REPORT

Using ForSAFE-Veg to investigate the feasibility and requirements of setting critical loads for N based on vegetation change – pilot study at Gårdsjön

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Report Summary

Project title

Kvävenedfall-vegetationsförändringar: NITREX långtid samt modellering kväve klimat

Project sponsor

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Title and subtitle of the report

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Keyword

vegetation, nitrogen, carbon, forest, soil, climate change, modelling, Gårdsjön, ForSAFE-Veg

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Abstract

The dynamic integrated ecosystem model ForSAFE-Veg was applied at the intensively monitored experimental catchment Gårdsjön, with the aim to investigate the performance of the model and the feasibility of using the composition of the ground vegetation community as an indicator of potential change due to N deposition. The quality, long term, and integrity of the measured data provided an ideal testing opportunity for evaluating the performance of the model, which proved satisfactory. The study shows that it is feasible to use the composition of the ground vegetation community as a biological indicator of ecosystem change. Yet, to be used in estimating critical loads of nitrogen (N) deposition, the biological indicator has to be simplified into a single-dimensional variable referred to as the average yearly exceedance (of change in the composition of the ground vegetation). The study shows that setting conditions to protect the dominant segment of the plant community, and thereby protecting ecosystem services, will also result in protecting the marginal plants proportion at the site. However, the choice of the segment of the plant community to be protected and the acceptable level of change remain bound to social preferences.

Contents

1 Introduction

There is increasing interest in finding a biological indicator for estimating critical loads of nitrogen (N) deposition in Europe. The reason behind this interest lies primarily in the limitations related to the chemical indicator used today in the modelling and mapping of critical loads of N in Europe. It has been suggested to use the composition of the ground vegetation community as an indicator for potential changes caused by N deposition. However, because of the complexity of this indicator, often involving more than one variable (one value for each potentially present species), there is a need to investigate the feasibility and applicability of the plant community as an indicator for change.

The challenge presented by the concept of using the composition of the plant community as an indicator for change lies in two levels. Firstly, adopting such an indicator requires robust integrated modelling able to reconstitute the composition of the plant community from the prevailing environmental factors at the site. Secondly, being a multidimentional indicator, the composition of the ground vegetation community needs to be translated into a single variable without loosing the biological relevance of the community composition.

2 Aims of the study

This study has been carried out in an overlap between the SCARP program and the CLRTAP activities. The aims of the study are two fold. Firstly, the study evaluates the performance of the model ForSAFE-Veg, and particularly the revised nitrogen dynamics module. Secondly, the study presents a set of attempts at estimating the critical loads of nitrogen deposition based on changes in the ground vegetation. For both parts of the study results from the N addition experiment carried out at Gårdsjön (Moldan et al., 2006) were used as a basis.

3 Definitions

Table 1. List of terms used in report and their definitions

Term	Unit	Description
Average yearly difference	$\%_{area}\cdot a^{-1}$	The total difference between a vegetation community under a certain N deposition and the reference population divided by the number of years for which the depositions differ.
Average yearly exceedance	$\%_{area}\cdot a^{-1}$	The total exceedance of the critical limit for a given vegetation community divided by the years for which the N deposition differs from the reference deposition.
Dominant plants	--	The individual plant or group of plants covering the highest plant specific ground cover.
Marginal plants	--	In the spectrum of specific ground covers, the plants covering least ground area are referred to as marginal plants
Plant specific ground cover	$m^2\cdot m^{-2}$ or $\%_{area}$	In $m^2\cdot m^{-2}$ is the fraction of the ground area covered by a single plant in 1 m2 of ground.
Reference population	--	The target population under N deposition according to MFR at any given year.
Reference N deposition	$\mu eq\cdot m^{-2}\cdot a^{-1}$	Future N deposition according to the Maximum Feasible Reduction (MFR) scenario of N emissions. MFR is the available N deposition scenario that provides the lowest possibly feasible projections of N deposition and therefore is assumed to produce the least N driven effects on the ground vegetation.
Target population	--	The segment of the ground vegetation community for which change is investigated. Different sizes of the target population are testes, such as the marginal 5%, the dominant 20%, or the dominant 80% of the entire population. The target population is the segment of the population that is wished to be protected.
Vegetation cover difference	$\%_{area}$	The difference in ground cover between the target population under a given N deposition scenario and the reference population.

4 Site description

The research site at Gårdsjön is located at 135-145 m elevation 12 km inland on the Swedish west coast (58° 04' N, 12° 03' E). The site receives moderate deposition of oxidised (NO_x) and reduced (NH_y) N species. Mean throughfall inputs (1989-2003) at G2 NITREX were 8 kg NO_x-N ha^{-1} yr^{-1} and 7 kg NH_y-N ha^{-1} yr^{-1}, respectively. Mean precipitation and runoff (1989-2003) were 1100 and 600 mm yr^{-1}, respectively (Moldan and Wright, 1998).

The 0.52-ha G2 NITREX catchment is covered by mature forest of 80-100 year-old Norway spruce (*Picea abies L. Karst*) with some Scots pine (*Pinus sylvestris L.*). Soils are predominantly silty and sandy podsols, and folisols in the upper parts of catchment, where organic material originating from forest litter overlays bedrock. The soils are drier in the upper catchment and peatier in the lower parts; mean soil depth is 38 cm (Kjønaas et al., 1998).

4.1 Nitrogen addition

Increased N deposition at G2 NITREX is achieved by weekly or fortnightly sprinkling of ammonium nitrate (NH_4NO_3) in addition to ambient throughfall. Annual additions are about 40 kg N ha^{-1} yr^{-1}. NH_4NO_3 is dissolved in de-ionised water and applied by means of 270 ground-level sprinklers installed in a 5x5 m grid over the whole catchment. The water added comprises about 5% of throughfall volume. The nearby lake Gårdsjön provides the source of water for the de-ioniser system.

4.2 Vegetation survey

Above-ground vegetation was mapped at the G2 catchment in 1992 (Wright ed., 1993). The catchment area was divided into a 5x5m squares and for every square (25 m2) all the species were recorded. Vegetation was divided into a 6 dominant vegetation types (Table 2) according to dominant species and moisture conditions at each square.

Table 2. Vegetation types identified at G2 catchment in 1992 vegetation survey (after Nygaard, P.H., et al in Wright et al, 1993)

Vegetation type	Description	Number of 25m^2 in the catchment (approximately)
1. *Cladonia (Cladina)*	Small patches dominated by lichens on drier locations	1
2. *Calluna vulgaris*	Drier rocky sites dominated by *Calluna Vulgaris*.	19
3. *Dicranum*	Dry sites dominated by *Dicranum majus*	21
4. Dry *Vaccinum myrtillus*	Dry sites with *Vaccinium myrtillus*	20
5. *V. myrtillus*	Mesic sites dominated by *V. Myrtillus.*	98
6. Humid *V. myrtillus*	Moist sites dominated by *V. myrtillus* and *Sphagnum girgensohni*	51

5 Model description

The ForSAFE model (Figure 1) integrates parts of four existing models, which were merged into a single structure with closed feedbacks representing the biogeochemical cycles of water, carbon and selected nutrients in a forest ecosystem. To model the growth of the forest cover, the processes of photosynthesis, allocation, respiration, evapotranspiration and litter production were derived from the PnET model (Aber et al., 1992). The growth of the forest cover is estimated from the availability of light and the ambient temperature as well as moisture and nutrients in the soil. To provide the necessary information about the nutrient status, the soil chemical processes of weathering, cation exchange, precipitation, mineralization and material mass balances were modeled as in the SAFE model (Alveteg et al., 1995, Alveteg, 1998). The release of carbon and nutrients from the litter as well as the recalcitration of the soil organic matter were modelled according to the principles developed in the DECOMP model (Wallman et al., 2006). The litter produced by the forest growth module is sorted into four pools of increasing resistance to decomposition, and the decomposition rate of each of these pools is controlled by soil moisture and temperature, soil solution acidity and the nitrogen content in the soil. Finally, the PULSE model for soil hydrology (Lindström and Gardelin, 1992) was incorporated into ForSAFE to simulate the vertical flow of moisture in the soil, simultaneously driving percolation and leaching of chemical elements.

A module for estimating the composition of the ground vegetation community (Veg) reads chemical and physical inputs calculated by the model and derives the probability of presence for a set of plant species that constitute the ground vegetation community (Belyazid, 2006; Sverdrup et al, 2007). The Veg module needs information about light intensity on the forest floor, soil moisture, air temperature, N concentrations in the soil solution, soil solution pH and calcifugicity. For each plant type, the module calculates the strength at the site given the listed conditions. The entire plant community then is reconstructed by sharing the ground area between the present plant types based on their individual strengths.

