Towards critical loads for nitrogen based on biodiversity: Exploring a fully integrated dynamic model at test sites in Switzerland and Sweden

and

Forecasting Air Pollution Impacts on Biodiversity and Habitat Quality: A British Study

Background document for the 18th CCE workshop on the assessment of nitrogen effects under the ICP for Modelling and Mapping, LRTAP Convention (UNECE), Berne, Switzerland, 21-25 April 2008

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Proposed method for estimating critical loads for nitrogen based on biodiversity using a fully integrated dynamic model, with testing in Switzerland and Sweden

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1. Introduction to the problem

Until present, the environmental effects originating from acid deposition, eutrophication and global climate change have been investigated independently. The 1999 Gothenburg protocol to abate acidification, eutrophication and ground-level ozone within the Convention on Long-Range Transboundary Air Pollution (CLRTAP) has the scope of decreasing emissions of nitrogen and sulfur substantially when fully implemented (UNECE 1999). National environmental goals for effect-oriented and optimized air pollution control policies are set i.a. on the basis of critical loads. However, at present, national environmental goals for biodiversity are defined in relatively vague and static terms. The connection to air pollution is only addressed in an indirect way, e.g. over empirical critical loads for nitrogen. In order to give the national authorities a starting point from which to develop more quantitative environmental goals for linking policy more firmly to critical loads for biodiversity, as well as a lead on how to approach the problem with a more dynamic approach, we intend to do this study as an illustration of what could be done and some options for the way forward.

Until now, the critical loads estimated regionally for nitrogen deposition and their exceedances have had no dynamic and quantified connection with biodiversity, because of lack of proper models. Neither were any models available which will combine the effects of climate change and deposition of sulfur and nitrogen using mechanistic approaches, before the arrival of the ForSAFE-VEG model. The Gothenburg protocol will be reevaluated and revised during the coming years, and models for predicting pollution impacts on biodiversity components can strengthen the case for stricter adherence to effects-based critical loads for multiple components of the ecosystems (Sverdrup et al. 2005, Martinson et al. 2005). The causal chain used in the effect-based critical load concept is:

Pollution input > abiotic response > biological component response > ecosystem effects

This is reversed in the critical load methodology to become back-casting from the goals:

ecosystem effect limit > diagnostic parameter > limit value > calculation > critical load

Traditional is that the limit is set on an abiotic parameter like pH, $[Al^{3+}]$ and a causality indicator, e.g. the BC/Al ratio (Sverdrup and Warfvinge 1993), linked with an empirical response function to ecological effect, and the critical load parameter iterated based on the

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abiotic limit (See Sverdrup and Warfvinge 1993 for a summary of the available European, Asian and North American data with respect to acidity). With the new generation of integrated ecosystem response models like ForSAFE-VEG, the diagnostic parameters can be formulated directly on an ecosystem response parameter (defoliation, growth rate, abundance, photosynthesis, etc), and the abiotic proxy is no longer needed. This implies that the critical load can be calculated directly on ecosystem effect, without the intermediary indicator such as ANC, BC/Al or an N concentration limit. The limit can be set directly on ecological response of trees, fishes or ground vegetation.

2. Objectives and focus

The focus of this study is to investigate how to estimate critical loads based on effects on biodiversity. The issues pertinent are:

1. Which parameters are adequate diagnostic variables for air pollution effects to biodiversity of the ground vegetation?
2. How different numerical settings of limitations in diagnostic variables will change the resulting critical load
3. How to address properly the feedback between nitrogen inputs and the effects of acidity, growth, management and differences between site conditions.
4. Conduct testing at sites in Sweden and Switzerland, where the possibilities suggested above are explored
5. How to create a valid procedure for estimating critical loads based on biodiversity in regional assessments on a regional scale

The final objective is to demonstrate a full calculation for a number of different sites, testing the whole concept. The objective is to use this as an input to the national environmental agencies for evaluation with respect to developing National environmental goals and environmental policy goals within the process under the LRTAP Convention (UNECE).

