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Effects of acid deposition on forest ecosystems in The Netherlands: Analysis of the Speuld Douglas fir site

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Abstract

Large efforts have been dedicated to investigate effects of acid atmospheric deposition on trees and soil at the forest stand level. For this purpose intensive monitoring programs and integrated simulation models were developed. This paper describes the application of the models NuCSAM, SoilVeg and ForGro to the Speuld site, a Douglas fir stand on a podzolic soil. The site was monitored between 1987 and 1992. Atmospheric inputs and element outputs at Speuld are fairly representative for Dutch forests. The models were parameterized and calibrated for this site. Simulated soil water contents, soil solution chemistry, foliage biomass and nutrient status and stem growth between 1987 and 1992 were comparable with observations. The generality of the SoilVeg and ForGro model was further tested by an approximate simulation of a site irrigation and fertigation experiment at a nearby Douglas fir site between 1987 and 1991. The direction and magnitude of simulated effects of irrigation and fertigation on stem growth, litter fall and needle nutrient status were generally right, but the observed enhanced N-mineralization could not be simulated. Simulations of site response to the Dutch target deposition scenario between 1994 and 2050 showed large differences between the three models, particularly for nitrogen cycling and foliage nutrient status. Nonetheless all models indicate a fast response of soil solution chemistry to changing deposition. Both SoilVeg and ForGro indicate that direct effects of air pollution and effects of soil pH and Al are subsidiary to effects of drought and nitrogen. Our understanding of effects of acid atmospheric deposition on forests, based on lab trials, relatively short site monitoring studies and integrated simulation models, is still inadequate to quantitatively predict the long-term impact of acid deposition on forests on a nationwide scale.

1. FOREST SITE RESEARCH IN A PERSPECTIVE

Small scale occurrence of forest dieback in central Europe is evident (Kandler, 1992). Proof for ongoing large scale forest dieback due to acid atmospheric deposition is still not found. Concern for adverse effects of acid atmospheric deposition in the Netherlands was triggered by the observation in the early eighties that tree vitality, expressed by leaf occupancy and discolouring, was poor throughout the Netherlands, and the observation that ambient concentrations of SO_2, O_3, NO_x and NH_3 exceeded no-effect levels. At the same time evidence was found in the field that forests in the Netherlands received high atmospheric inputs of sulphur and nitrogen compounds leading to elevated concentrations and accelerated cycling of SO_4, N and Al in underlying soils (Van Breemen et al., 1982, De Vries et al., 1994). These simultaneous observations led to several hypotheses linking forest growth and forest vitality to air pollution, atmospheric deposition, soil acidification and disturbed nutrient cycling. Examples are the Al-toxicity hypothesis (Ulrich, 1989) and the nitrogen saturation hypothesis (Gundersen, 1992). A major problem when proving these hypotheses was the large difference between scales of time and space at which various effect observations were done, ranging from pot trials to nation wide surveys and from hours to decades. Another specific problem for field trials was the separation of air pollution and acid deposition related response from natural variation of tree growth and nutrient status. This was one of the motivations to start intensive integrated field studies in forest stands, in which weather, air quality, atmospheric deposition, soil hydrology, soil chemistry, nutrient cycling and forest growth were monitored over a number of years. These integrated monitoring programs were started in the US (Hubbard Brook), Norway (Birkeness, Sogndal), Sweden (Gardsjon, Skogaby), Germany (Solling, Höglwald), Denmark (Klosterhede) and the Netherlands (Speuld, Kootwijk). An important tool to analyse and integrate the observations at the forest stand level was the budgeting approach (De Vries et al., 1994; Posma et al., 1994), in which the fate of carbon, nutrients or protons was determined by quantifying all relevant inputs, outputs and stores. However, the budgeting approach was not suitable to test hypothetical effect mechanisms and to predict the response of the forest stand to changes of atmospheric inputs. This was one of the motivations to develop mechanistic and comprehensive simulation models of a forest stand. A second motivation was the need to generalize and quantify the effect relationships for air pollution and atmospheric deposition, to be able to evaluate the effectiveness of national environmental policies for the Dutch forests. The integrated models describe the water, carbon and nutrient status of the forest and forest soil as a function of weather, atmospheric deposition and air quality, given the inherent properties of the soil and the tree species, and taking into account the relevant transformation and transport processes in tree and soil. These models have been fairly successful to explain the water and chemistry status of the forest ecosystem (Landsberg 1991; Van Grinsven et al., 1995). Efforts to develop fully integrated models, that include forest hydrology and soil chemistry and forest growth, and apply these models to comprehensive site datasets, are rather scarce.

