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Dynamic nitrogen deposition thresholds during forest stand development in a Douglas fir forest analysed with two nitrogen models SMART2 and MERLIN

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Abstract

In contrast to the classical *critical load* (*CL*) concept, based on long-term steady state conditions, a dynamic deposition threshold (*DDT*) is introduced. This *DDT* takes into account all relevant dynamic aspects of vegetation development/forest growth, mineralisation, immobilisation and denitrification, depending on the successional stage of the forest. *DDT* values for nitrogen were determined for a Douglas fir rotation by two process-based nitrogen models SMART2 and MERLIN using three different criteria for critical nitrogen leaching. During most of the rotation time, the predicted *DDT* values were higher than the corresponding traditional *CL*. SMART2 and MERLIN predicted a maximum *DDT* of 4.9 and 4.6 kmol N ha^{-1} yr^{-1} (69 and 64 kg N ha^{-1} yr^{-1}), respectively, when accepting a critical N leaching level of 1.73 kmol N ha^{-1} yr^{-1} related to impacts on ground water quality. This is due mainly to relatively high tree uptake during the first 50 years of a forest rotation, compared to a long-term estimate, i.e. the average tree uptake during a rotation period, used in the traditional *CL* calculation. At the lowest critical N leaching level of 0.10 kmol N ha^{-1} yr^{-1}, corresponding to a level that might be critical for vegetation changes, the calculated *DDT* value and related N availability was such that it influenced tree growth, indicated by an increased CN ratio in foliage and organic matter. The two models SMART2 and MERLIN predicted comparable absolute levels of *DDT* but with a completely different temporal pattern. This was caused by differences in timing of mineralisation in the soil. Both models showed the importance of the soil for supplying N for tree growth in young and productive forests, but the timing of this mobilisation of N from the soil was different. This difference between the two models reflects the lack of knowledge of the mechanisms of the role of soil organic matter in satisfying tree N demand. Nevertheless, this method has a high potential for increasing more detailed insight into the dynamic behaviour of *CL,* which will make it possible to focus management options on a smaller spatial and temporal scale.

Keywords: critical load, dynamic deposition threshold, nitrogen, forest, SMART2, MERLIN

Introduction

The critical load (*CL*) concept was developed in an attempt to determine thresholds of pollutant inputs from atmospheric sources. A *CL* is defined as a quantitative estimate of an exposure to one or more pollutants below which no significant harmful effects on specified sensitive elements of the environment occur (Grennfelt and Thörnelöf, 1992). A widely accepted method to quantify a *CL* is the steady-state mass balance approach (e.g. Posch *et al*., 1995). Different *CL* values are defined using different criteria for environmental effects. The *CL* for nitrogen (N) as a nutrient (*CL(N)*) for instance, aims at preventing eutrophication of the terrestrial ecosystem and linked freshwater ecosystems. It is calculated as the total amount of N that, given a certain critical N leaching level, can be absorbed by major long-term N sinks (net vegetation uptake, long-term acceptable soil N immobilisation and denitrification) without long-term adverse ecological effects.

One of the crucial aspects of the critical load concept is that it considers only an ecosystem at steady state. That means that all dynamic aspects in the nitrogen cycle are ignored. This assumption is made to gain insight into long-term acceptable loads, thus focusing the policy makers' view on the ultimate emission reductions that are needed (De

Vries, 1993; Sverdrup *et al.*, 1990). This implies that critical loads are relevant to assess the ultimate emission reductions, but an excess of those loads does not necessarily imply that the forest ecosystem is at risk yet. To gain insight into the relationship between ecosystem risk and atmospheric deposition, the threshold at the time under consideration must be known. Such thresholds are denoted as present deposition thresholds (De Vries et al., 2002), being the deposition levels that lead to concentrations of nitrogen (or acidity) in soil solution that are equal to critical limits at present (not in a steady-state situation).

To gain insight into the dynamics of impacts of emission reductions up to critical loads, dynamic models are needed since the dynamics in ecosystem behaviour lead to situations where the presently acceptable N input is higher or lower than the *CL(N)* (Pardo and Driscoll, 1996). For instance, if pH increases due to deposition reduction, mineralisation will accelerate, which in turn will result in higher nitrate leaching fluxes. Consequently, during such (temporary) circumstances a nitrogen input at critical load will still cause violation of the critical N leaching level. Conversely, in the case of a newly planted forest, net N accumulation in the trees will be rather large, which in turn may tolerate a higher N deposition level without violating the critical leaching level. It might even be possible that N inputs equal or less than *CL(N)* result in an unfavourable situation in respect of forest growth.