3. Theory

3.1 Defining a critical load

To state that we want critical loads based on biodiversity has ramifications. First of all, biodiversity incorporates some of the systemic properties of an ecosystem. Biodiversity also represents a quality aspect of an ecosystem, in functionality to provide a rich species range for continued evolution. It also implies a morally defined obligation by humans to keep impacts on the surroundings within reasonable and controllable frames. From this follows that the critical loads will necessarily incorporate a strict attitude towards pollution. The general critical load is defined as:

The maximum amount of pollutant input to an ecosystem that will not lead to adverse effects on ecosystem structure or functions

It is important to realize that several pollutants and disturbances affect biodiversity, so we have at least these critical loads that have from strong to weak connection to biodiversity:

1. Critical load for nutrient nitrogen

2. Critical load for acidity
3. Critical load for phosphorus
4. Critical loads for heavy metals (Hg, Pb, Cd)
5. *Critical loads for persistent organic chemicals (POPs)*
6. *Critical loads for phytoactive organic pollutants (PhOPs)*
7. *Critical loads for endocrine disruptive organic pollutants (EDOPs)*

Those in italics have yet not been assessed and proper methods to establish Critical Loads are at the moment not available. All of the above aspects are coupled through the feedback system of the ecosystem, making estimating the critical load for nitrogen alone far from trivial. The critical load has a connected relative, the critical level, developed with a similar philosophy, which also represents parameters with potential effect for biodiversity. We can define the critical atmospheric level for:

1. Critical levels for tropospheric ozone (O_3: local, regional)
2. Critical levels for sulfur dioxide (SO_X: local)
3. Critical levels for nitrogen oxides (NO_X; local)
4. Critical levels for ammonia (NH_3, local)
5. Critical levels for volatile organic compounds (VOCs: local)
6. Climate change
    i. *Critical levels for carbon dioxide and other GHC gases (global)*
    ii. *Critical thresholds for temperature (local)*
    iii. *Critical thresholds for precipitation (regional)*

The critical load for nitrogen can probably be specified into two distinct critical loads for ammonium and nitrate. These are probably not independent, but the present state of our knowledge does not allow us to differentiate between the impacts of ammonium and nitrate. Unless specific research will be forthcoming, it will remain so for the next future. The critical load for nitrogen excludes its acidifying effect; this is included in the critical load for acidity. Many persistent organic pollutants are phytoactive (PhOP's) and may probably be able to distort both biodiversity, ecosystem functions as well as warp individual species.

3.2 What is good and what is bad, defining ”adverse effects”

The first challenge on the path to critical loads is to define what is implied by the expression ”adverse effects” to either ecosystem structure or function. Typically, the diagnostic parameter for observing effect is plotted versus the immediate causal factor, and the limit for adverse is drawn on the effect axis in order to be able to derive the limit in the causal factor. For example, the effect of nitrogen concentration in the leaves is plotted versus the incidence rate of contracting the Valdensia parasitic fungus (Nordin et al, 2002). Hypothetically, we may determine that when 20% of a population has been affected, then that is enough. For acidification, this was done using growth of trees as the diagnostic effect parameter and BC/Al in the soil solution as the causative indicator. At this point, this requires us to state our risk philosophy, in order to clarify what we protect and which risks we are willing to take.

The *maximum allowable damage principle* (MAD-P) is the principle used in traditional acidification critical loads. A certain degree of effect is accepted as being stress, but still not adverse damage. In the case above a 20% effect on growth was seen as the maximum, implying a limit of BC/Al=1.2 (Black line in Fig. 1). Considering the dispersion in points in Fig. 1, the range given by the dispersion in points is BC/Al: 0.4<1.2<4. The dispersion is not necessarily inaccuracy in the data, but also reflects variability between individual plants of the same species. According to MAD-P, we accept a certain degree of effect as not adverse, and then we can defend to use a cutoff value at 20% impact to growth.

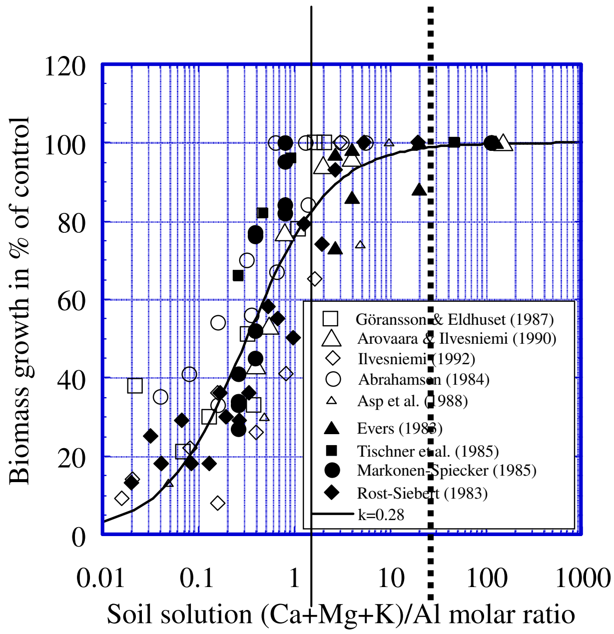


Fig. 1. *Cause-effect diagram for Norway spruce used to set the critical limit used in critical loads calculations. For this variable, experiments provide a fully documented response-curve where clear effect cut-off can be made. These diagrams are possible, when other factors can be held sufficiently constant. With nitrogen, such diagrams are seldom available in the same way.*