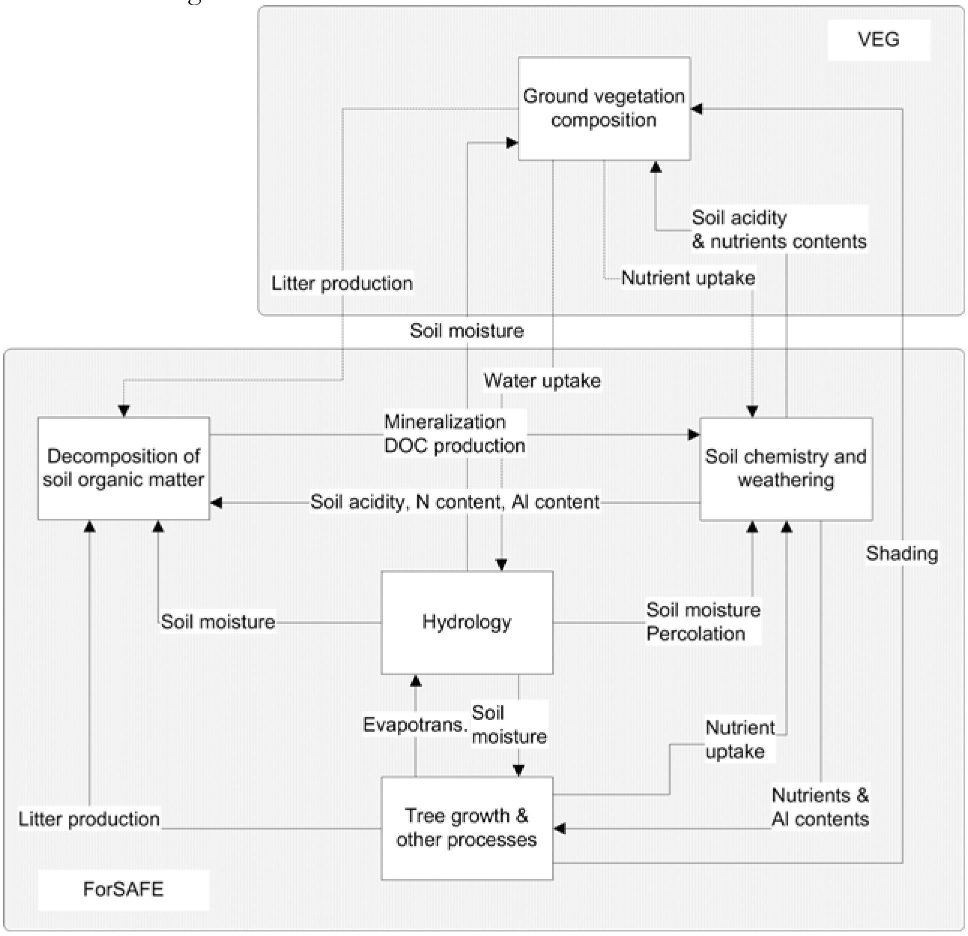


Figure 1. ForSAFE-VEG is composed of different internal modules, which together simulate a closed forest ecosystem.

6 Site inputs

6.1 Soil

The soils were sampled across the whole catchment G2. In average the soil profile consisted of 10 cm thick humus layer (LFH) underlain by 6 cm of light coloured bleached A horizon followed by 16 cm of mineral soil (B+BC). The dominating bedrock is gneissic and granitic. In the valley bottom the parent rock is covered by a layer of compacted glacial till. The soils are generally thin at the slopes and thicker in the valley bottom near the catchment outlet. The simulations cover the upper 32.2 cm of the soil at the G2 catchment at Gårdsjön, which is assumed to cover the main rooting zone of the dominant spruce trees.

The soil parameters measured at Gårdsjön G2 are presented below in Table 3 through to Table 7. Table 3 presents the basic physical soil properties measured at the site, some of which are referred to in an earlier study (Martinson et al., 2003). The respective soil thickness values adopted correspond to the observed average soil layers thicknesses at the site. The physical properties in Table 3 are used by the soil chemistry module in ForSAFE, which corresponds basically to the soil chemistry mass balance calculator of the SAFE model (Alveteg et al., 1995). The soil chemistry module estimates aluminium solubility through the hypothetical Gibbsite solubility process.

Table 3. Average physical and mineralogical properties of the upper 32.2cm at Gårdsjön-G2

Layer	layer thickness (m)	Bulk density (kg·m^{-3})	specific surface area (m^2·m^{-2})	pCO2 (x ambient)	Kgibbsite solubility coefficient (l^2·mol^{-2})	CEC (keq·m^2)
1	0.103	135	480000	2	6.5	3.56E-04
2	0.062	743	1200000	5	7.5	6.10E-05
3	0.156	844	1110000	20	8.5	5.00E-05
Ref.	(1)	(1)	(2)	(2)	(2)	(2)

(1) Site measurement

(2) Martinson et al. 2003

Weathering rates are estimated for each soil layer by the model based on the mineral contents in the soil (Table 4). The mineralogy of the soil was estimated from total analysis of the soil carried out by Martinson et al. (2003). The total weatherable minerals consists between 30 and 40% of the mineral soil minerals, meaning that the soil is relatively poor with low weathering rates (less than half a keq ·m^{-2} ·a^{-1}).

Table 4. Mineral contents at the different soil layers modelled at Gårdsjön-G2

	% Mineral*													
Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	15.00	14.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	15.00	14.00	0.00	0.50	0.00	0.50	0.10	0.50	0.00	0.40	0.00	0.10	0.00	0.00
3	18.00	15.00	0.00	1.50	0.00	0.50	0.10	0.50	0.00	0.40	0.00	0.20	5.00	0.00

*1: Feldspar, 2: Plagioclase, 3: Albite, 4: Hornblende, 5: Pyroxene, 6: Epidote, 7: Garnet, 8: Biotite, 9: Muscovite, 10: Chlorite, 11: Vermiculite, 12: Apatite, 13: Kaolinite, 14: Calcite. Quartz complements the listed minerals to 100%.

Table 5. Hydrological properties of the soil at Gårdsjön-G2

Layer	Field capacity (m3·m^{-3})	Wilting point (m3·m^{-3})	Field saturation (m3·m^{-3})
1	0.45	0.177	0.65
2	0.37	0.14	0.62
3	0.35	0.14	0.60

Table 6. Organic carbon and nitrogen and live root distribution at Gårdsjön-G2

Layer	Soil organic carbon (g·m^{-2})*	Soil organic nitrogen (g·m^{-2})*	Root content (% of total root biomass)
1	7100.0	240	60
2	Not calibrated	Not calibrated	30
3	Not calibrated	Not calibrated	10

* measured values from 1990, used for calibrating the initial size of the soil organic pools

Table 7. Sulfate adsorption parameters measured at Gårdsjön-G2

Layer index	so4Hratio	qso4	p1so4	p2so4
1	2	0.067	0.12	0.17
2	2	0.08	0.12	0.17
3	2	0.08	0.12	0.17
Ref.*	(1)	(1)	(1)	(1)

* (1): Martinson et al., 2003

6.2 Vegetation

The growth of the dominant tree species is driven by nitrogen concentration in needles according to the linear response described in Aber et al. (1992). The important growth parameters used in the model are listed in Table 8 below.

Table 8. Model parameters for photosynthesis, respiration and water use for Spruce

Parameter	Description	Value	Unit	Reference
AmaxA	Intercept of the linear photosynthetic response to foliage N%	5.30	$nmol_{CO2} \cdot g^{-1} \cdot s^{-1}$	Aber et al. 1996
AmaxB	Slope of the linear photosynthetic response to foliage N%	21.50	$nmol_{CO2} \cdot g^{-1} \cdot s^{-1}$	Aber et al. 1996
HalfSat	Half saturation light intensity	200.00	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Aber et al. 1996
BFolResp	Base dark foliar respiration	0.10	Fraction of gross photosynthesis	Aber et al. 1996
FolRet	Needle retention	3.00	Year	--
SLW	Specific leaf weight	170.00	$g \cdot m^{-2}$	Belyazid and Braun, 2009
K	Constant of light attenuation through the canopy	0.50	--	Aber et al. 1996
GRespFrac	Growth respiration	0.25	Fraction of allocation	Aber et al., 1995
WUE	Water use efficiency	2.75	Fraction of vapour pressure difference	Belyazid and Braun, 2009

6.3 Climate

The simulations assume a change in future climate according to scenario A2 of the Intergovernmental Panel on Climate Change (IPCC) report (Nakicenovic and Swart (Eds.), 2000; Houghton et al. (Eds.), 2001). Globally, scenario A2 implies an increase of average temperatures by 4.1°C by 2100 as compared to the period between 1960 and 1990. At Gårdsjön, the A2 climate scenario was modelled using the MPI_ECHAM5 model from the Max Planck Institute, and downscaled at Göteborg University (Chen, Deliang pers comm). A2 implies an increase in the yearly average minimum temperature of 4.5°C, and a 4.8°C increase in the yearly average maximum temperature. The yearly average temperature increases through the simulation period, particularly during the last 100 years (Table 9). Besides, while the yearly precipitation volumes will not change significantly (Table 9), there will be a significant decrease in rainfall during the growing season, particularly between May and August, that will be compensated for during winter. Photosynthetically active radiation (PAR) will not experience marked change between 1900 and the 2100 (Table 9).