In this paper, a procedure for a dynamic critical load calculation is proposed that takes into account relevant site specific dynamic aspects of the N cycle. In accordance with the present deposition threshold, this is called the Dynamic Deposition Threshold (*DDT*).

Contrary to the classical *CL* that can be assessed by using a steady state model, the *DDT* can be assessed only by dynamic models. SMART2 (Kros *et al.,* 1995) and MERLIN (Cosby *et al.*, 1997) are two process-based dynamic N models, which are suitable for the calculation of such a *DDT*. Both models are developed to simulate N cycling at scales varying from the ecosystem scale up to a regional scale. In addition, both models have been applied to the Douglas fir experimental forest near Speuld (Tiktak *et al.*, 1995; Tietema *et al.*, 1998). These two models have been used to evaluate the *DDT* during stand development in this Douglas fir forest.

Material and Methods

SITE DESCRIPTION

The Speulderbos (52°13´N, 5°39´E) is located a few kilometres south of the town of Speuld, in “de Veluwe”, in the central part of The Netherlands. At the study site, an oak coppice, planted in 1909, was felled in 1960. The soil was neither ploughed nor fertilised before planting Douglas fir seedlings (*Pseudotsuga menziesii* (Mirb.) Franco.) in 1962.

At the time of the experiments, tree density was about 800 ha^{-1} and average tree height around 22 metres. There was no undergrowth present. The forest soil has a 4–7 cm thick organic layer. The humusform was classified as a mormoder (Green *et al.,* 1993), the soil as a Haplic Podzol (Koopmans *et al.*, 1995) or as a Cambic Podzol (Tiktak *et al.*, 1995). The soil is well-drained, consisting of fluviatile deposits with textures ranging from fine sand to sandy loam. Soil pH_{H2O} ranges from 3.7 in the organic layer to 5.1 in the mineral soil. Base saturation in the mineral soil is almost zero. The groundwater table is always below 40 m.

Total N deposition in The Netherlands increased in the early 1950s, coinciding with the start of the massive development of agricultural activity after the second world war. The current level of deposition was reached in 1980 (Erisman and Bleeker, 1997). Atmospheric nitrogen input measured as throughfall in this forest in the period from 1985 to 1995 ranged from 40 to 50 kg N ha^{-1} yr^{-1}, about 75% as ammonium.

MODEL DESCRIPTION

SMART2

SMART2 is a simple soil acidification and nutrient cycling model that includes the major hydrological and biogeochemical processes in the vegetation, litter and mineral soil (Kros *et al.,* 1995; Mol-Dijkstra *et al.*, 1998). The soil consists of two compartments, a litter layer and a mineral soil layer. Apart from pH, the model predicts changes in aluminium (Al^{3+}), base cation (BC), ammonium (NH_4^+), nitrate (NO_3^-) and sulphate (SO_4^{2-}) concentrations in the soil solution and solid phase characteristics depicting the acidification status, i.e. carbonate content, base saturation, readily available Al content and N content in organic matter. The SMART2 model consists of a set of mass balance equations, describing the soil input-output relationships, and a set of equations describing the rate-limited and equilibrium soil processes. The soil solution chemistry in SMART2 depends on net element input from the atmosphere and groundwater, canopy interactions, geochemical interactions in the soil and a complete nutrient cycle (root uptake, litterfall, mineralisation, nitrification and denitrification) for basic cations, sulphur and nitrogen. The model is based on the assumption that the amount of organic matter (C) is in a steady state. N mineralisation is described in SMART2 by a first order reaction. Growth and litterfall of the vegetation are modelled by a logistic growth function, which acts as a forcing function for nutrient uptake. Nutrient uptake is limited only when there is a shortage in the soil solution. Microbial N immobilisation is described in SMART2 by an increase in N content in soil organic matter.