The *precautionary principle* (PP) implies that we intend to exclude the occurrence of effects with a certain safety margin or certainty. Applying the precautionary principle for Norway spruce, interpreting it such that we want to exclude effects completely, also considering the dispersion of the data points in Fig. 1, gives the value BC/Al=4 as critical limit. If the criterion is to eliminate any recorded response, we must adopt the value BC/Al=22 as limit (dotted line in Fig. 1). The difference in implication is that if the critical load at a particular site was 1.0 kEq ha^{-1}yr^{-1} of acidity using the *maximum allowable damage* principle, it will be approximately 0.3 kEq ha^{-1}yr^{-1} using the *precautionary* principle and something like 0.1 kEq ha^{-1}yr^{-1} for total risk elimination. The difference in policy is evident, the smaller the risk, the bigger the mitigation cost will be. It becomes clear that the economic cost of pollution mitigation is depending on the risk philosophy adopted. In the European critical loads mapping program, the *maximum allowable damage* principle was the one applied so far, even if this is not explicitly stated in any policy document. In many political arenas, the *precautionary principle* is frequently used in speech rhetoric, but when it comes to real policy, it generally becomes transformed into something based on the *maximum allowable damage* principle.

To estimate a critical load for nitrogen is more complex than it was for acidity, as nitrogen is both a necessary nutrient and a pollutant. In ecosystems, many plants interact in mutual competition, and the definition of its effect is confounded by the fact that nitrogen acts differently on different plants. The physiological effect of nitrogen on plants is modified depending on the competition in every new moment. However, nitrogen is only one of several strong factors affecting competition. A simple response diagram alone cannot be used, as it does not incorporate the effect of other factors nor includes competition in a way that makes it readable. Diagrams based on field observations are equally limited as they assume many parameters to be constant when they vary freely and somewhat without control relative to the observation, assumptions made to be able to reduce everything to simple plots. Fig. 2 shows on the left an example of a response diagram for blueberries with respect to average nitrogen soil solution concentration. Fig. 2 shows the combined effect of acidity (BC/Al-ratio in the soil solution) and nitrogen concentration in the soil solution for blueberries alone in the field (utan konkurrens=without competition). Next you find the response with 6 other plants present and competing with the blueberries (konkurrens). There is no easy way to use these diagrams to come up with a simple concentration limit for acidity or nitrogen to be entered into a simple mass balance type of calculation. Instead, we must use the full model to substitute for a simple diagram, as the diagram we seek is not any simpler and cannot be displayed on paper. The causal parameter is therefore defined as the nitrogen system input.

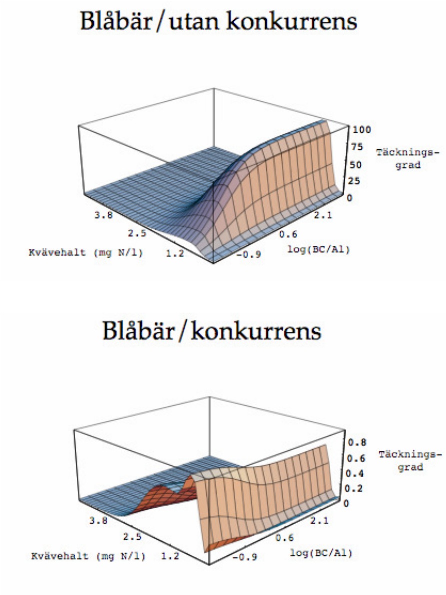


Fig. 2. *Simple example for blueberry showing the effect of plant response with (Swedish: konkurrens) and without competition (Swedish: utan konkurrens)*

The effect parameters are ecological and have several manifestations, and we will enter into a discussion of these below.

There is a widespread misunderstanding that plants in nature occupy their optimal range. Studies that record field occurrence of plants are used to try to define ”optimal” environmental ranges for plants. In reality, the inherent assumption behind this is almost never correct. All plants are in competition with other plants for the same room in the territory. Most of them occupy sub-optimal parts of their own potential range, because that is what they can get in the competition with other plants. The plants do not associate because they belong together, nor do they like each other, but their coexistence is caused rather from their competitive expression getting similar outputs under certain conditions. As soon as the site conditions change substantially, the plants in the associations will seem to fly apart as their competition strengths change differently and then they seem to create new plant associations. The plant in an association is in fierce competition with every other plant in that association. Thus, the composition of a plant association is not a constant property, it is an ecosystem output that is variable with time. The assumption of plant associations being a conserved variable is equivalent to assume that competition within the community is fixed at all times and cannot change. The assumption that competition in an ecosystem will stay constant forever is not correct. It is the dynamic competition that is the core essence of any ecosystem. In this study the association is generated as an output from the system simulations. It is not mathematically possible to untangle the field response of individual plants or plant groups back to individual plant responses, because the necessary information in terms of independent variables is not available in such observations. Thus, trying to observe optimal ranges from field studies, and use it to control plants in prediction models is not likely to capture the state at the critical load. Models based on such optimal ranges will risk giving predictions with strong errors. Thus, we need to use the intrinsic properties of each plant group, and then let it act into the competition with all the others.