Table 9. Climate indicators at Gårdsjön from three different time periods

Period	Yearly average temperature (°C)	Yearly precipitation (mm)	PAR* ($\mu mol_{photons} \cdot m^{-2} \cdot a^{-1}$)
1900-1910	5.9	849	532
1960-1990	6.2	820	539
2090-2100	9.9	885	549

* PAR = photosynthetically active radiation

6.4 Atmospheric deposition

The historical atmospheric deposition values were derived from the CCE database for atmospheric deposition, based on the historical trends reported in Shöpp et al (2003) (Figure). The trends were calibrated to the measured values at the site available for the period between 1989 and 2004. The historical deposition prior to 1991 is similar among all scenarios (see below).

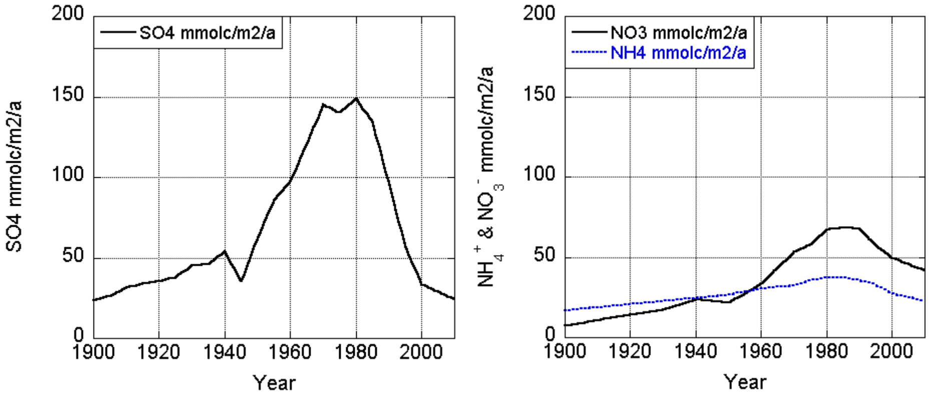


Figure 2. Deposition levels of SO4, NO3 and NH4 at Gårdsjön G2.

Future deposition levels differ between the different scenarios (Table 10). The different deposition levels of CLE and MFR will be reached by 2020, having the same deposition historically and until 2010, while NITREX is assumed to take place from 1991 onwards. MFR has the lowest deposition levels of both N and S. NITREX is assumed to have the same S deposition as CLE, while N deposition is assumed to be equal to CLE+289 meq $\cdot m^{-2} \cdot a^{-1}$ (40kg $\cdot ha^{-1} \cdot a^{-1}$ on top of atmospheric deposition) in the form of ammonium nitrate.

Table 10. Future deposition levels for SO4, NO3 and NH4 under the three deposition scenarios investigated in the study

Deposition scenario	SO_4^{2-} dep. ($mmolc \cdot m^{-2} \cdot a^{-1}$)	NH_4^+ dep. ($mmolc \cdot m^{-2} \cdot a^{-1}$)	NO_3^- dep. ($mmolc \cdot m^{-2} \cdot a^{-1}$)
MFR (2020 and later)	10.06	12.91	18.41
CLE (2020 and later)	23.79	22.04	38.46
NITREX (2020 and later)*	23.79	166.54	182.96

* N deposition under NITREX is equal to CLE +144.5 $meq \cdot m^{-2} \cdot a^{-1}$ both for NH_4^+ and NO_3^- already from 1991.

7 Deposition and climate scenarios

Three scenarios were selected to investigate the effects of nitrogen deposition and climate change on the ground vegetation at Gårdsjön (Table 11). The scenarios are listed in increasing order of N deposition and labelled as follows: S-01 assumes deposition according to MFR, S-02 assumes deposition according to CLE, and S-03 assumes deposition according to NITREX.

Table 11. Three scenarios were simulated to investigate the effects of N load and climate change

Scenario	N deposition	Climate scenario
S-01	According to MFR	With climate change (IPCC climate scenario A2)
S-02	According to CLE	With climate change (IPCC climate scenario A2)
S-03	According to NITREX (elevated N input)	With climate change (IPCC climate scenario A2)

8 Evaluation of model performance

The model was calibrated for soil base saturation measurements from the year 1990, as well as for soil organic carbon and C/N ratio for the same year. Below is a comparison of modelled and measured data for variables that were not calibrated apart from the following exceptions: soil organic carbon and the C/N ratio were calibrated to the first measurement point, but not the subsequent measurements.

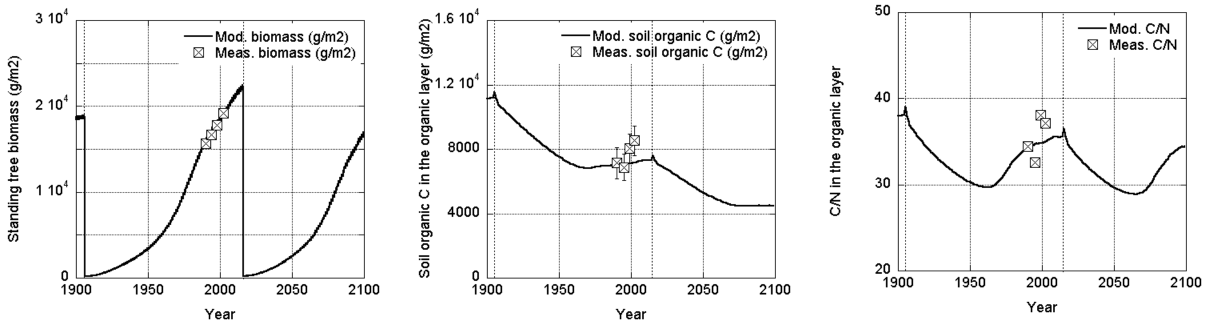
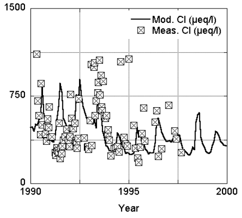
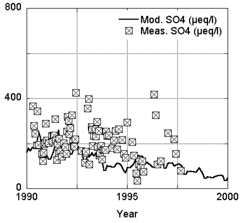
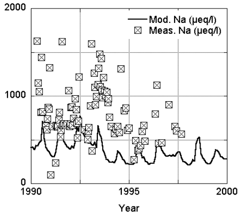
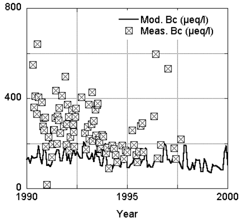
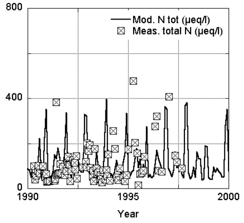
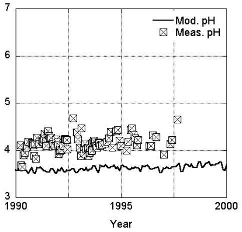
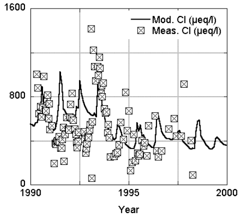
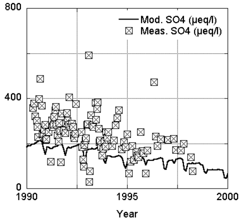
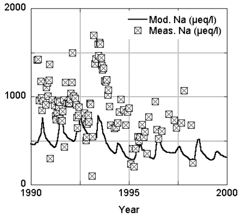
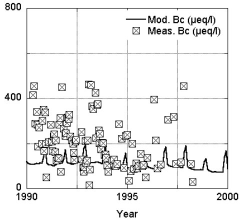
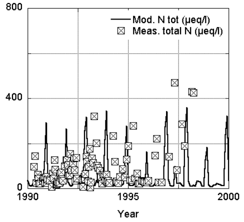
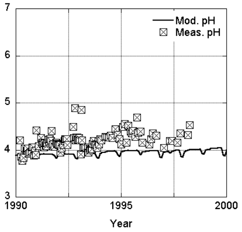
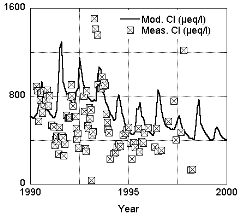
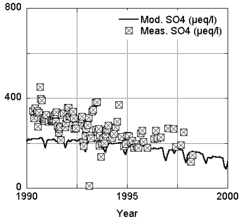
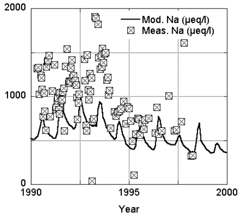
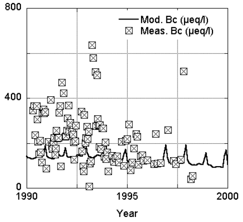
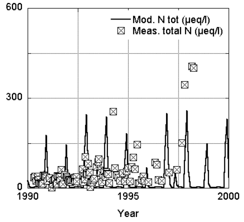
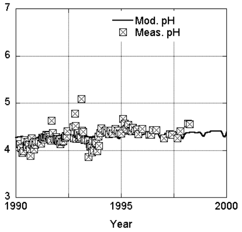
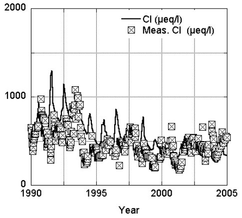
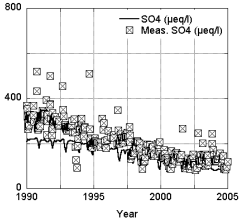
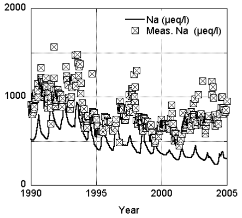
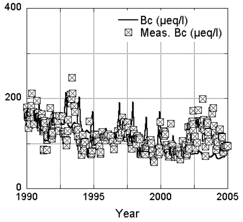
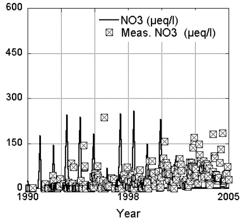
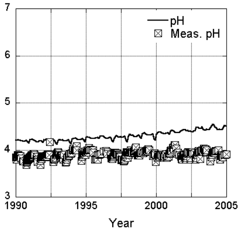