MERLIN

MERLIN (Cosby *et al*., 1997) is an aggregated, ecosystem-scale mass balance model of linked carbon and nitrogen cycling, simulating nitrogen cycling and leaching in forested ecosystems. The structure of MERLIN includes a tree compartment and two organic soil compartments. The plant compartment is an aggregated pool of carbon and nitrogen representing the "active" portion of the vegetation. In forests, this pool conceptually includes foliage and fine roots. Wood production can be thought of as long-term storage losses from that pool. Soil organic material is divided into labile organic matter (LOM) and refractory organic matter (ROM). The LOM pool may be identified as the forest floor, providing a soil organic compartment that can respond rather quickly to changing external conditions. The ROM pool represents the bulk of slowly decomposing organic matter in the soil profile down through the A, B and C horizons. Fluxes in and out of the ecosystem and between compartments included in MERLIN are atmospheric deposition, hydrological discharge, plant uptake, litterfall, wood production, microbial immobilisation and mineralisation and nitrification. Nitrogen fluxes between compartments are controlled by carbon productivity, by the C/N ratios of organic compartments and by inorganic nitrogen availability in soil solution. MERLIN requires the input of historical sequences of carbon pools and fluxes, of hydrological discharge, and of external sources of inorganic nitrogen, as well as current amounts of nitrogen in the compartments. In addition, it needs parameters specifying plant uptake and microbial immobilisation and soil characteristics such as depth, porosity and bulk density. The output generated by MERLIN includes fluxes of inorganic nitrogen in drainage, total nitrogen contents and C/N ratios of the compartments and rates of nitrogen immobilisation (uptake) and mineralisation. A detailed description of MERLIN is given by Cosby *et al*. (1997).

DYNAMIC DEPOSITION THRESHOLD

Calculation method of the Critical Load

A critical load for nitrogen (*CL(N)*) is defined as the maximum total N input to an ecosystem, which consists of the sum of permanent plant uptake, long term accumulation of N in the soil, denitrification, and the acceptable leaching of nitrogen from the perspective of eutrophication (Nilsson and Grennfelt, 1988) according to (cf. De Vries, 1993):

$$CL_N = N_{gu} + N_{im,m} + N_{de} + N_{le(crit)} \qquad (1)$$

where:

N_{gu} = Net growth uptake of N (mol$_c$ ha^{-1} yr^{-1})
$N_{im,m}$ = Net microbial N immobilisation (mol$_c$ ha^{-1} yr^{-1})
N_{de} = N denitrification (mol$_c$ ha^{-1} yr^{-1})
$N_{le(crit)}$ = Critical N leaching (mol$_c$ ha^{-1} yr^{-1})

In Eqn. (1) all terms at the right hand side are in fact influenced by atmospheric deposition. For the calculation of critical loads these terms must be derived at a deposition level that equals the critical load (De Vries, 1993). Furthermore, the critical load concept considers only an ecosystem at steady state. That means that all dynamic aspects in the nitrogen cycle are ignored.

Calculation method of the Dynamic Deposition Threshold

The calculation of the *DDT* is comparable to the steady-state *CL* (see Eqn. (1)), but it differs in having time-dependent terms for N uptake through vegetation development/forest growth (N_{up}), N (im)mobilisation in the soil (N_{im}) and denitrification (N_{de}). Similar to the steady-state *CL,* these terms are dependent on deposition. The *DDT* (mol$_c$ ha^{-1} yr^{-1}) at a particular time (*t*) is calculated as:

$$DDT(t) = N_{up}(t) + N_{im}(t) + N_{de}(t) + N_{le(crit)} \qquad (2)$$

where:

$N_{up}(t)$ = net change of N in the vegetation at time *t*
$N_{im}(t)$ = net change of N in the soil at time *t*
$N_{de}(t)$ = N denitrification at time *t*
$N_{le(crit)}$ = critical N leaching (mol$_c$ ha^{-1} yr^{-1})

The net change in the vegetation ($N_{gu}(t)$) consists of the total N uptake by the vegetation, to be divided in maintenance uptake (N_{mu}) and growth uptake (N_{gu}) minus the loss through litterfall (N_{lf}):

$$N_{up}(t) = N_{gu}(t) + N_{mu}(t) - N_{lf}(t) \qquad (3)$$

where:

$N_{gu}(t)$ = growth uptake N at time = *t*
$N_{mu}(t)$ = maintenance uptake N at time = *t*
$N_{lf}(t)$ = litterfall N at time = *t*

In a steady state situation, assumed in the *CL*(*N*) calculation, litterfall equals maintenance uptake and N_{up} calculated with Eqn. (3) equals N_{gu} calculated with Eqn. (1).

The net change in the soil nitrogen pools ($N_{im}(t)$) consists of the total N input through litterfall (N_{lf}) and the microbial N immobilisation ($N_{im,m}$) minus the loss through mineralisation (N_{mi}):

$$N_{im}(t) = N_{lf}(t) - N_{mi}(t) + N_{im,m}(t) \tag{4}$$

where:

$N_{mi}(t)$ = N mineralisation flux at time = *t*
$N_{im,m}(t)$ = microbial N immobilisation at time = *t*

In a steady state situation, litterfall equals mineralisation and N_{im} calculated with Eqn. (4) equals the net microbial N immobilisation $N_{im,m}$ calculated with Eqn. (1).