3.3 Defining ”effect” and diagnostic biodiversity state variables

Biodiversity is defined in terms of many variables. In terrestrial ecosystems we have components such as:

- Plants
- Soil microorganisms
- Soil microfauna
- Insects
- Animals

All these live in a feedback web where single chemical limits no longer contain enough of the system property for a critical load determination. Along with this we have aspects of structure and habitat quantity and quality. We will be concentrating here on the ground vegetations components. The critical load is exceeded at the time, when the input of pollution has transgressed the limit where it will eventually lead to significant shifts in vegetation composition, abundance or the entry or departure of one or more plant groups. This will in many cases be well before such effects are actually observed, because of system delays. Thus, waiting for observation of effects in the field is a disaster-proposition, with such an approach, the countermeasure will always be too late with respect to a preventive strategy. Because no environmental decision has been made for how to define the limit for biodiversity in terrestrial ground vegetation communities at the present moment, we will test a series of proposals based on limitations in 3 different aspects of biodiversity and ecosystem protection:

1. The internal ecology of the vegetation, how relative abundance between groups are changed as competition strength is changed in the midst of everything else, by nitrogen pollution specifically

2. Conservation ecology, long term stability in species composition and presence, loosing resident or gaining immigrants by nitrogen pollution specifically

3. The primary production is changed by change in nutrient nitrogen supply, so, how much wood biomass change there is per unit land with change in nitrogen input

The first criterion is change in the abundance of the plant groups, and shifts in relative dominance. The ground vegetation is made up of trivial plants, and changes in these are much more readily predicted than rare or specialized species. Several ground vegetation groups are of great ecosystem interest, both as a component of biodiversity and for sustaining certain ecosystem functions. The rare species live in the environment of the trivial bulk vegetation groups, and their existence depend on the conditions provided by the presence of these groups, and with little or no substantial feedback on the dominant trivial vegetation groups. Thus, in order to predict rare species dynamics, trivial plant dynamics are a prerequisite. However, not only N determined the site abundance as expressed by fraction of the area occupied. This is also caused by long term changes in temperature, moisture and soil acidity. Another diagnostic change may be a change in the amount of biomass in the ground vegetation. The amount produced and maintained is dependent on nutrient availability, primarily pushed by P and N, limited when these are limited, but also potentially limited by base cations, acidity, drought or shadow. Traditional species richness is not really relevant as it counts all plants regardless of reference frames. A loss of 9 out of 10 species can be compensated for by a gain of 9 new plants. The richness index does not change, but the ecosystem does change a lot. The new approach is that we are no longer able to define unique and one-dimensional response diagrams that can be used to set simple single parameter limits from which we can calculate critical loads. Since the target is now a system-integrated output, biodiversity, only a system-integrated calculation will do. In this way the procedure is much simpler, we go straight from ecosystem effects via the integrated model to target state to get the critical load of pollutant:

ecosystem effect limit > integrated calculation > critical load

Traditional conservation ecology is preoccupied by number of resident species as a measure of biodiversity. We have defined that the plant groups take the place of species in our assessment, all in order to make it feasible in terms of calculation and quantitative estimate. We may set a limit for how many plant groups we allow to disappear, before we say stop based on our protection philosophy. At the same time, the invasion of one or more new plant groups may also be undesirable, and we may set limits for it. However, climate change may be a significant driver for biodiversity change, as many European plants are limited by temperature and climate towards the north. Thus, increased nitrogen input may have a similar effect to climate warming. A critical load estimate should take all of the factors discussed into account. We propose numbers on the aspects proposed as follows:

1. A shift in composition by more than x % for each aggregate group
2. A change in ground vegetation biomass index by more than y %
3. The loss of z number or more of existing plant groups
4. The entry of w number or more of new plant groups