It was soon clear that at the integrated monitoring sites boundary conditions changed slowly, and the variation in the response of tree and soil were small or non-existent, hampering a meaningful test of any integrated stand effect model. This knowledge was a major motivation to start experimental field manipulation, very often at the location of the intensive monitoring sites (De Visser, 1994). By artificially and drastically changing the inputs of water and nutrients to the stand, the soil water, nutrient and soil chemical status were forced to change, thus providing information about the rate and magnitude of response of the ecosystem. Data from these experiments are presently coming available and appear to be very valuable for testing models and effect hypotheses. However, as the duration of the experiments seldom exceeds three years, there is a danger that transient artifacts initially dominate the response of the ecosystem.

This paper describes the application of the soil acidification model NuCSAM and two integrated models SoilVeg and ForGro to a Douglas fir stand at Speuld in the Netherlands. First the Speuld monitoring program is described, followed by a discussion of the modelling philosophy and model principles. Next, model calibration to Speuld, results of application to a nearby manipulation experiment and analysis of one deposition scenario are described. Finally, conclusions are presented with respect to monitoring and modelling at the forest stand level.

2. THE SPEULD EXPERIMENTAL FOREST

Since 1980 a total number of 17 forest sites has been monitored intensively (Van Breemen and Verstraten, 1991) and 150 sites have been studied extensively (De Vries et al., 1994). In intensive monitoring studies, boundary fluxes and states for hydrology, soil chemistry and sometimes tree structure and carbon and nutrient status have been measured at various times within a year, in general over a period of more than three years. The extensive survey is characterized by a one time assessment of a smaller selection of soil chemical and tree nutrient states. The most complete intensive monitoring studies, with a relative emphasis on pollution climate and on tree carbon and nutrient status, were carried out on two Douglas fir stands at Speuld and Kootwijk (Evers et al., 1987).

The Speuld Douglas fir site is located at 52.1 °N, 5.4 °E. 50 m above sea level. Annual average rainfall is 808 mm, potential evapotranspiration is 534 mm, and temperature 9.3 °C. Average air temperature in January is 2 °C, in July 17 °C. The age of the Douglas fir in 1990 was 32 years, stand density 812 ha^{-1}, mean tree height 20.4 m and basal area 35.2 m^2 ha^{-1}. The underlying soil is a Cambic podzol developed on sandy loam. The saturated volumetric water fraction ranges from 0.21 to 0.33, the saturated conductivity ranges between 1 to 8 m/d. Soil pH-H_2O ranges from 3.7 to 4.3, CEC from 28 to 105 $mmol_c/kg$, Base Saturation is below detection limit. The organic matter content ranges from 0.2 to 2.4% (w/w), the free Al-oxide content from 160-490 mmol$_c$/kg. The total mineral CaO content is about 30, the MgO content ranges from 30-60, the K_2O content is about 200 mmol$_c$/kg. The air pollution climate can be characterized by an ambient SO_2 concentration of 10 µg m^{-3} (1990), ambient O_3 concentration of 40 µg m^{-3}, an annual N-deposition of 3.4 kmol ha^{-1} (2.7 NH_4, 0.7 NO_3) and S-deposition of 1.1 kmol ha^{-1}.

Monitoring at Speuld was carried out between 1986 and 1993, however, hydrological and soil chemical monitoring was restricted to the period between 1987 and 1990 (Table 1).

Table 1
Characterization of major monitoring activities at Speuld.

1.	hourly	Meteorology (rainfall, temperature, radiation, vapour pressure, wind speed, sunshine duration)
2.	hourly	Ambient concentrations of SO_2, NH_3, O_3 and NO_2 (average and/or peak values)
3.	hourly	Dry atmospheric deposition fluxes (SO_2, total S, NH_3, NO_x, total N, base cation aerosols, total Cl)
4.	bi-weekly	Wet deposition of all major compounds
5.	bi-weekly	Bulk deposition of all major compounds
6.	bi-weekly	Throughfall of all major compounds
7.	daily	Transpiration, litter evaporation and net CO_2 flux (only in 1989)
8.	daily	Soil water potential, water content and temperature at various depths
9.	bi-weekly	Soil solution concentration at various depths
10	monthly	Weight, length and nutrient status of roots
11.	monthly	DBH and stem basal area
12.	annually	Volumetric growth, ratio of sap and heart wood
13.	variable	Tree height, height of lowest living whorl, biomass of stem, branches and foliage (per needle year class), nutrient content (C, N, P, S and base cations) of wood and foliage, stem and branch density, LAI, SLA, sugar, starch, cellulose and lignin content of foliage, litterfall and nutrient status of litter, vitality classification

Speuld has a high foliage mass (18-23 ton/ha between 1987 and 1992) and a very high ratio of foliage to fine root mass (6-7). Further Speuld is deficient for phosphorus in foliage (0.08-0.12% w/w) and high for nitrogen in foliage (1.5-2.0 % w/w). Speuld is classified as a fairly vital and well growing stand producing over 5 tons of stem wood per year.