Combining Eqns. (2), (3) and (4) results in:

$$DDT(t) = N_{tu}(t) - N_{mi}(t) + N_{de}(t) + N_{im}(t) + N_{le(crit)} \tag{5}$$

where $N_{tu}(t)$ stands for the total (or gross) uptake by the vegetation, i.e. the sum of the maintenance and growth uptake. In this study, the time and deposition dependent terms (i.e. N_{tu}, N_{mi} and N_{de}) were calculated using the two dynamic N cycling models MERLIN and SMART2. Since these terms are dependent on the deposition, used as model input, the calculation of *DDT* makes sense only when it is calculated at a deposition level that equals the *DDT*. So, Eqn. (5) has to be solved with the deposition equal to *DDT*.

In this study, however, the *DDT* was approximated by updating its value, used as model input, at each timestep (*t*) by using the difference between the critical N leaching flux ($N_{le(crit)}$) and the modelled N leaching flux ($N_{le,M}$). This yields the maximum allowable deposition that meets the N leaching limit. The *DDT* at time = *t* is thus calculated as:

$$DDT(t) = DDT(t-1) - \left(N_{le,M}(t) - N_{le(crit)}\right) \tag{6}$$

where:

$DDT(t\text{-}1)$ = the *DDT* from the previous time step, i.e. the N deposition used for the calculation of $N_{le,M}(t)$ ($\text{mol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$)
$N_{le,M}(t)$ = N leaching flux at time = *t* and deposition = $DDT(t\text{–}1)$ ($\text{mol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$)
$N_{le(crit)}$ = critical N leaching ($\text{mol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$)

At *t* = 1, the value of *DDT(t–1)* was set equal to the present deposition. When *DDT(t–1)* became negative, it was set to zero. This method assumes that the difference between $N_{le,M}(t)$, that follows from the calculation with *DDT (t–1)* being the N deposition used for the calculation, and $N_{le(crit)}$, that should be the outcome when calculating a *DDT,* can be compensated directly by either increasing or decreasing the *DDT* value. This is, however, a simplification because all relevant processes depend on the N deposition and will thus change accordingly. Ideally, the value of *DDT* should have been calculated iteratively within an optimisation procedure. However, neglecting iteration affects the outcome only in the first years. Within a short time the difference $N_{le,M}(t) - N_{le(crit)}$ is small thus reducing the error to a negligible value.

Criteria

DDT values were evaluated with three criteria on $N_{le(crit)}$ (Table 1).The EU standard of 50 mg l^{-1} (0.8 $\text{mol}_c\ \text{m}^{-3}$) was used as *drinking water standard* ($N_{le,\ crit}$ (*dw*)). For the application of the models MERLIN and SMART2, a constant precipitation excess of 216 mm yr^{-1} was used. This implies that $N_{le(crit)}$ (*dw*) = 0.8 $\text{mol}_c\ \text{m}^{-3} \times 2160\ \text{m}^3\ \text{ha}^{-1}$ = 1730 $\text{mol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$. The criterion based on preventing *vegetation changes* ($N_{le(crit)}$ (*vc*)) was set to 100 $\text{mol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$ (De Vries, 1996). The critical N leaching related to a *critical N content in needles* ($N_{le(crit)}$ (*nc*)) was based on a

Table 1. Overview of the critical N leaching, NO_3 concentration and *CL(N)* values used for the dynamic deposition threshold (*DDT)* calculations.

Criteria	*Description*	*N leaching flux*[*] *($\text{kmol}_c\ \text{ha}^{-1}\ \text{yr}^{-1}$)*	*NO_3 concentration ($\text{mol}_c\ \text{m}^{-3}$)*	*CL(N) (kmol_c N $\text{ha}^{-1}\ \text{yr}^{-1}$)*
$N_{le,crit}$(dw)	Drinking water standard	1.73	0.80	2.68
$N_{le,crit}$(nc)	Critical N content in foliage	0.91	0.42	1.76
$N_{le,crit}$(vc)	Vegetation changes	0.10	0.05	0.87

[*] Based on the precipitation excess at Speuld (216 mm yr^{-1}).