The aggregate groups may as a first approach be plant types such as lichens, mosses, heatherling, grasses, herbs and bushes. We may also use groupings into dominant, sub-dominant and minor groups as the aggregate groups. Finally, we may use each and all of the defined groups on the list. To set the limiting value on the limits to change x, y and z is a separate issue, as well as to iterate by changing the percentages stepwise and taking out the highest nitrogen deposition that does not exceed these change limitations. The ground vegetation community is sorted into three groups: dominant, sub-dominant, and marginal (Figure 3). The classification is carried out based on the percent cover of the different species present at a certain site. The dominant group can contain one to three species or plant types, occupying at least 50% of the site cover. The marginal group represents species or plant types occupying at most 10% of the site cover. The subdominant group represents at most the remaining 40% of the site cover or any fraction under the dominant cover and higher than 10%. If the total cover of the marginal and subdominant plant species or types is below 20%, both are treated as a marginal group. The distribution in Figure 3 relates the modeled composition of the ground vegetation community to the traditional plant associations, without having to follow the exact definition of these associations. For example, trivial changes in the % cover of blueberries in a blue berry type association would still preserve the integrity of the habitat. On the other hand, having a specific class for marginal species would allow the methodology to detect changes in rare or red-listed species as well as eventual invasions by species or plant types which were not present at the original association. Plant species or types in the marginal group have the potential of displacing or disturbing the dominant group or the marginal group, but may still oscillate within small enough margins that they do not cause a shift in association. The criteria of change were defined for each of the three vegetation classes in Figure 3. At this stage, two scenarios of limits are proposed for the dominant class and will be tested numerically as described below before one of the two scenarios is adopted. Firstly, the cover of the dominant class should not be allowed to be reduced by either 30% (scenario 1) or 50% (scenario 2) and at the same time (valid for both scenarios) no shift in the dominant species or plant type (with the largest area cover) is allowed. Secondly, the total cover of the subdominant class should not be allowed to double or be reduced by half, and no shift in the species or plant types making up this class should occur. Thirdly, no loss or incursion of species or plant types should be allowed in the marginal class. Within these limits the vegetation is allowed to change without it being considered undesired change.

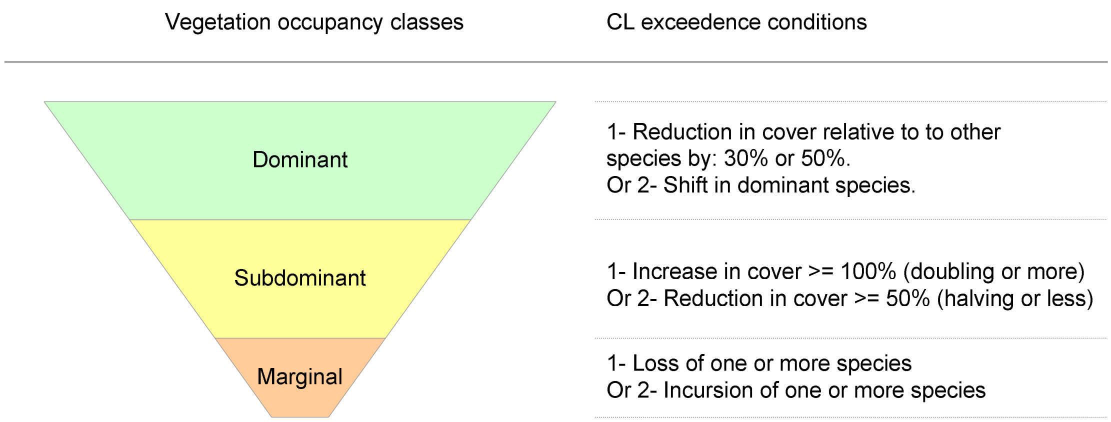


Figure 3: *plant species or types distribution based on % cover and the group specific criteria for acceptable limits of change.*

4. Finding the critical load calculation method for biodiversity

The basis for carrying out calculations for critical loads of acidity and nitrogen based on biodiversity will be the ForSAFE-VEG model. The guidelines described above will be tested initially using the ForSAFE-VEG model according to the algorithm in Figure 4. The validity of the model and its reliability are investigated in parallel efforts and will not be discussed in this report. Initially, the theoretical composition of the ground vegetation under background N deposition and historical (real) trends of climate, land use and other elements deposition will be estimated by the model (right part in Figure 4). Subsequently, a loop (left side in Figure 4) will use the model to simulate the composition of the ground vegetation under different N deposition levels. The N deposition levels will start at the background level plus an increment step that defines the resolution of the CL calculations (the smaller the steps, the higher the resolution). The simulated vegetation community will be compared with the reference level, and as long as the criteria for CL exceedance are not fulfilled the deposition is incremented and the comparison carried out again. This loop will run until a deposition is found which produces a ground vegetation community sufficiently different from the reference community (i.e. fulfills at least one of the criteria as defined in chapter 3.3). The N deposition at this stage will be taken as the critical load of N. The change in the composition of the ground vegetation community is evaluated against a reference community. This later is the composition under background N deposition but including historical changes in climate, land use and the deposition of other compounds (such as SO_4^{2-}). The background N deposition is defined as the total pre-industrial deposition of reduced and oxidized nitrogen compounds. Obviously, the reference composition is a theoretical community composition, but it is used to isolate the change in the composition caused by N deposition. Linking the reference level to the background N deposition implies that we are trying to protect or revert to the vegetation communities under pre-industrial N deposition conditions, but still under today's climate, land use, and other elements' deposition.