Figure 3. Modelled and measured values of tree biomass, humus soil organic carbon and C/N ratio

The standing tree biomass (excluding foliage, twigs and roots) was accurately reproduced by the model (Figure 3, left). On the other hand, the variability of soil organic matter over the measurement period was not reproduced by the model (Figure 3, centre), although both measurements and model show a positive trend. The recorded change in C/N ratio between the four measurement points was not reproduced by the model, despite that the model was calibrated the first point (Figure 3, right). Assuming that the model produces reasonable values of litterfall given that the living biomass is well reproduced, the discrepancy between the modelled soil organic C and C/N ratios and the measured values points to short comings in the decomposition routine. It is possible that the effect of the climatic change taking place during the comparison period was not captured by the model, although the latter incorporates dynamic responses to changes in temperature and moisture. In particular, the response to changes in temperature may be underestimated by the model.

The model reproduces the concentrations of chloride in the soil solution and in the runoff water relatively well (Table 12). This indicates that the Cl deposition (a model input) is well estimated and that soil hydrology is appropriately modelled. However, the episodic peaks in Cl concentrations may indicate an elevated evapotranspiration under drier conditions as estimated by the model. This effect reappears in other modelled concentrations. Sulphate concentrations are slightly underestimated by the model, and so are the concentrations of sodium and nutrient base cations (Ca^{2+}, Mg^{2+}, K^{+}). The underestimation of sulphate and sodium concentrations can be due to an underestimation of deposition levels given that the soil hydrological transport is appropriately modelled. On the other hand, the underestimation of base cations probably lies in the biological cycle of uptake, litter fall and decomposition/mineralization. It may indicate the need to better parameterise the biota compartments, which are today simplified into three components (leaves, wood and fine roots). The inclusion of twigs and bark, which have different nutrient concentrations than the modelled three compartments may be necessary to improve model performance when it comes to the cycling of macronutrients. Nitrogen concentration in the upper soil layer is reasonably well reproduced, if not for the reoccurring peaks caused by elevated evapotranspiration during dry periods. Down the soil horizon and in runoff, however, the modelled concentrations of nitrogen are lower than the measured ones, apart from the elevated evapotranspiration events. The discrepancy in nitrogen concentration down the soil horizon may reflect the fact that the dominant spruce trees take up most of their nitrogen in the upper layer, while they are allowed in the model to take up 40% of their nitrogen requirements in the mineral soil (Table 6). The higher uptake rates at the lower depths may cause the model to produce lower N concentrations at those depths.

Table 12. Measured and modelled chemical indicators in the soil solution and runoff water

Depth	Soil solution [Cl] (µeq/l)	Soil solution [SO₄] (µeq/l)	Soil solution [Na] (µeq/l)	Soil solution [Bc] (µeq/l)	Soil solution [N] (µeq/l)	Soil solution pH
5 cm						
10 cm						
20 cm						
Runoff						

Model's prediction of ground cover for different plant groups is compared to results of the site survey presented earlier in section 5.2 (Figure 4). The model reproduces the dominance structure of the vegetation observed at Gårdsjön. Vaccinium myrtillus dominates the plant community, with mosses as the subdominant plant type. On the other hand, the model predicts the presence of herbs and grasses (Deschampsia) that were not recorded in the survey at G2, but appear in the survey of adjacent catchment G1 where it covers more than 15% of the ground area (Wright ed., 1993). This difference can be due to the surveying method described in section 5.2, where only the dominant type of each survey square is reported. On the other hand, the model reproduces the occurrence of each species in relation to all the other modelled plants, thus predicting the presence of some plants that although not reported in the survey may occur at the site.

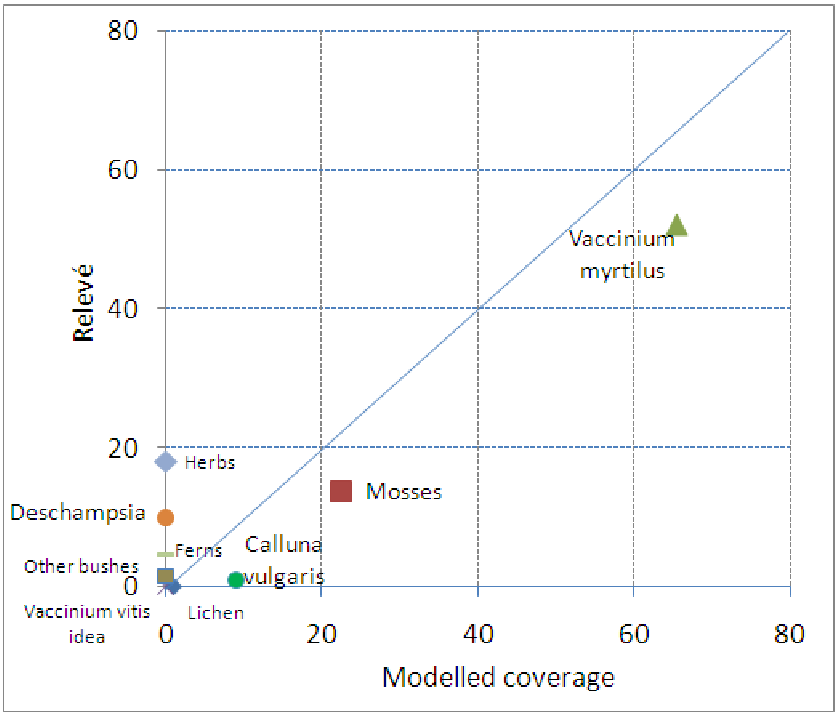


Figure 4. Observed and modelled ground area covers of plant groups at catchment G2 NITREX at Gårdsjön

9 Historical and future changes of the ground vegetation community under historical N deposition and MFR as the future deposition: The reference population

N deposition according to MFR was adopted as the future reference deposition of N. The composition of ground vegetation in Figure 5 is used as the reference population. Figure 6 shows exactly the same population changes over time as Figure 5, with the difference that the former shows the plants grouped into eight functional types for readability. The site has experienced a clearcut in 1905, the effect of which is seen on the ground vegetation population by a sharp decline of the dominant Vaccinium myrtillus to the benefit of a more diverse population containing more grasses, other bushes, herbs and ferns. The changes following the clearcut are due to the combination of increased nutrient and light availability. A similar dynamic takes place after the second clearcut presumed in 2015, though the model predicts relatively more herbs than bushes other than Vaccinium myrtillus. The changes in Figure 5 shows that clearcuts have a more expressed, although relatively short lived, effect on the composition of the ground vegetation community than does N deposition. The simulation includes future changes in climate.

Divergence in the composition of the ground vegetation is estimated in relation to the community composition shown in Figure 5.

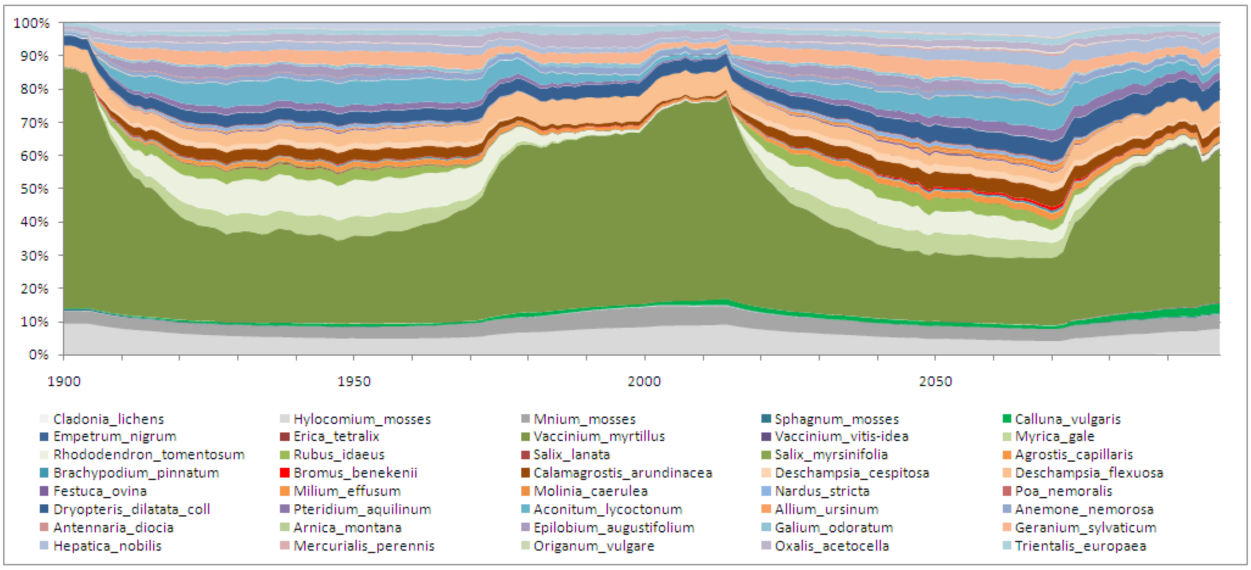


Figure 5. Composition of the ground vegetation under MFR deposition of N.