content of 1.8%, which is a value from pine forests (Erisman *et al.*, 1998). To link this foliage N concentration to a soil solution concentration, data from 150 extensively monitored forest sites were evaluated (De Vries and Leeters, 2001; Leeters *et al.*, 1994). From this set, 25 spruce and Douglas fir sites were used to identify the following regression model:

$$ctN_{fl} = 1.967 + 0.443 \cdot \log(cN) \tag{7}$$

with R$^2_{adj}$ = 51 and N = 25, where ctN_{fl} = N content in foliage (%) and cN = N concentration in the soil solution of the 0–30 cm layer (mol$_c$ m^{-3}). Using a critical ctN_{fl} of 1.8% and a precipitation excess of 216 mm yr^{-1}, Eqn. (9) yields a $N_{le(crit)}(nc)$ of 0.42 mol$_c$ m^{-3} × 2160 m^3 ha^{-1} = 907 mol$_c$ ha^{-1} yr^{-1}. The soil solution concentration thus derived is close to the target value for drinking water in the Netherlands, i.e. 0.40 mol$_c$ m^{-3} (25 mg l^{-1}).

For the three criteria used, the classical site specific *CL*(N) values were calculated with Eqn. (1). Site specific values for growth uptake (N_{gu}) and immobilisation (N_{im}) were derived from Tiktak *et al.* (1995). For N_{gu} 425 mol$_c$ ha^{-1} yr^{-1} was used, based on a average growth rate of 10.7 m^3 ha^{-1} yr^{-1} during the rotation period. For N_{im} a value of 329 mol$_c$ ha^{-1} yr^{-1} was used, based on a litter layer of 3 cm to be formed over the past 100 years. Denitrification (N_{de}) was calculated as a fraction of the critical N leaching flux according to (cf. De Vries, 1993):

$$N_{de} = \frac{fr_{de}}{1 - fr_{de}} N_{le(crit)} \tag{8}$$

where fr_{de} is the denitrification fraction, which was set to a generic value for dry sandy soils of 0.1 (De Vries, 1996).

Depending on the criterion used, *CL(N)* resulted in a range from 0.87 to 2.68 kmol ha^{-1} yr^{-1} (see Table 1). The spread in range is determined fully by the critical N leaching.

The present calculation method, assuming a critical N leaching of 0.4 kmol ha^{-1} yr^{-1}, yielded a *CL* of 1.20 kmol ha^{-1} yr^{-1}. This value is above the maximum of the range of calculated *CL(N)* values for the Speuld site by Reynolds *et al.* (1998) who reported a minimum of 0.47 and a maximum of 1.04 kmol ha^{-1} yr^{-1}, with the same value of 0.4 kmol ha^{-1} yr^{-1} as critical N leaching. This range was caused by uncertainties in tree uptake due to a wide range of possible values based on the use of the nutrient limitation method of calculating this term.

MODEL ADAPTATIONS AND APPLICATION

To make an objective comparison between the SMART2 and MERLIN applications, a few adaptations to both models were made. A response function between N concentration in foliage and in soil water according to Eqn. (9) was included in SMART2 to get a more direct coupling between the two characteristics. To calculate two entire growth cycles, whole tree harvesting was included in SMART2 by adding an amount of N and base cations in debris to the amount of N and base cations in litter. Foliar uptake of nitrogen was included in MERLIN as a fraction (10%) of total deposition.

For this analysis of dynamic critical loads, existing applications of both models on the Speuld site were used (Tiktak *et al.*, 1995; Tietema *et al.*, 1998). To minimise the effects of differences in data used by both models, the input data for both models were tuned. The hydrology was constant during the whole period. In both models, a precipitation surplus of 216 mm yr^{-1} was used as input, based on measurements of precipitation and modelled evapotranspiration (Belmans *et al.*, 1983; Van der Salm *et al.*, 1998). For both models the N deposition was calculated as *DDT* according to Eqn. (6). Litterfall was included as an input sequence corresponding to the MERLIN application at Speuld (Tietema *et al.*, 1998). The N content in litterfall was estimated at 1.8% in the MERLIN application and 1–2.5% in the SMART2 application depending on N deposition.