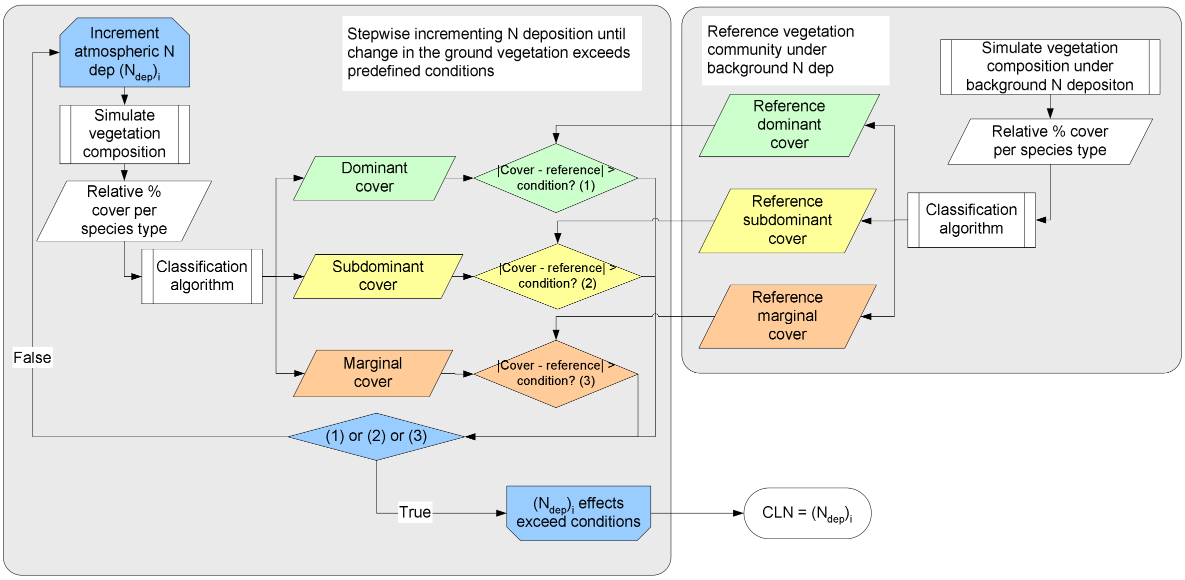


Figure 4: *Proposed algorithm for calculating critical loads of N based on divergences of the composition of the ground vegetation from the reference community.*

The critical loads estimation methodology will be the following flow of work:

1. **The standard run.** Initialize and calibrate the ForSAFE-VEG model with today's inputs to have a calibrated version for each site; the standard S and N deposition history until present, this is the **standard** run. The calibration parameters are kept from this particular run for all the other runs after this. For climate change we use the A2 scenario as defined by IPCC.

2. **The reference run.** We run the ForSAFE-VEG model with all parameters and the calibration set of initial values from the **standard run** to establish the reference ground vegetation composition for a pollution and climate change unaffected version of the site. The reference settings should be:

    1. Acidifying input to be maintained at the at no more than 1860-1880 level
    2. The nitrogen deposition rising with time to the baseline nitrogen deposition at 1860-1880 level
    3. The forest management and net harvest volumes rising to the present and continuing at the planned long term future level or as limited by sustainability based on supply of N, P, K, Mg and Ca.
    4. Some driver parameters as set to fixed trajectories in the basic run:
        - No climate change after 1900
        - Wildlife management with present history and present level
        - Forest fires as present history and kept at present level

3. **Iteration runs.** A set of runs used to show how the nitrogen depositions violate the critical load criteria stepwise from the background level up to the present deposition. The calibrated initial values from the standard run are then used for all other runs as initial starting values, and no calibration is done on the following scenarios. Forest fires and wildlife management are been set with present history and level. The minimum set of iterations would be:

    1. normal history S to 2010, then CuL[5] S, no N, and climate change
    2. normal history S to 2010, then CuL S, 33% of CuL N, and climate change
    3. normal history S to 2010, then CuL S, 66% of CuL N,
    4. normal history S to 2010, then CuL S, 100% CuL N and climate change (Standard run)

    The output is used to interpolate the critical load for CuL N is the current legislation deposition. For S this is close to or at critical load in this area.