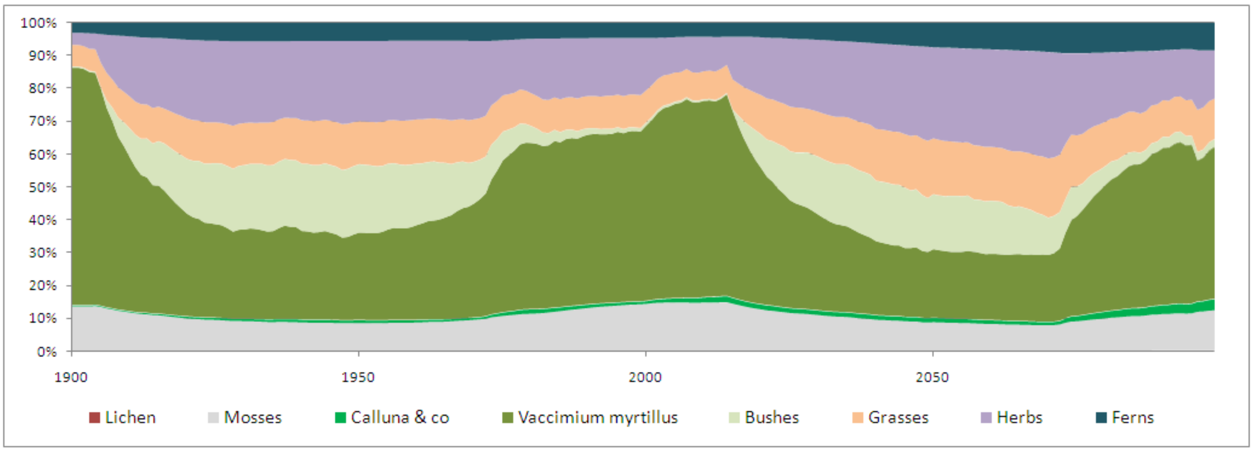


Figure 6. Modelled changes in prominent plant groups at Gårdsjön G2 between 1900 and 2100

10 Nitrogen input effect on the composition of the ground vegetation

To illustrate how different nitrogen loads affects the composition of the ground vegetation community, Table 13 below shows the modelled cover of different indicator plants 75 years after the clearcuts. The delay of 75 years is assumed to give the forest stand enough time to mature after clearcutting, thereby discounting the transient effect of the clearcut and keeping focus on the effect of N deposition.

75 years after the 1905 clearcut, the ground vegetation community would have been dominated by Vaccinium myrtillus to 51% (i.e. Vaccinium myrtillus would have occupied an area of 0.51 $m^2 \cdot m^{-2}$) of the ground cover. If the atmospheric N deposition would proceed according to MFR in the future, Vaccinium myrtillus would decrease in cover to 48% of the ground cover by 2090, 75 years after the planned 2015 clearcut. Of the 18 plants predicted by the model to have existed in 1980, 6 would decrease in cover and 4 would increase in cover under MRF, while Deschampsia cepitosa would appear at the site. The change in the specific ground covers would be evenly distributed throughout the population distribution spectrum between the historical population in 1980 and the future population in 2090 under MFR (as much among marginal as among sub-dominant and dominant).

In the future, CLE would cause relatively minor changes in the ground vegetation as compared to the reference population under MFR in 2090. It is unclear if the small differences in ground vegetation cover between MFR and CLE reflects the limited N status of the site under both MFR and CLE, or if it is due to the model's inability to capture the effects of the relatively small difference in N availability under both scenarios. Under NITREX on the other hand, there would be considerable increases in the ground covers of marginal plants at the cost of the dominant Vaccinium myrtillus, and the model predicts even the appearance of plants that would have been absent under MFR and CLE.

Table 13. Composition of the ground vegetation community 75 years after clearcutting

Plant	Cover 1980 (m2/m2)	Cover 2090 nder MFR (m2/m2)	Cover 2090 under CLE (m2/m2)	Cover 2090 under NITREX (m2/m2)
Vaccinium_myrtillus	0.51	0.48	0.47	0.36
Hylocomium_mosses	0.07	0.07	0.07	0.08
Deschampsia_flexuosa	0.07	0.06	0.06	0.07
Dryopteris_dilatata_coll	0.04	0.06	0.06	0.05
Mnium_mosses	0.05	0.04	0.05	0.06
Aconitum_lycoctonum	0.04	0.03	0.03	0.02
Hepatica_nobilis	0.02	0.03	0.03	0.01
Pteridium_aquilinum	0.01	0.03	0.02	0.01
Anemone_nemorosa	0.02	0.02	0.02	0.03
Calamagrostis_arundinacea	0.01	0.02	0.03	0.03
Calluna_vulgaris	0.01	0.02	0.02	0.00
Geranium_sylvaticum	0.02	0.02	0.03	0.05
Rhododendron_tomentosum	0.04	0.02	0.02	0.02
Trientalis_europaea	0.03	0.02	0.02	0.03
Agrostis_capillaris	0.01	0.01	0.01	0.03
Deschampsia_cespitosa	0.00	0.01	0.01	0.02
Myrica_gale	0.01	0.01	0.01	0.01
Oxalis_acetocella	0.03	0.01	0.02	0.05
Urtica_dioica	0.01	0.01	0.01	0.01
Bromus_benekenii	0.00	0.00	0.00	0.01
Galium_odoratum	0.00	0.00	0.00	0.02
Milium_effusum	0.00	0.00	0.00	0.01
Molinia_caerulea	0.00	0.00	0.00	0.01
Retreats	History	Reference	2	5
Increases	History	Reference	4	10
Disappearances	History	Reference	0	1
New plants	History	Reference	0	4

When compared to the future plant community under MFR, the elevated future depositions under NITREX promote nitrophilous species at the expense of plants adapted to lower N loads such as Vaccinium. Interestingly, CLE (around two thirds of N deposition during the 1980s peak) causes no major shifts particularly related to nitrophilous or nitrophobic species as compared to MFR or the historical population in 1980, indicating that Gårdsjön has a ground vegetation community which is already adapted to the current N deposition level.

11 Estimating critical change of ground vegetation composition

Three parameters are crucial to estimating whether a change in the composition of the ground vegetation due to N deposition is acceptable or not:

1. The reference population under a given reference deposition, against which eventual changes in the composition of the vegetation are evaluated. Here focus is put on N deposition, the same climate and management scenarios are used in all cases. N deposition according to the maximum feasible reduction in emissions (MFR) is adopted as the reference N deposition (S-MFR in Table 11).
2. The target population, i.e. the segment of the ground vegetation community for which change is evaluated. This is tested in two legs as described below, first selecting a target population among the dominant plants, and second selecting a target population among the marginal plants.
3. The limit of acceptable change, which is the magnitude of divergence from the reference population beyond which change in the target population (see above) is unacceptable. The limit can be a certain percentage, for example that if the target population diverges by more than 20% from the reference population, it would be considered unacceptable change.

N deposition according to MFR is adopted as the reference N deposition for the simulation beyond 2010, yielding the reference community shown in Figure 5. Below, the implications of selecting the target population among the dominant end or the marginal end of the community are investigated. The definition of the limit is also discussed for each case.

11.1 Defining the target population

Change caused by N deposition has to be defined in relation to a reference state through a given indicator. In turn, the reference state can be defined as the composition of the ground vegetation community in whole or in part. The section of the vegetation population which is used to follow change is referred to as target population. Different sizes of the target population have been tested below in two different ways. The first way focuses on the dominant plants by assuming the dominant 20% of the reverse pyramid in Figure 7 as the target population, and then alternatively increasing the selection up to 80% of the entire population as the target population (80% from the wide end of the reverse pyramid and down). The second way to select the target population is by starting at the marginal end of the population reverse pyramid. The target population then is assumed to be the marginal 5% of the population, and alternatively increasing the selection by including further marginal plants up to 20% of the entire ground cover.

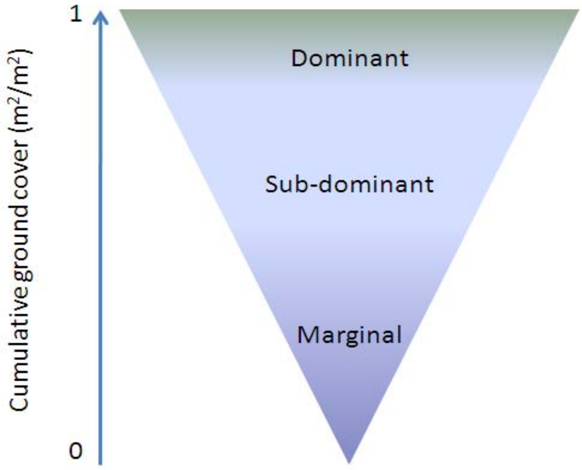


Figure 7. The ground vegetation reverse pyramid with the three classes

Change in the target population will be used as the biological indicator of the effect of N deposition on the composition of the community. If the target population is, for example, the marginal 20%, it is this section of the population which we are interested in protecting from excessive change due to N deposition. In the same way, if the target population is the 60% of the population starting at the dominant end, it is the dominant plants making up 60% of the ground cover that are of interest for protection. This raises the questions of whether the protection from change due to N deposition is to be directed towards marginal and rare species or towards ecosystem function in the form of the dominant plants. Both parts are tested below and implications for the detection of undesired effects due to N deposition are drawn.