The litter mineralisation rate constant in SMART2 was calibrated to simulate the same litter amounts in 1980 and 1990 as simulated by MERLIN. In SMART2, a logistic growth function for woody biomass was used, based on the fit to a growth curve for Douglas fir given by Jansen *et al.* (1996). This curve fitted the increase of biomass between 1990 and 1995 at Speuld (Fig. 1). These stem biomass data were derived by regression from yearly diameter and tree height measurements (Steingröver and Jans, 1995; Dik,

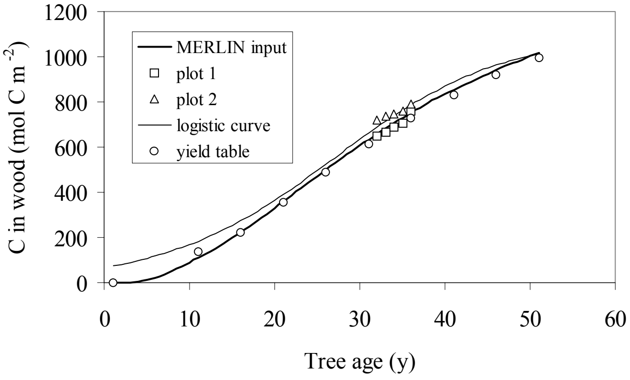

Fig. 1. *Net accumulation of carbon in the trees: yield table results (Jansen et al. 1996), the logistic growth curve used in SMART2 and the carbon sequence used in MERLIN. In addition, stem biomass data from the Speuld forest between 1990 and 1994 on two different experimental plots are given.*

1984). The growth curve refers to the gross increase of biomass, which means that the result of thinning was added to the net increase of biomass. In MERLIN the same curve was used as an input sequence for wood biomass (Fig. 1).

Results and discussion

The *DDT*, calculated by SMART2 and MERLIN differed considerably during the simulation period (Fig. 2). In general, at all three critical leaching levels, MERLIN predicted the highest *DDT* values (up to 4.6 kmol ha^{-1} yr^{-1} or 64 kg N ha^{-1} yr^{-1} with 1.73 as criterion for critical leaching level) during the first 15 years of the rotation. Conversely, SMART2 predicted the highest *DDT* values (up to 4.9 kmol ha^{-1} yr^{-1} or 69 kg N ha^{-1} yr^{-1}) in the mature 50-year old Douglas fir forest. During most of the rotation time, the predicted *DDT* values were higher than the corresponding traditional *CL(N)* (Fig. 2).

The dynamics of the *DDT* during the rotation depended on the model. The differences between both models could be attributed largely to differences in the timing of N immobilisation in the soil (Fig. 3). In the MERLIN application, net N immobilisation decreased from approximately +1.8 to –1.9 kmol ha^{-1} yr^{-1}. This decrease in N immobilisation was caused primarily by an increased gross mineralisation rate in the refractory organic matter (ROM) pool that contributed to supplying N for tree growth. During the second half of the rotation, gross mineralisation of ROM decreases again, causing a positive net N immobilisation in the soil (Fig. 3). In general, N dynamics are highly constrained by C dynamics and optimal CN ratios in the vegetation and soil compartments in MERLIN. Both characteristics are input to the model. In the Speuld application they were based on data characteristic of the oak coppice in 1960 and the data collected around 1990 in the Douglas fir forest. The input sequences of C pools between 1960 and 1990 and the optimal CN ratios in 1960