4. **Set critical loads for N**
    Record the lowest nitrogen deposition that did not cause violation of one or more of the criteria; this is the critical load of nitrogen for biodiversity.

Adoption of these points has some ramifications that need to be realized and discussed.

- Maintaining the acidifying input at critical load implies that we believe that the present policy will ultimately lead to critical loads being achieved. For S this seems a likely scenario. That critical loads will be reached by 2010 in Europe is not certain. Especially, the mitigation of agricultural and automotive emissions of nutrient nitrogen has several tough hurdles to pass.

- Adopting the minimum of present harvest and sustainable harvest assumes that the forest industry will succeed in adapting to sustainability practices, which is not done at the moment. The realization of the need and the will to do the required substantial measures has not yet passed the rhetorical level within the forest research community as well as in the forest industry.

- The nitrogen critical load is not an independent parameter. It depends strongly on forest management and the total system input of all acidifying pollutants. The effect of the acidity carried with the nitrogen into the system is embedded in the approach.

- A separate iteration design is required to properly find the effect and critical load due to acidity input alone. Since nitrogen generates both acidity and eutrophication effects in the same dose, the issue is not straightforward to solve. This issue was outside the scope of our study.

- The present model does not include ozone impacts on trees or ground vegetation. The phosphorus balance and the impact of phosphorus on biodiversity are not yet included.

[5] CuL is deposition according to **Cu**rrent **L**egislation

To a smaller degree it also depends on the trajectory of the climate change scenario. This makes the critical load less simple to interpret, and may lay bare goal conflicts in forestry, acidifying pollution and nitrogen mitigation policies, nature conservation policies and climate change mitigation policies. A similar methodology may be devised for establishing the critical load of acidity for biodiversity. The difference is that we no longer can ignore and not address the effect of acidity or climate change on what nitrogen causes.

5. The model in outline: ForSAFE-VEG

Several factors are known to have a strong effect on biodiversity, and these are fully coupled in the natural ecosystem, complicating our task considerably. In a forested landscape, these are:

1. Nitrogen
2. Acidity
3. Forest management
4. Climate change

These have roughly equal importance for the biodiversity, and none can be ignored without significant implications. Any method we use must be able to handle the effect of these on biodiversity and reasonably well describe their effect in the system. A full description of ForSAFE is available in Sverdrup et al. (2007), Belyazid et al (2006, 2007) and in the PhD thesis of Belyazid (2006). The integrated FORSAFE-VEG model includes the following ecosystem components (April 2008):

1. The tree vegetation layer (canopy, stems, roots)
2. The ground vegetation layer
3. The soil chemistry and geochemical processes
4. The soil stocks and cycling of nutrients (Ca, Mg, K, P, N) and carbon
5. The soil hydrology and energy balance
6. Effluents from the system: carbon dioxide, Dissolved Organic Carbon, solution chemistry

In order to synthesize an integrated multiple stress system, ForSAFE-VEG provides simultaneous predictions of ecosystem effects of climate change, soil acidification and eutrophication with vegetation changes on forest growth, cations, acidity, nitrogen and carbon cycling. ForSAFE contains fully mechanistic nitrogen- and carbon cycle sub-models as well as predictions of forest growth under production management. The ground vegetation composition in a forest or field is determined by a number of **drivers** in the submodel VEG:

1. Soil solution nitrogen activity (kmol m^{-3})
2. *Soil solution phosphorus activity (kmol m^{-3})*
3. Soil chemistry in terms of acidity, antagonists and co-agents: ([H^+], [BC^{2+}], [Al^{3+}])
4. Soil water activity (soil moisture, m^3 water m^{-3} soil)
5. Site soil temperature (^oC), *including wind chill effects (m s^{-1})*
6. Light reaching the ground (micromol photons m^{-2} s^{-1})
7. Grazing by ungulents (moose units/km^2)
8. *Wind tatter, mechanically damaging soft tissue plants (m s^{-1})*
9. *Direct effect of gases (SO_x, NO_x, CO_2, O_3)*
10. Forest fires

11. Forest management

Factors in *italics* are not fully activated in the model yet. An important feature of the ForSAFE-VEG model is that the plants have to compete for their share of the territory. The drivers act to give each plant group a competition strength. The competition is made up of the following elements where the individual plant groups have feedback on the drivers, affecting partly itself and some specifically other plants:

1. The above-ground competition strategy of the plant group for capturing light and preventing others from getting it, is depending on plant height and its shading capacity.
2. The root competition strategy is for capturing water and nutrients, as well as exposure to soil chemistry (H^+, Al^{3+}, BC^{2+}), expressed through root distribution in different soil depths, to take up nutrients competitively.