11.2 Target population defined among the dominant plants

The compositions of the ground vegetation under CLE and NITREX N deposition (S-02 and S-03 in Table 11) are compared to the reference population under MFR. Figure shows the change relative to the reference population for target populations of 20%, 40%, 60% and 80% defined among the dominant plants under CLE and NITREX. The vegetation differences shown in Figure 8 are relative to the total ground cover, and not to the size of the target population. If the target population is the dominant 20% of the total population, then N deposition according to CLE will cause a change in this segment of the population (i.e. dominant 20%) according to the black line in Figure 8 left. In this case, CLE will cause a negligible change in the target population up until 2060, when the change in the target population under CLE will grow to reach 10% by 2070, and then recede to about 5% by 2080 and remain on a slightly upwards trend thereafter. If the target population is made up of the 40% dominant plants, it will respond to CLE according to the red line. After 2060, the change in the 20% and 40% target populations converges to the same value, indicating that a single plant occupies at least 40% of the ground cover (in this case Vaccinium myrtillus)

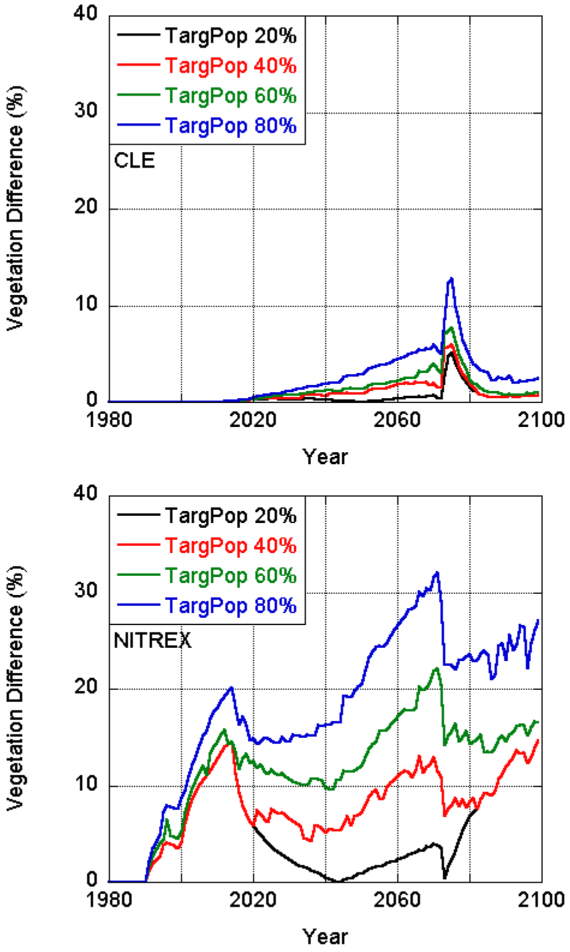


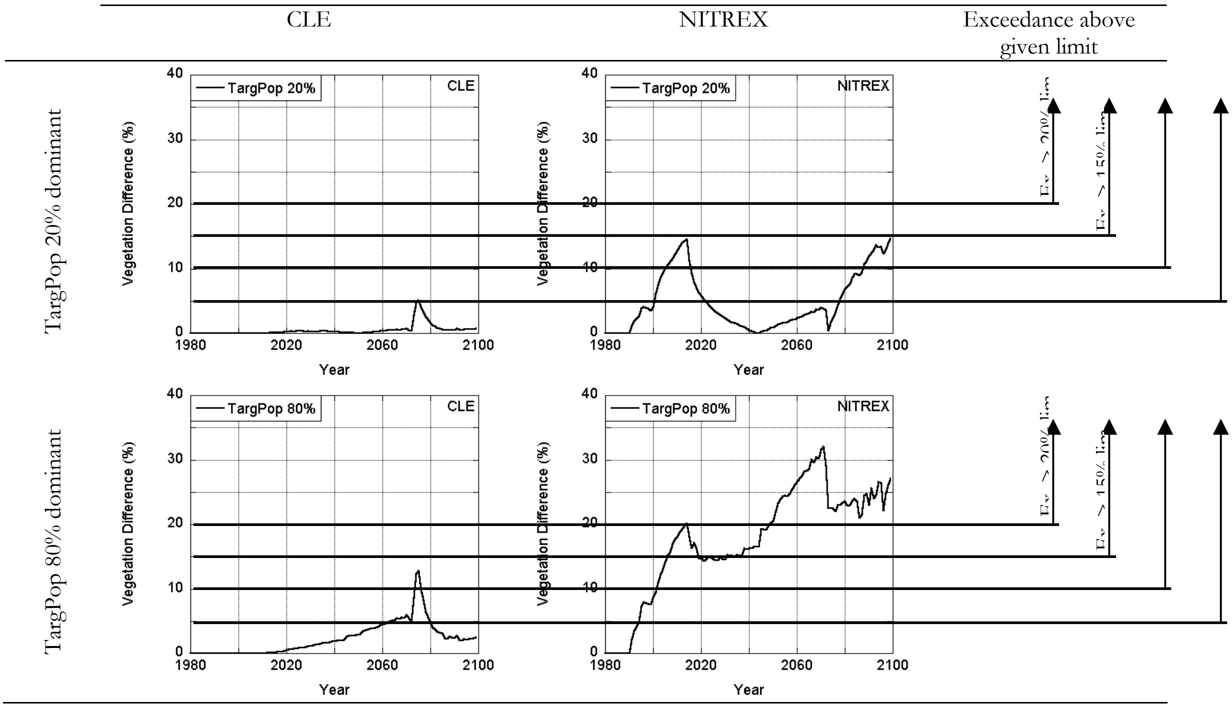
Figure 8. Differences in the ground vegetation composition under N deposition according to CLE (top) and NITREX (bottom). The reference scenario is N dep according to MFR.

N deposition according to NITREX on the other hand (Figure 8, bottom), causes a fast response from 1990 to 2010 when the stand is expected to be harvested. The harvest causes a decline in the difference of the ground vegetation between NITREX and the reference scenario, which will last until around 2060. After 2060, NITREX drives a large and expanding change in all target populations in comparison to the reference scenario. It is also evident that the larger the target population chosen, the larger the divergence from the reference population. Under both NITREX and CLE, the contribution of additional increments in the size of target population increases with the size of the latter.

Expectedly, NITREX N deposition causes a bigger divergence from the reference MFR deposition than does CLE, and while the simulation stops at 2100, the divergence trend seems to continue upwards, with a higher slope under NITREX than under CLE.

To evaluate the gravity of the difference in the composition of the ground vegetation from the reference population, a limit for acceptable change needs to be defined. Table 14 displays vegetation differences and selected limits to illustrate the events when vegetation differences may exceed the limits. In defining the critical acceptable change in the composition of the ground vegetation, it is the magnitude of the difference line above the limit and the duration of the period when the vegetation line overpasses the limit that defines the gravity of the exceedance. For example, under CLE and with a target population of 80%, the 10% critical limit will only be exceeded for a short period around 2075. On the other hand, NITREX will drive a chronic and considerable exceedance of the 5% critical limit.

Table 14. Exceedance levels of vegetation differences for two target populations defined among the dominant plants and four hypothetical limits



A single value can be derived from the exceedance curve in Table 14 to simplify the use of the concept in defining critical loads. We refer to this value by the name average yearly exceedance, which is the sum of the difference between the vegetation difference line and the critical limit line for each year, divided by the number of years for which the deposition of N has been different.

Table 15. Average yearly exceedance values ($\%_{area} \cdot a^{-1}$) for specific target populations and critical limits under CLE N deposition

	TargPop 20%	TargPop 40%	TargPop 60%	TargPop 80%
Limit 5%	0.0	0.0	0.1	0.2
Limit 10%	0.0	0.0	0.0	0.0
Limit 15%	0.0	0.0	0.0	0.0
Limit 20%	0.0	0.0	0.0	0.0

Table 16. Average yearly exceedance values ($\%_{area} \cdot a^{-1}$) for specific target populations and critical limits under NITREX N deposition

	TargPop 20%	TargPop 40%	TargPop 60%	TargPop 80%
Limit 5%	2.1	3.8	8.1	14.4
Limit 10%	0.5	0.7	3.5	9.7
Limit 15%	0.0	0.0	0.7	5.3
Limit 20%	0.0	0.0	0.1	2.4

CLE causes the average yearly exceedance to go over zero (to one decimal) only for target populations beyond 60% and for the strict critical limit of 5% (Table 15). That is to say that CLE will only cause excessive change in the composition of the ground vegetation if at most 5% change is allowed in at least 60% of the population. NITREX on the other hand, causes exceedance of the critical limit as high as 20% for target populations beyond 60% (Table 16). However, N deposition under NITREX will not cause excessive change in the composition of the ground vegetation if the protected target population consists of the dominant 40% or less and the critical limit is set at 15% or above. On the other hand, if the protected target population is 80% of the plant community, even a critical limit of 20% will be exceeded under NITREX. This means that under NITREX, a quarter of plants excluding the marginal 20% will be completely different from the reference population under MFR.