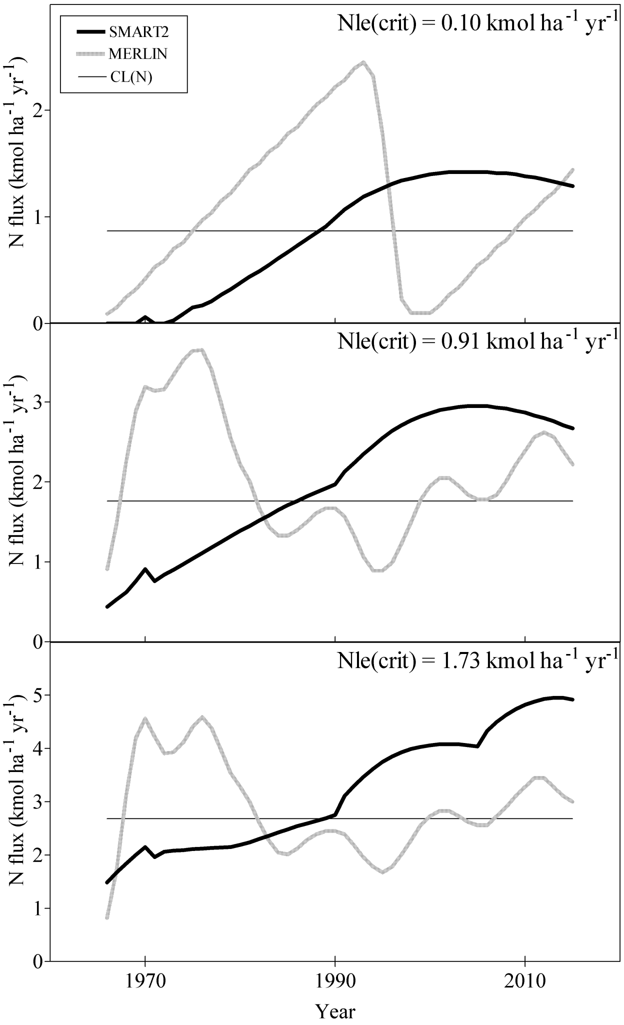

Fig. 2. *Dynamic Deposition Threshold (DDT) values predicted by SMART2 and MERLIN, in relation to the CL(N). The three graphs correspond with different critical N leaching criteria. All graphs with a time sequence start in 1966 to avoid the large fluctuations occurring as a result of clear-cutting and planting the young Douglas firs in the period 1960 – 1965.*

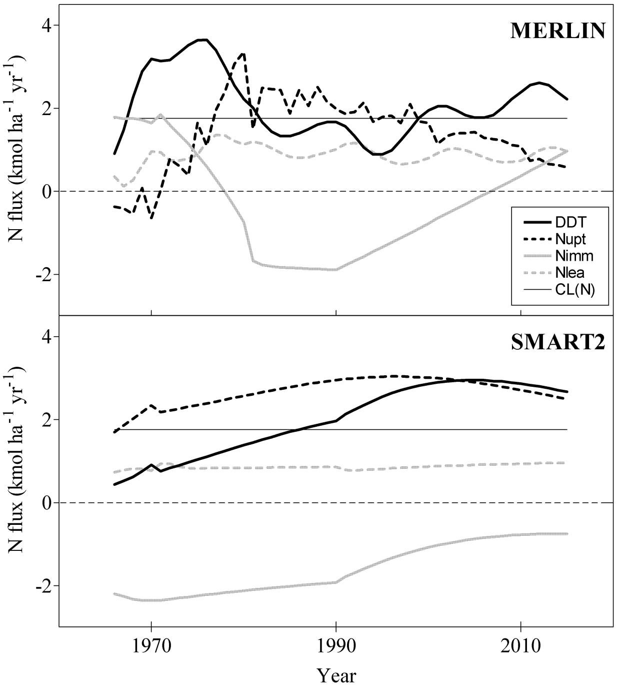

Fig. 3. *Dynamic Deposition Threshold (DDT), net N accumulation in the trees (Nupt), net N immobilisation in the soil (Nimm), N leaching (Nlea) and corresponding CL (N) at a critical N leaching level of 0.91 kmol ha^{-1} yr^{-1} calculated by MERLIN (above) and SMART2 (below).The N flux by denitrification (Nde) is calculated by both models as being negligible in this dry sandy soil.*

and 1990 were obtained by interpolation, based on the results of the NITREX experiments (Tietema *et al.*, 1998). These experiments showed a very fast reaction of nitrate leaching to a sudden decrease in N deposition. This fast reaction implied a decreased role of N mineralisation from ROM in 1990 and as such it constrained the interpolation of the ROM C sequence. This input sequence was kept constant in this application. In SMART2, net immobilisation in the soil increased steadily from –2.3 to –0.7 kmol ha^{-1} yr^{-1} during the rotation (Fig. 3). This increase in net immobilisation is caused solely by a decreased gross mineralisation in litter. In SMART2, it is the mineralisation of N in fresh litter that contributes to the N supply for tree growth. This mineralisation is an autonomous first-order process governed by litterfall, the amount of litter and a mineralisation rate constant. This rate constant was obtained by calibrating to 1980 and 1990 C pool values simulated by MERLIN. However, the temporal pattern of N mineralisation rate between these years is determined purely by litterfall. As with the terms of the *CL* calculation, the immobilisation term in the soil is the great unknown relative to the other terms. The dynamics of this process is of the utmost importance for analysing *DDT* values. This generates a relatively weak basis for this *DDT* calculation, as little is known about the role of the soil in supplying N to fast growing young trees.

With the lowest critical value of 0.1 kmol ha^{-1} yr^{-1}, corresponding to the objective to avoid the occurrence of nitrophilous plant species, the ecosystem is kept at a very low level of nitrogen nutrition which means that all nitrogen deposition is retained. The effect of the lack of nitrogen in a growing forest with such a strict leaching criterion can be seen in the dynamics of the CN ratio in all organic N compartments calculated by SMART2 (Fig. 4). The CN ratios in foliage and in litter are higher during most of the simulation period using the 0.10 kmol N ha^{-1} yr^{-1} leaching criterion compared to the other criteria. Similar increased CN ratios in the ecosystem compartments — plants, LOM and ROM — are predicted by MERLIN at the lowest critical leaching criterion of 0.10 kmol ha^{-} yr^{-1} (Fig 5).