Element inputs and outputs at Speuld are very comparable to those of other intensively monitored stands (Table 2; Van Breemen and Verstraten, 1991), but S-inputs and N-outputs, and by result also S and Al-outputs, are high compared to fluxes inferred from a nation wide extensive forest survey (n=147) in 1990 (De Vries et al., 1994). The discrepancy between the S-budget of the intensive and extensive sites can be attributed to a substantial decrease of S-deposition in the past decade (Erisman et al, 1993). The discrepancy for N can be explained in part by the relative absence of wet oak stands with a high potential for N-immobilization in the set of intensively monitored sites.

Table 2
Comparison of element budgets for Speuld with those for other Dutch intensively and extensively monitored forest sites

Element flux or ratio $kmol_c\ ha^{-1}\ a^{-1}$	Speuld (n=1) 1987-1990	Intensive (n=17) 1980-1990	Extensive (n=147) 1990
S-input	2.3	2.8	1.8
N-input	3.6	4.0	4.2
S-output	3.1	3.0	1.9
NO_3-output	2.2	3.0	0.8
NH_4-output	0.0	0.3	0.0
Al-output	4.6	4.6	1.0
S-out/S-in	1.3	1.1	1.1
N-out/N-in	0.6	0.8	0.2
Al-out/(N+S)-out	0.9	0.9	0.4

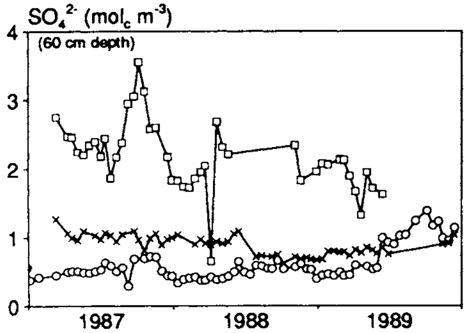

Figure 1. Concentration of SO_4 at 60 cm depth for three adjacent plots under a Douglas fir stand at Speulderbos.

A major problem for integrated model analysis of the Speuld data set was the large spatial variability of throughfall amount and chemistry, soil hydrology (Bouten et al., 1992) and soil solution chemistry. An example is given for SO_4 concentration at 60 cm depth (Figure 1), were both mean values and trends are incomparable for three plots at short distance. In view of the small number of replicates as compared to this large variability it had to be decided to use either a unreliable site mean value (n≈6) of observations for model validation or to use unrepresentative mean values of observations (n≈2) for hydrological and soil chemical variables taken in or near one soil pit. We chose for the latter to maintain reliable temporal dynamics in the soil solution data.

3. THE MODELS

In the Dutch Priority Program on Acidification (Heij and Schneider, 1993) considerable emphasis was put on the development and application of the dynamic process-oriented simulation models NuCSAM, a site version of the model ReSAM (de Vries et al., 1994), SoilVeg (Berdowski et al., 1991; Van Heerden et al., 1995) and ForGro (Mohren et al., 1993). All three models aim at simulating the behaviour of a forest stand over one rotation as a function of climate, air pollution and atmospheric deposition at a near to daily resolution. ReSAM and SoilVeg were also applied at a nationwide scale and an annual resolution (Heij and Schneider, 1991). The major characteristics of the three applied models are summarized in Table 3. The three models consider all major chemical species and plant nutrients, H, Al, SO_4, Na, Cl, NH_4, NO_3, K, Ca, Mg and PO_4 (not in SoilVeg). ForGro uses NuCSAM as soil chemistry submodel.

The models are particularly useful for testing the hypotheses that episodes with high Al, low pH and low water content, typically occurring in summer, or episodes with high ambient concentrations of O_3, SO_2 or NH_3 can cause a long-term decrease of foliage and root mass. The models NuCSAM, SoilVeg and ForGro were already applied to the Solling site (Van Grinsven et al., 1995) together with 13 other models of various complexity and completeness with respect to the description of the water, nutrient and carbon cycles. Some important conclusions from this workshop were:

- differences between the models were largest for the calculation of nutrient demand and uptake
- all models reproduced the average observed water, nutrient and carbon status of the Solling spruce stand fairly well, but seasonal dynamics and year to year variation poorly
- none of the models could explain the observed NO_3 mobilization and leaching
- the input demand and complexity of the models varied widely, but the performance of models did not systematically become better with increasing complexity, at a common level of output aggregation

The application to the Speuld Douglas fir stand is described in more detail by Tiktak et al. (1995). Both for the Solling and the Speuld application the three models followed similar guidelines for evaluation of model performance, based on Janssen and Heuberger (1995).