11.3 Target population defined among the marginal plants

The protection of marginal plants has an established conservational importance. In this section, the effect of N deposition on the marginal species is investigated by following the effect of N deposition according to CLE and NITREX on a set of target populations selected among the marginal plants. The vegetation cover differences of the marginal 5, 10, 15 and 20% are shown in Figure 9 below for CLE and NITREX.

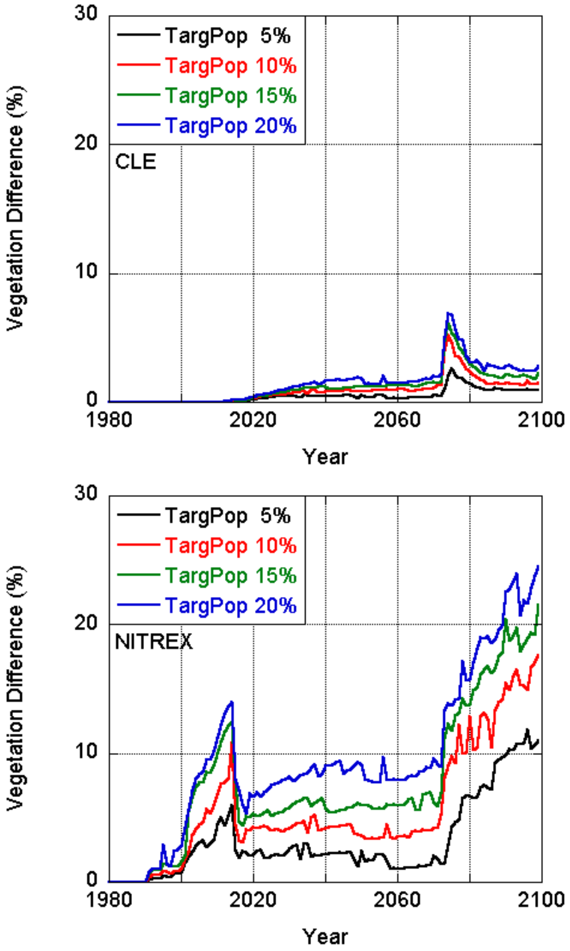


Figure 9. Vegetation difference among the marginal 5, 10, 15 and 20% of the population under CLE (top) and NITREX (bottom). The reference deposition is MFR.

N deposition according to NITREX causes larger differences in the marginal vegetation population than under CLE. Marginal nitrophilic herbs and grasses are promoted by the increased N load under NITREX (Table 13), while the cover of the dominant Vaccinium myrtillus is reduced by 23.5% from the cover it would have under MFR (CLE will also cause a less severe reduction by about 5.8%).

Intuitively, the more species included in the target population, the higher the cumulative and the average yearly vegetation differences both under CLE and NITREX. Yet, the contribution of the specific plants is more important for the most marginal plants, and less so as more plants are included in the target population, producing the concave shape of the curves in Figure 10. For example, under CLE, using the most marginal 20% of the population as the target sample gives an average yearly exceedance of 5.1%, while a target population consisting of the lowest 40% plants gives an average yearly difference of 7.3%, and the next 60% yields 9.3% average yearly difference. Under MFR, the lowest 20% target population gives an average yearly exceedance of 13.0%, a 40% target population yields 19.5% and a target population of 60% gives 26.7% average yearly difference.

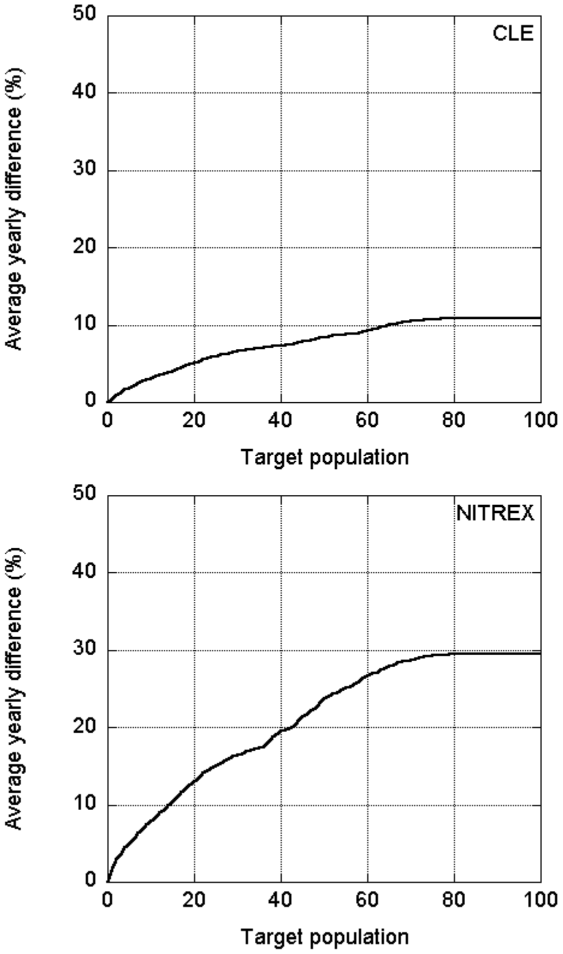
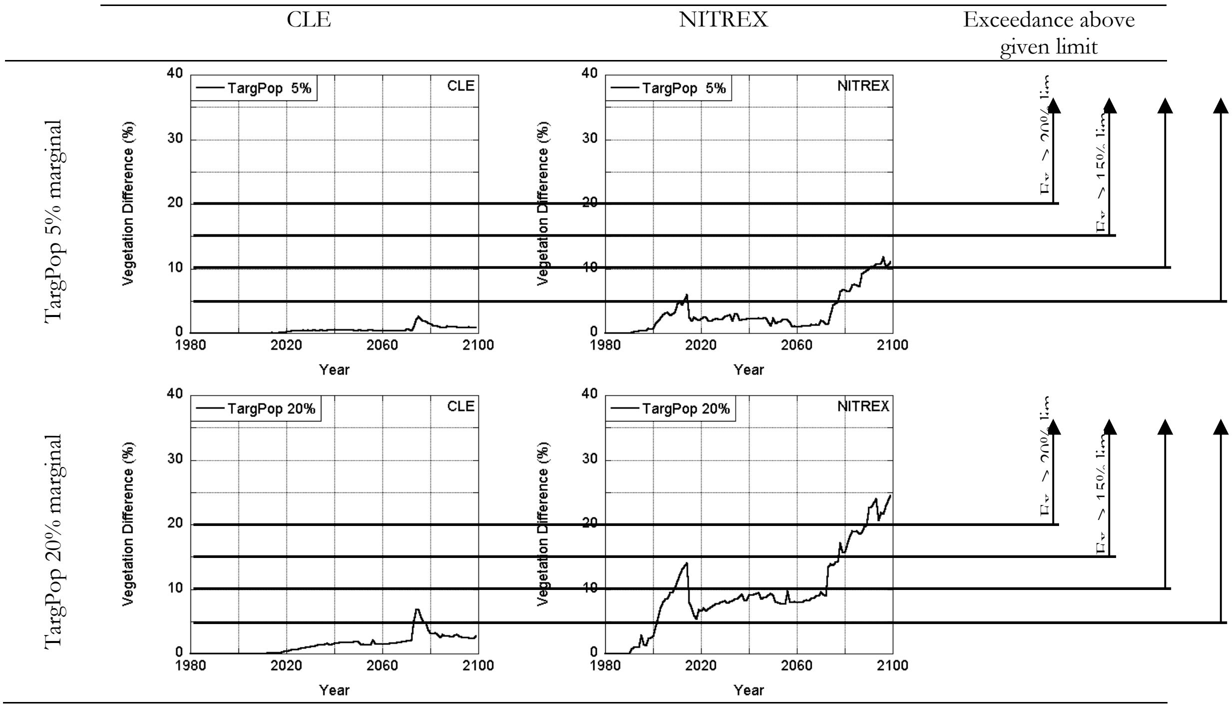


Figure 10. Average yearly differences as functions of the selected target populations show a consistent concave shape both under CLE and NITREX. The reference scenario is MFR.

Different target population sizes and different limits for acceptable change yield different levels of exceedance as seen in Table 17. Bigger target populations give larger changes and thereby higher levels of exceedance, while at the same time higher limits for acceptable change yield lower exceedance levels (the higher the limit, the more change is required to exceed it). The change caused in a 5% marginal target population under CLE deposition will never exceed 5% for the simulation period. On the other hand, the change in a 20% marginal target population will exceed the 5% limit only for a short period around 2070 (meaning that the marginal 5% population will either disappear or double in ground cover), while it will never exceed the 10% within the simulation period.