The results indicate that the *DDT* can fluctuate a great deal during a forest rotation. This is not surprising as steady state conditions in semi-natural ecosystems in a rapidly changing global environment are an illusion. The assumption of steady state facilitated the definition of the traditional *CL* as a relatively easy-to-use, standardised measure of critical loads of pollutants in the long term. On a short time scale, the steady state approach may not be appropriate, especially when focussing on (i) set intermediate goals (target loads) and (ii) performing conservation management.

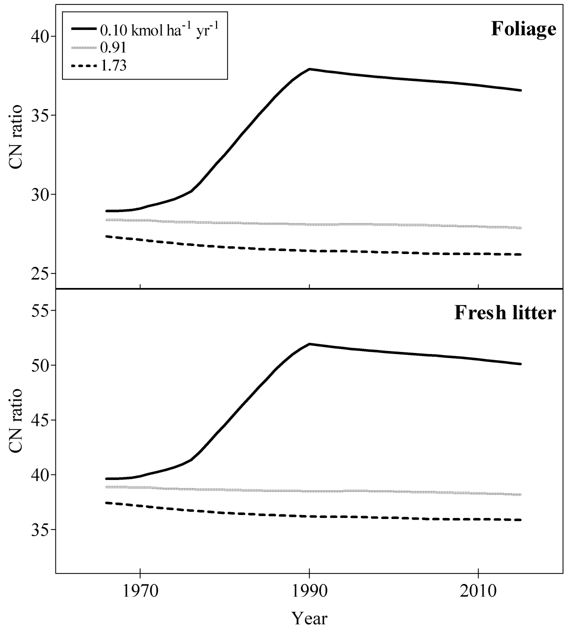

Fig. 4. *CN ratios of the ecosystem compartments foliage and litter, calculated by SMART2 at three different levels of critical N leaching (0.10, 0.91 and 1.73 kmol ha^{-1} yr^{-1}).*

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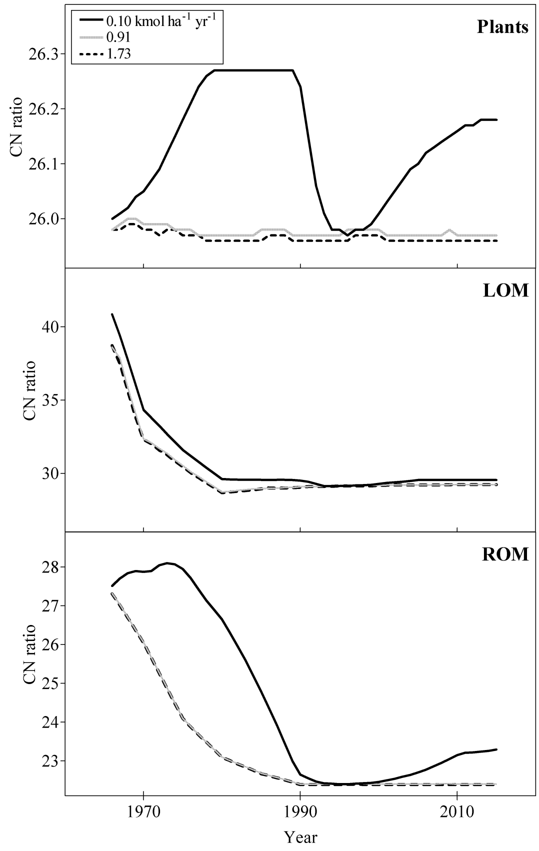

Fig. 5. *CN ratios of the ecosystem compartments plants, LOM and ROM, calculated by MERLIN at three different levels of critical N leaching (0.10, 0.91 and 1.73 kmol ha^{-1} yr^{-1}).*

During most of the time, the *DDT* is higher than the traditional *CL* calculated with the mass balance approach. Despite its uncertainties, the presented method of analysing temporal patterns in *CL* load may be of great importance in evaluating the effects of management on the *CL*. In this study deposition was optimised with a criterion of nitrate leaching. With the same approach, it is possible to optimise, for instance, plant uptake within an actual deposition scenario. Plant uptake can be influenced by various forest management options such as fertilisation and thinning.

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