4. MODEL PARAMETERIZATION AND CALIBRATION

Although calibration procedures for the three models were different and rather unstructured, a logical sequence for calibration was adapted which was guided by the strength of the interactions between hydrology, soil chemistry and tree processes. Hydrology strongly affects soil solution chemistry but not vice versa. The effects of soil hydrology and soil solution chemistry on nutrient uptake and tree growth are stronger than vice versa.

Table 3
Major principles of the forest stand level models NuCSAM, SoilVeg and ForGro.

	NuCSAM	SoilVeg	ForGro
hydrology	Solution of water potential in Richard's and Darcy's equation. Potential transpiration from Makkink and an empirical crop factor	Solution of water content from empirical equations with soil water flux and water uptake. Potential transpiration as in NuCSAM	Solution of water content from empirical relation with water flux. Transpiration from Penman-Monteith
soil chemistry	Gaines-Thomas cation exchange. 1° order nitrification and silicate weathering. Elovich Al-oxide weathering	Equations and parameterization as in NuCSAM. PO_4 is not considered	ForGro uses NuCSAM as submodel
nutrient uptake	Forced by stem growth, biomass turnover and fixed nutrient contents	Driven by water uptake, nutrient concentration in soil solution and selectivity coefficients	Driven by demand and limited by radial diffusion from the bulk soil to the root
forest growth	Logistic stem growth and fixed biomass ratios	Gross photosynthesis is forcing function. Adapted, multiple nutrient productivity concept	Photosynthesis is driven by light interception. Gross carbon assimilation is summed per leaf layer
tree effect relations	no effect model. Empirical relation between N-deposition and N-content of foliage	empirical reduction of photosynthesis with ambient SO_2 and O_3. Al and pH effects on root uptake and root growth. Direct canopy uptake of ambient NH_3. Increased respiration plant N status	Nutrient shortage, and stomatal uptake of SO_2 and O_3 in foliage will reduce photosynthesis. Al effect on root growth and nutrient uptake. Direct canopy uptake of ambient NH_3. Increased respiration plant N status

Parameterization of conductivity and percolation functions, and water uptake distribution with depth is fairly straightforward for all three models. The hydrology modules were validated against a common data set of water contents in 1989 and against Cl and SO_4 data. Due to the low sorption capacities of the soils at Speuld, Cl and SO_4 are practically conservative tracers. The derivation of exchange coefficients, silicate and oxide weathering rates, mineralization and nitrification rate constants and sulphate and phosphate sorption isotherms could be harmonized, in view of the similarity of the soil chemistry submodels. Parameterization of the nutrient uptake and growth was model specific and posed most problems. Calibration of these submodels for NuCSAM was simple as growth is a forcing function. Calibration needs for SoilVeg probably were largest, mainly because this model uses empirical multi-parameter S-shaped age dependent forcing functions for gross nutrient uptake and allocation of carbon and nutrients. Adjustment of the default parameterization of the growth module in ForGro was kept to a minimum. However, allocation of assimilates to foliage had to be increased to simulate foliage masses in accordance with observations at Speuld. An example of the complexity of the calibration was the parameterization of the carbon turnover and allocation process using litterfall data. Initial estimates of annual litterfall from litter traps (1 m^2), litter nets (45 m^2) and inferred from the standing needle mass ranged from 2.2 tot 6.8 Mg ha^{-1} a^{-1}. Taking into account spatial variability of biomass in the stand and after matching litterfall to standing foliage mass a most probable annual litterfall of about 5 Mg ha^{-1} a^{-1} was used. This example illustrates that biomass and nutrient data for Speuld in fact did not allow any fine-tuning or validation of the carbon turnover and allocation parameters. The parameters for effect submodels were inferred from fumigation and hydroculture experiments.

Model performance was judged by comparing model output with observations at a rather aggregated level: viz. water contents, soil solution concentrations, stem and foliage mass and the nutrient status of foliage. For soil hydrology and soil solution chemistry objective performance criteria were used. Differences between hydrology submodels are largest in the growing season. In this period observations show a response of water content to individual rain events at depths up to one meter, while none of the models showed such a response. This discrepancy could be an indication of short circuit flow. Simulated annual hydrological fluxes showed considerable differences; eg. in 1988 transpiration ranged from 301 to 323 mm, interception from 303 to 456 mm, soil evaporation from 19 to 79 mm and drainage from 17 to 255 mm. Validation of the hydrological calibration with Cl and SO_4 was unsuccessful. As compared to experiences from model application to Solling (Grinsven et al., 1995), model performance for Cl and SO_4 is rather poor (Figure 2).