Table 17. Exceedance levels of vegetation change for two target populations future N deposition according to CLE and NITREX



When testing the effects of NITREX N deposition, exceedance levels are markedly higher than for CLE. The deposition of N under NITREX increases the nitrogen load at Gårdsjön so that the change in the ground vegetation has an upwards trends, leading to higher exceedance levels further into the future in the same way as seen above for the dominant plants. The increasing N load under NITREX will lead to exceedance of the set critical limits of 5% and 10% of both the marginal 5% target population and the marginal 20% target population. Once started, the exceedance levels increase over time, meaning that the vegetation community diverges further and further from reference community that would establish under the reference MFR scenario.

It is interesting to note that there is a transient effect in the form of a short lived peak in the exceedance curves in Table 17 above, which corresponds to canopy closure at the site. Canopy closure induces a change in the nitrogen cycle that is reflected on the availability of N in the soil and thereby on the composition of the ground vegetation community. The long term effect of the two tested N deposition levels (CLE and MFR) appears after the transient canopy closure effect has receded in the form of a steadily increasing trend of exceedance of the critical limit.

If the target population is selected among the marginal plants, we suggest using a target population size of 20%, i.e. that the marginal 20% of the reference population is to be protected from excessive change due to N deposition. We also suggest that a critical limit of 5% be adopted. A 5% critical limit implies that the integrity of the 20% target population is preserved to three quarters.

Table 18. Average yearly exceedance values ($\%_{area} \cdot a^{-1}$) for specific marginal target populations and critical limits under CLE N deposition

	TargPop 5%	TargPop 10%	TargPop 15%	TargPop 20%
Limit 5%	0.00	0.00	0.01	0.02
Limit 10%	0.00	0.00	0.00	0.00
Limit 15%	0.00	0.00	0.00	0.00
Limit 20%	0.00	0.00	0.00	0.00

Table 19. Average yearly exceedance values ($\%_{area} \cdot a^{-1}$) for specific marginal target populations and critical limits under NITREX N deposition

	TargPop 5%	TargPop 10%	TargPop 15%	TargPop 20%
Limit 5%	0.81	2.16	3.79	5.78
Limit 10%	0.06	0.80	1.66	2.38
Limit 15%	0.00	0.09	0.51	1.06
Limit 20%	0.00	0.00	0.02	0.26

The average yearly exceedance under CLE is below a decimal fraction for all selected marginal target populations and critical limits (Table 18). Under NITREX on the other hand, average yearly exceedance of the 5% critical limit is positive for all selected marginal target populations (Table 19). This is analogous to the change in the dominant population, asserting that NITREX will cause extensive change in the composition of the ground vegetation that is beyond acceptance both for the marginal as well as the dominant segments of the ground vegetation community. CLE deposition on the other hand will not cause the vegetation change to exceed most of the tested critical limits.

12 Discussion

Adopting MFR as the reference deposition implies that the reference plant community will be as close to nitrophobic as feasible in the future. This is a reasonable supposition as it is the closest one can come in the future to the pre-industrial low N loads in terrestrial ecosystems. However, the nitrogen load can continue to be elevated even if N deposition is reduced, due to the accumulated nitrogen as a result of the elevated deposition of last century and the internal cycling mechanisms of an ecosystem that retain the nitrogen in a nearly closed cycle between the vegetation, soil organisms and organic matter, and the mineral soil and soil solution. Yet, MFR will still favour the establishment of species that are more competitive under reduced N availability as compared with other deposition scenarios, or at least disfavour the more nitrophylic plants in the long run. This means that by adopting MFR as the reference scenario, we are aiming at protecting or obtaining a plant community characterised by low nitrogen affinity. The implications of such a community on ecosystem services would probably differ from those of communities with high nitrogen affinity in terms of nitrogen retention, growth response to nitrogen addition, carbon sequestration, the quality of runoff water, exchanges of greenhouse gases and so on.

Based on this study and on the importance of ecosystem services, we suggest directing the critical loads focus on the dominant part of the population. The door remains open to adapt the methodology to the conservation of marginal plants. Ye, we see from the present study that protecting the integrity of the dominant part of the plant population is likely to results in the protection of the marginal plants as well, at least when the critical limits of change in the composition of the ground vegetation are set to substantial levels of at least 5% of the ground cover. It was shown in fact that the potential effect of elevated N deposition is to promote nitrophylic plants that would be marginal under a low N deposition regime to the detriment of the nitrophobic plants that would dominate under low N deposition.

At Gårdsjön, an increased N deposition in the future above MFR will lead firstly to a reduction in the dominant species and secondly to an increase in the marginal species. This may appear counterintuitive, but it is due to the fact that the dominant species are characteristic of low nitrogen loads, while the marginal plants are subordinate in ground cover precisely because of nitrogen limitation. This suggests that it is the dominant plants who are indicators of the nitrogen status of Gårdsjön.

Interestingly, protecting the dominant segment of the population or the marginal segment would require comparable limitations on N deposition. This is reflected in the fact that the exceedance levels of dominant and marginal target populations are comparable for similar critical limits, due to the fact that the change in the dominant species due to elevated N deposition is often a reduction in favour of corresponding expansion of the marginal species. This mirror effect of the vegetation dynamics at Gårdsjön means that we should probably be able to set a single critical load of N deposition to protect the dominant as well as the marginal segments of the population, or in other words the entire community. Nor does the establishment of alien invasive species promoted by N availability disturb this balance at Gårdsjön. The establishment of new species did not dislodge any marginal plants, but happened at the expanse of the contracting dominant plants. Further investigation is needed to elucidate this point.

The acceptable limit appears to be the strongest factor controlling the exceedance of acceptable change. No exceedance incidents happen for limits above 50% at Gårdsjön, and the exceedance increases sharply as the limit is set lower. This means that if nitrogen deposition is allowed to cause up to 50% change in the composition of the ground vegetation, then not even the current 50kg/ha of nitrogen input at Gårdsjön under NITREX will cause unacceptable change within the coming 100 years. On the other hand, we suggest the use of a 5% critical limit on the change in the vegetation composition, regardless of the target population. Choosing the 5% limit captures unwanted change already before 2100, but also infers further possible change beyond 2100 as the long term trends of the vegetation change and those of exceedance are positive.

Overall time scales of vegetation changes expected to take place when the current deposition of ca 10 kgNha/yr is enhanced by additional 40 kgN/ha/yr in the NITREX scenario are surprisingly slow. The vegetation response is arguably modest provided such an extreme scenario, with N load well above any concievable deposition, future or past, experienced at the site. If less stringent criteria are used, the NITREX scenario does not cause unacceptable vegetation during this century. Similarly, the differences in response were surprisingly small between CLE and MFR scenarios. That indicates that if the change in vegetation is to be used for setting the critical loads, relatively distant time horizons or very stringent limits will be necessary to show differences between future deposition scenarios, for which CLE and MFR are upper and lower limits. The robustness of the vegetation cover and relative insensitivity to N deposition at Gårdsjön is most likely due to the fact that elevated N deposition over the last decades was sufficient to result in vegetation community which simply is relatively adapted to the present N load at the site.

13 Conclusions

The application of the ForSAFE-Veg model at Gårdsjön was possible because of the high quality of the monitoring and manipulations data at the site, and the availability of long term series spanning disturbance events such as changes in atmospheric deposition and manipulation regimes. The study stresses the need to continue the long term monitoring and manipulation experiments at ecosystem level for their unique value in testing and validating dynamic modelling tools. The comparison between the model reconstruction of biological, chemical and hydrological indicators at the site indicates that the model performance is satisfactory, thus supporting confidence in the model predictions.

The study thus confirms the feasibility of integrated ecosystem modelling, and contributes to establishing the soundness of the adopted modelling method for estimating the composition of the ground vegetation community and its responses to environmental change. The integrated ecosystem modelling method applied in the study forms the basis for the estimation of critical loads of N deposition based on a biological indicator which is the composition of the ground vegetation community.

The idea of using the composition of the ground vegetation community as an indicator for change of the ecosystem has been shown to be feasible in this study. Yet, it was also demonstrated in the study that the complexity of the plant community needs to be simplified into a single-dimensional variable for it to be useful for the estimation of critical levels of N deposition. The concept of average yearly exceedance was put forward as a way to express excessive change in the composition of the ground vegetation community in a single variable. For the concept to work three variables need to be defined. The first is the reference plant community linked to a hypothetical low N deposition in the future which is assumed as most desirable. The study assumed that the reference population corresponds to N deposition according to the maximum feasible reduction of emissions (MFR). The second variable is the target population, i.e. the segment of the plant community which is to be protected from change. The third variable is the critical limit, i.e. the level of divergence from reference population beyond which change is unacceptable. The target population as well as the critical limit carry a value judgment of what society perceives as worthy of protection and to what extent. However, the study has shown that protecting the dominant plants would also protect the marginal plants.

In the future, CLE would cause relatively minor changes in the ground vegetation as compared to the reference population under MFR in 2090. That indicates that Gårdsjön has a ground vegetation community which is adapted to the current and recently experienced N deposition levels of 10 – 15 kgN/ha/yr.

14 References

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