is lower, then N is immobilised, otherwise N is mineralised. The daily uptake is limited to be a fraction (c_{Up}) of the ammonium (N_{NH4}) and the nitrate (N_{NO3}) contents (Eckersten et al., 1998).

$$N_{Org \to Mineral} = N_{Mic} - C_{Mic}/CN_{RatioMic} \qquad \leq c_{Up} (N_{NH4} + N_{NO3}) \qquad (A15)$$

Mineral N is taken up by microbes as ammonium and nitrate (cf. Molina et al., 1983) in proportion to the abundance of the two forms. N is mineralised from microbes as ammonium.

Nitrification

N is mineralised from dead organic matter as ammonium, which in turn is transformed to nitrate. Nitrification is proportional to the excess of ammonium in relation to nitrate (Johnsson et al., 1987).

$$N_{NH4 \to NO3} = k \, e_T \, e_\theta \, (N_{NH4} - N_{NO3}) \qquad \leq c_{Up} \, N_{NH4} \qquad \text{and} \geq 0 \qquad (A16)$$

where, nitrification respond to abiotic conditions in the same way as decomposition (eqs. A5-6).

Root N uptake

The root uptake of mineral N is limited by the plant demand for N (N_{Dem}) if the avialable amount in the soil is larger than the demand. Otherwise, the uptake is a fraction ($c_{UpPlant}$) of the mineral N ($N_{NO3} + N_{NH4}$), reduced by the amount taken up by microbes ($-N_{Org \to Mineral}$) (Eckersten and Jansson, 1991).

$$N_{RootUptake} = c_{UpPlant}(N_{NO3} + N_{NH4} + N_{Org \to Mineral}) \qquad \leq N_{Dem} \qquad (A17)$$

In case of low soil relative water content (θ) the fraction of the mineral N, that can be taken up daily, is reduced. The limit for reduction is set similar to those of e_θ (eq. A8).

$$c_{UpPlant} = c_{Up} \, (\theta - 0.25)/(0.4 - 0.25) \qquad 0 \leq c_{UpPlant} \leq 1 \qquad (A18)$$

Site description

Table A1. *Summary of the site and plantation characteristics for the high fertilised test and calibration sites at Uppsala ("modellskogen"). No stand was watered, except Modellskogen. Harvest was made in winter. (From Noronha Sannervik, 2003).*

Site	Field	Management	Soil	Size and density of plantation	Plantation year and harvest	Source
Uppsala	Modellskogen	1985-1992 the stand received 50 to 300 kg N ha^{-1} y^{-1} and 50 to 400 mm water. 1993 and 1994 was not fertilised or watered.	Clay	2.7 ha; 2.04 cuttings m^{-2}	Planted 1984. Harvested winters 1986/87, 1990/91 & 1994/95.	Verwijst, (1996)
	Gottsunda	Fertilised with 70 to 140 kg N ha^{-1} y^{-1}.	Clay loam	0.69 ha; 2 cuttings m^{-2}	Planted 1994. Harvested winter 1997/98	Personal comm. Nils-Erik Nordh
	Brunnby	Fertilised with 50 to 120 kg N ha^{-1} y^{-1}. No fertilisation the years 1997 and 1998.		0.52 ha; 2 cuttings m^{-2}	Planted 1990. Harvested winters 1993/94 & 1997/98	
Västerås	Korrvike C	Fertilised with 90 to 150 kg N ha^{-1} y^{-1}	Clay	896 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Korrvike D	Fertilised with 150 to 180 kg N ha^{-1} y^{-1}				
	Bännebo C	Fertilised with 90 to 150 kg N ha^{-1} y^{-1}.		156 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Bännebo D	Fertilised with 150 to 180 kg N ha^{-1} y^{-1}				
Vingåker	Grimstad C	Fertilised with 90 to 150 kg N ha^{-1} y^{-1}	Loamy sand	780 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	Alriksson, (1997)
	Grimstad D	Fertilised with 150 to 180 kg N ha^{-1} y^{-1}				
Malmslätt	Logården C	Fertilised with 90 to 150 kg N ha^{-1} y^{-1}.	Clay loam	780 m^2; 2 cuttings m^{-2}	Planted 1988 Harvested winter 1991/92	
	Logården D	Fertilised with 150 to 180 kg N ha^{-1} y^{-1}.				
Lund	Borgeby C	Fertilised with 90 to 150 kg N ha^{-1} y^{-1}.	Sandy loam	780 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Borgeby D	Fertilised with 150 to 180 kg N ha^{-1} y^{-1}.				

Table A2. *Summary of the site and plantation characteristics for the non and low fertilised test. No stand was watered. Harvest is made in winter. (From Noronha Sannervik, 2003).*

Site	Field	Management	Soil	Size and density of plantation	Plantation year and harvest	Source
Västerås	Korrvike A	No fertilisation	Clay	896 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	Alriksson, (1997)
	Korrvike B	Fertilised with 45 to 75 kg N ha^{-1} y^{-1}				
	Bännebo A	No fertilisation		156 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Bännebo B	Fertilised with 45 to 75 kg N ha^{-1} y^{-1}				
Vingåker	Grimstad A	No fertilisation	Loamy sand	780 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Grimstad B	Fertilised with 45 to 75 kg N ha^{-1} y^{-1}				
Malmslätt	Logården A	No fertilisation	Clay loam	780 m^2; 2 cuttings m^{-2}	Planted 1988 Harvested winter 1991/92	
	Logården B	Fertilised with 45 to 75 kg N ha^{-1} y^{-1}				
Lund	Borgeby A	No fertilisation	Sandy loam	780 m^2; 2 cuttings m^{-2}	Planted 1989. Harvested winter 1992/93	
	Borgeby B	Fertilised with 45 to 75 kg N ha^{-1} y^{-1}				