Correct simulation of pH and Ca generally failed. Simulated concentration increases for Al and NO_3 in the growing season are larger than the observed increase (Figure 2). This discrepancy can only partly be attributed to the impossibility to use suction cups for soil solution sampling when the soil water suction exceeds the air entry values of the cup lysimeters (≈ 800 mbar). The moderate success of the soil chemistry calibration is also illustrated by values (Table 4) of Normalized mean absolute errors (NMAE) and Normalized Mean Errors (NME) (Janssen and Heuberger, 1995). The NMAE and NME are zero when model results and observations are identical. Actual values lie around 50% for NMAE and strongly vary for NME. Results for 90 cm depth are better than for 20 cm depth. Overall model performance for Solling was better than for Speuld, which can be explained by smaller spatial variability at Solling and a longer data set (17 years for Solling as compared to 3 years for Speuld).

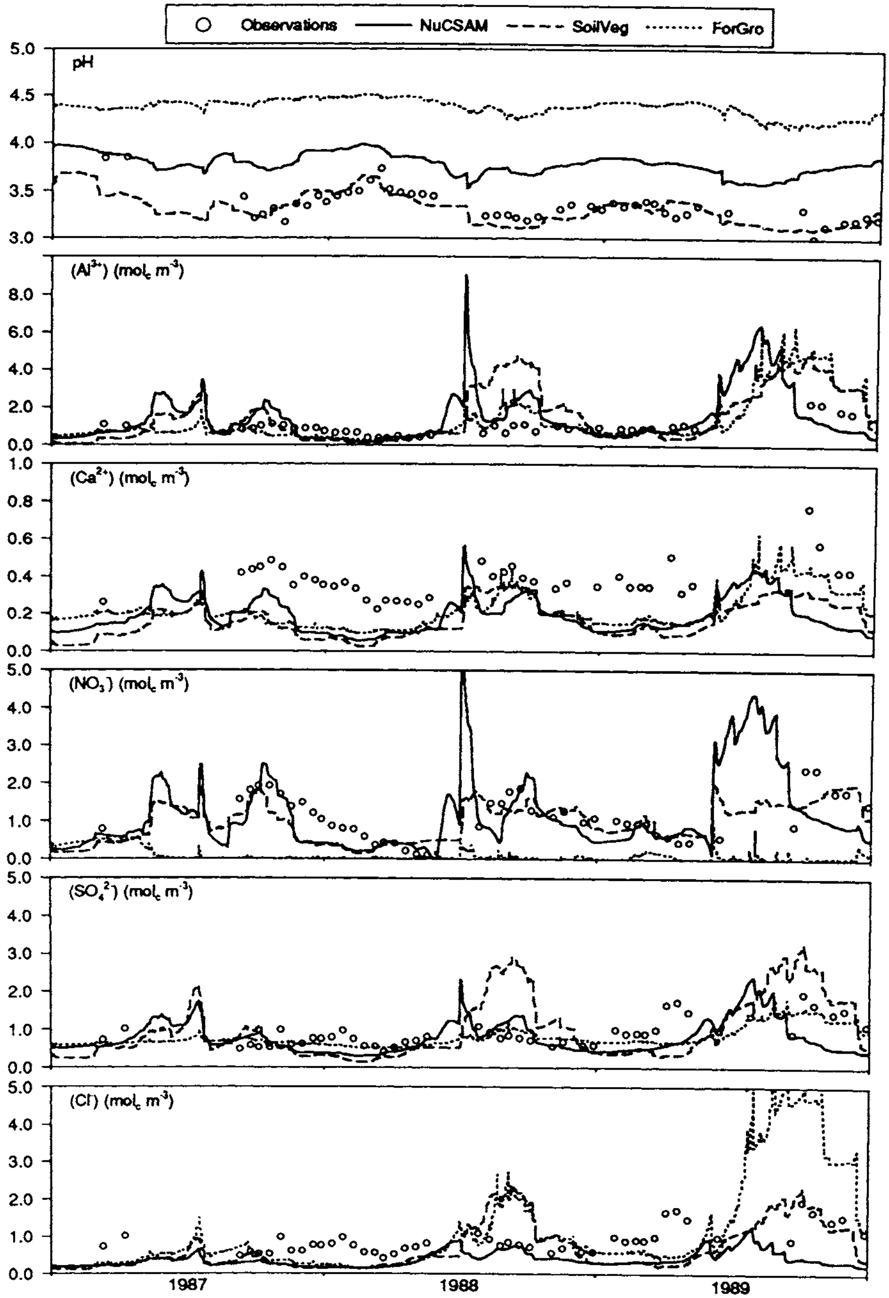

Figure 2. Observed and simulated soil solution concentrations at 20 cm depth for a Douglas fir site at Speulderbos between 1987 and 1991.

Tabel 4.
Performance for NuCSAM, SoilVeg and ForGro for application to the Speuld Douglas fir dataset and for SoilVeg to the Solling spruce dataset, expressed by the Normalized Mean Absolute Error (NMAE) Normalized Mean Error (NME)

	Depth	NuCSAM		SoilVeg Speuld		ForGro		SoilVeg Solling	
		NMAE	NME	NMAE	NME	NMAE	NME	NMAE	NME
						[%]			
H	20	81	-81	21	7	91	-91		
Al	20	49	10	104	54	52	12	45	-24
Mg	20	86	-86	48	-48	38	-27	28	-14
NO_3	20	41	-24	35	-14	95	-95	62	-41
SO_4	20	44	-33	73	5	28	-15	47	4
Cl	20	47	-40	81	27	110	81	48	-5
H	90	32	20	40	34	25	-20		
Al	90	57	28	55	-40	30	22	34	-32
Mg	90	54	-54	25	-10	22	18	37	33
NO_3	90	53	2	62	34	73	-53	41	-11
SO_4	90	40	2	41	-18	68	68	30	-20
Cl	90	52	4	50	24	44	3	22	-11

SoilVeg and ForGro could reproduce the high observed needle mass at Speuld (Figure 3), but tended to overestimate stem mass which is a consequence of the high gross assimilate production predicted by the models given the high needle mass. Average contents of N, Ca, Mg and K (and P for ForGro) in foliage could also be reproduced by SoilVeg and ForGro. The time series of nutrient contents and biomass were too short to evaluate if SoilVeg and ForGro could explain the observed year to year and seasonal variations.

The uncertainty and validity of the model calibrations for the Speuld site was not systematically analysed, which in fact is a prerequisite before meaningful scenario analysis. Questions arose like "How unique is the present calibration? "What is the predictive power of the calibrated models?" and "What is the added value of the model to the original observations?". The uncertainty of the model calibration can be illustrated by the variation of simulated mean total annual plant uptake of NO_3, and NH_4 between 1988 and 1991, respectively 98 and 5 for SoilVeg, 39 and 41 for ForGro and 54 and 49 kg/ha for NuCSAM. Nitrogen uptake is a key process, but can not be checked against observations. However, the validity of the model calibrations was qualitatively touched by evaluating whether SoilVeg and ForGro could reproduce the observed effects of experimental manipulations as conducted for a nearby Douglas fir site (De Visser, 1994). For this purpose these results were compared in a relative way to a simulation of his irrigation and fertigation experiments by the models calibrated for Speuld (Table 5). It should be stressed that the simulation was

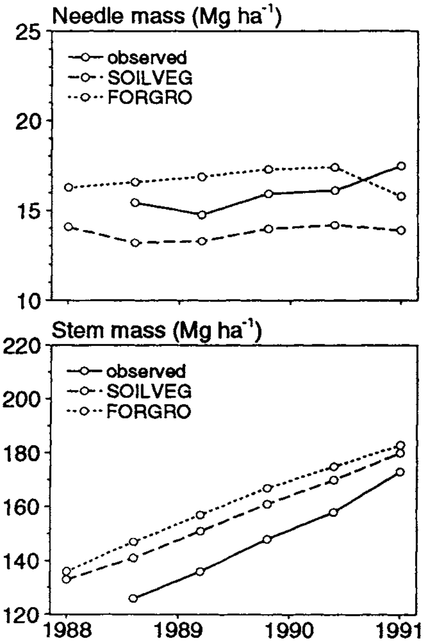

Figure 3. Observed and simulated needle and stem mass for a Douglas fir stand at Speuld.

only approximate, as site conditions at Speuld and the manipulation plot are different and model implementations of elimination of water and nutrient stress are not identical to experimental procedures. Both in SoilVeg and ForGro irrigation amounts were equal to the difference between daily potential transpiration and precipitation if the water content was below field capacity. Elimination of nutrient stress in SoilVeg was accomplished by simulating the maximum fertilizer additions of the field experiment, while ForGro switched off all effects of nutrient shortage. Observations and simulation were compared after four years of treatment. From this single comparison (Table 5) it can be concluded that directions and magnitudes of predicted changes in the tree and soil are about right but that differences can be considerable. In particular prediction of effects on N-mineralization and the effect of fertigation on N-content in foliage are not very good.

Table 5
Comparison of observed effects of irrigation (I) and fertigation (IF) on a Douglas fir site at Kootwijk (De Visser, 1994) with simulated effects by SoilVeg and ForGro for a Douglas fir site at Speuld, relative (%) to an untreated control case.

	Observed		SoilVeg		Forgro	
	I	F	I	F	I	F
[Cl] 20 cm depth	-52	-53	-17	-11		
$[NO_3]$ 20 cm depth	+46	+82	-6	+46		
[Mg] 20 cm depth	-37	-10	-16	+60		
[Al] 20 cm depth	+16	+28	-17	+34		
stem increment	+19	+25	+6	+62	+19	+24
litter fall	-7	+9	+1	+18	+9	+5
N content foliage	-10	+1	-2	+8	-8	-7
Mg content foliage	-2	+8	-4	+11	-2	0

5. SCENARIO ANALYSIS

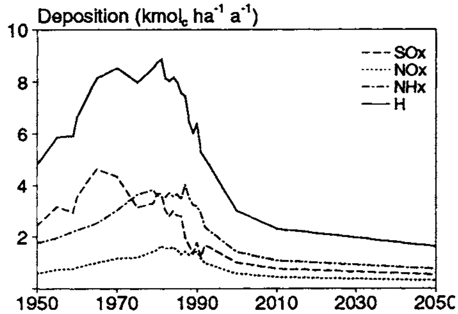

Figure 4. Deposition scenario for SOx, NOx, NHx and potential acidity for Douglas fir in the central part of the Netherlands

All models were applied to evaluate a deposition scenario between 1992 and 2050 representing the present targets of Dutch environmental policy (Figure 4). This scenario is obvious an optimistic one with respect to the reduction of deposition. Simulations were started in 1950. For this purpose model parameterizion for Speuld was adapted to match a so-called generic Douglas fir site a Cambic podzol and a generic Scots pine site on a Albic arenosol. Generic means that standard databases are used for soil and tree parameters. The evaluated generic soil-forest combinations are assumed to be representative and suitable for regional presentation. Weather data were randomly selected by a statistical model of historically observed weather data. The results of this scenario analysis are only meant as an example of model use for predictive purposes as only one deposition scenario and one realization of weather data was evaluated. For some key stand states, eg. [Al], Al/Ca ratio, stem mass (and growth), the three models give comparable output differences between tree species and between results for 2010 and 2050 (Table 6). However, for pH, nitrate leaching, nitrogen uptake by trees (not shown), needle mass and N-content in foliage differences are dominated by differences between models. Some apparent effects of the scenario, are a fast improvement of [Al] and Al/Ca ratio in soil solution, a slow improvement of soil solution pH and N content in foliage, small effects on needle mass and considerable depletion of Al-oxides, ranging from 13-25% for Douglas fir.

Table 6
Mean predicted soil and tree status simulated by NuCSAM, SoilVeg and ForGro between 1980 and 1990, and between 2040 and 2050 for Speuld (SD), a generic Douglas stand on a Cambic podzol (DF) and a generic Scots pine stand on a Albic arenosol (SP).

	NuCSAM		SoilVeg		ForGro		
	DF	SP	DF	SP	SD	DF	SP
			mean 1980-1990				
pH 20 cm depth	3.8	4.0	3.2	3.8	4.3	4.4	4.5
[Al] 20 cm depth (mol_c/m^3)	1.1	0.6	1.4	0.3	1.6	0.9	0.3
Al-oxide 0-20 cm ($mmol_c/kg$)	89	59	92	58	159	95	71[1]
NO_3 leaching (kg ha^{-1} a^{-1})	47	33	23	7	6	5	7
Al/Ca ratio 0-20 cm	3.4	1.5	1.9	9.5	-	-	-
Needle mass (ton/ha)	(10.9)	(7.5)[2]	16.2	8.6	16.5	15.7	8.1
Stem mass (ton/ha)	-	-	150	70	150	143	64
N content foliage (% w/w)	2.6	2.4	1.9	1.8	2.1	2.0	1.9
			mean 2040-2050				
pH 20 cm depth	4.0	4.8	3.3	4.0	4.6	4.7	4.7
[Al] 20 cm depth (mol_c/m^3)	0.1	0.0	0.9	0.3	0.4	0.2	0.2
Al-oxide 0-20 cm ($mmol_c/kg$)	66	54	79	50	133	85	62[1]
NO_3 leaching (kg ha^{-1} a^{-1})	9	3	18	9	-	5	3
Al/Ca ratio 0-20 cm	0.8	0.0	0.4	0.3	-	-	-
Needle mass (ton/ha)	(10.9)	(7.5)[2]	12.9	8.6	18.4	17.7	5.0
Stem mass (ton/ha)	-	-	228	177	303	288	179
N content foliage (% w/w)	1.0	1.0	1.6	1.8	1.9	2.0	2.0

[1] ForGro data apply to the soil layer between 10-20 cm depth
[2] Needle mass and stem growth are boundary conditions for NuCSAM

6. CONCLUSIONS AND DISCUSSION

Conclusions that can be drawn from model simulations of the Speuld site, of the manipulation experiment and of the single scenario are provisional because models could not be validated, and are specific because only one stand and two generic datasets were analysed. In this context the following conclusions are drawn:

- it is not possible to find unique parameter sets for site models and to validate integrated site models against observation data,
- average observed water, nutrient and carbon status of the Solling spruce stand are fairly reproduced, but seasonal dynamics as well as year to

year variation are poorly reproduced,

- directions and magnitudes of the response of forest soil to naturally occurring variations of weather and deposition and to artificial manipulations agree with observations,
- for the tree component both observation data and model behaviour are too uncertain to make statistical comparisons or quantitative predictions,
- different components of the ecosystem respond at different rates to reduced deposition: SO_4 and Al in soil solution respond within 1-2 years, NO_3 in soil solution after 5-10 years, N in foliage takes more than 50 years.
- models predict a quick decrease of Al and Al/Ca ratios in soil solution to below critical values after a reduction of deposition,
- models indicate that nitrogen related effects dominate the effects of air pollution and atmosphere deposition on forest in the Netherlands
- site observations in combination with model application indicate that, for the Dutch pollution climate, direct effects of air pollution with SO_2, O_3 and NH_3 on tree growth, and indirect effect of pH and Al on root functioning, are relevant at stand scale; direct effects appear to be less important than soil mediated effects,
- SoilVeg and ForGro predict high foliage and low but sufficient fine root (not shown) biomass throughout the scenario, and that stand growth is sustained; the models are inconclusive about the long-term forest production; it should be noted that both stand age and the applied thinning scheme are not realistic for a production stand; similar provisional results are found for Scots pine on a more sensitive Albic arenosol,
- models do not indicate that short-lived unfavourable soil conditions will cause dieback of the presently productive and vital Speuld stand.
- models predict considerable depletion of Al-oxides and accumulation of organic nitrogen.

These conclusions do not allow a general statement about success or failure of the approach, let alone a statement about the long-term fate of Dutch forests in relation to future air pollution climate and atmospheric deposition. A major shortcoming of the stand level approach is the inability, as yet, to include known catastrophic effects on stand growth and vitality like (i) bacterial, fungal and insect infestations and (ii) bud damage due to frost and (iii) severe drought and (iv) wind throw. Events like these will very likely occur several times within one stand rotation and the susceptibility of the stand to such effects is related to nutrient (nitrogen) status and biomass of foliage and roots. For now, these effects can only be considered in terms of increased risk for occurrence. Given these limitations, and acknowledging that we still cannot bridge the gap in time and spatial scales between experimental effect assessment and regional effect observations, any prediction of long-term effect of air pollution on forests is bound to be very uncertain. Assessment of long-term effects and response of the soil forest is less uncertain. The long-term depletion of Al-oxide pool, which is the major source of acid buffering in poor sandy soils, is beyond discussion. Depletion will further lower pH and may destabilize organic matter and enhance DOC and heavy metal mobility (Westerhof et al., 1994). Also the strong accumulation of organic N is evident, but its long-term stability is uncertain. Although the reliability of the submodels for soil hydrology and soil chemistry allows meaningful regional application of the models, the uncertainty about the growth and effect submodels is still too large too allow meaningful long-term and regional prediction of the carbon and nutrient status of forests. Forest stand models do not confirm the validity of present critical levels for Al, Ca/Al ratio and loads for acidity and nitrogen (De Vries, 1993) for prevention of meaningful harmful effects to the forest component. The models do not provide better alternatives, but models could be helpful to redefine critical loads for the tree component (De Vries et al., 1995), if harmful effect are defined more clearly. Critical levels and loads are best supported by effects on other, more sensitive component of the forest ecosystem.

Perhaps expectations with respect to the answers from site monitoring and modelling have been too high, although enormous progress was made in the past five years. There certainly is a need to continue monitoring at the stand level, but perhaps lower sample frequencies (eg. annual) and a smaller selection of parameters are adequate to detect magnitudes and trends of effects of weather, air pollution and atmospheric deposition on soil N and proton buffer status, tree nutrient status, and growth. There is not a good reason to rebuild the site models. At present, process-oriented forest stand models are, above all, suitable and probably the only available tools to integrate and synthesize mechanistic formulations of hypothetical or proven relationships between the various states of a forest stand. After calibration, these models can be used to indicate directions and magnitudes of short-term and long-term responses of the stand to changes of the pollution climate and weather. Present model versions should be used to further explore available observation sets (EXMAN, NITREX) and present site calibration could be used to assess the uncertainty of qualitative predictions for the calibration, deposition scenarios and weather. Perhaps uncertainty analysis of the integrated forest stand models could be carried out in a risk perspective, after empirical incorporation of the indirect "catastrophic" effects.

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