The competition strength is the weight each group has when the territory claim assigned to a plant group is determined. The plant group then must use this and the passage of time to take that much of the territory. Phosphorus has been conceptualized and only partly parameterized, but still remains to be integrated into the model and the parameterization validated. The plant groups are assumed to be groups of plants with identical responses to all parameters. Indicator plant species are identified for each group. At present we have the ability to consider many tree species as seedlings and as mature trees, in addition to ground vegetation groups. Tree mixes are being integrated at the moment of writing; inter-species tree competition beyond the juvenile stage has not yet been fully integrated into the model.

At present the ForSAFE-VEG model handles ground vegetation and trees, only an aspect of biodiversity. Development work is ongoing to make this more complete. The ForSAFE-VEG system can at present handle the following ecological functional groups:

1. Trees
2. Bushes and shrubs
3. Ground vegetation
    a. Lichens
    b. Mosses
    c. Grasses
    d. Herbs and flowers
    e. Brackens
4. Soil biology
    a. Collemboles
    b. Earthworms
    c. Mollusks and snails
5. Soil functions
    a. Organic matter decomposer bacteria
    b. Organic matter decomposing fungi
    c. Nitrifiers
    d. Denitrifiers
6. Insects
    a. Stationary insects of the forest canopy
    b. Insects of dead wood and tree bole habitats
    c. Insects of the soil habitat

Items in *italics* have been conceptually framed in equations, but not yet included in the model. Items in *blue italics* have been framed in equations, but not yet parameterized. For collemboles, earthworms, the coefficients of the equations have been preliminarily parameterized. The normal lettered ones are fully integrated in the model with full environmental responses parameterized and field tested in Sweden, Iceland and Switzerland. The ForSAFE-VEG model does at present not address aquatic systems. The ForSAFE-VEG development is run as an open process, and the model is generally available to any.

The VEG model parameterization

The plant group parameterization for this study was carried out in two steps. It is an integral part of the development process within VEG, and the setting of the parameters automatically calls up the response functions for a reasonability test. In order to parameterize, the ecologists involved fully understood the feedbacks of the model and the implication of the formulation of the response functions. First the Swedish parameter list for 43 plant groups were set by using literature data and unpublished data from plant ecologist colleagues in the group of Prof. Bengt Nihlgård, Department of Plant Ecology at Lund University, collected and edited by Harald Sverdrup. Next the remaining empty slots in the parameter list was complemented by Professors Bengt Nihlgård from Lund University, Prof. Lars Ericson at Umeå University and Harald Sverdrup from Lund University in Sweden, in a Deplhi process where expert knowledge was used to scale the unknowns between the knowns. In a second process, further 5 grasses were parameterized for a Danish plant functional group list with the help of Prof. Sven Jonasson at Plant Ecology at Köbenhavn University. A list of 24 plants groups is also available for Iceland, this list has also a good overlap with the Swedish list.

For Switzerland, first a subset of the Swedish list found to be relevant for Switzerland was transferred to the Swiss list (Table 1). This was based on the fact that many plants are common to both Switzerland and Sweden. Next a full list of 89 Swiss functional groups was defined by Prof. em. E. Landolt of ETH-Z and Prof. Em. Bengt Nihlgård, a some responses filled in with parameter values derived from available published data. Finally the remaining empty slots in the Swiss plant group parameter list was complemented by E. Landolt from ETH-Z and Bengt Nihlgård and Prof. Harald Sverdrup from Lund University, and Dr. Sabine Braun from IAP, Basel, in a Deplhi process where expert knowledge was used to scale the unknowns between the knowns. A third step was that some adjustment was made to the original Swedish parameters in both the Swiss and the Swedish lists, as the added experience from field studies in Switzerland modified the picture of responses and justified some adjustment to the light sensitivity of Oxalis *acetosella* and Rubus *fructicosa* in particular, and a general increase in shade tolerance to all the grasses.

Table 1. *The Swiss plant group parameter list.*

Latin name	yrs	a0	k+	w+	k-	w-	kbc/al	kbc	kph	W min	W top	W max	T min	T top	T max	L min	L max	h(m)	height	k (P)	k (G)
Dicranella heteromalla	20	1	0.05	1	1000	0	0.2	0	3000	-0.1	0.15	0.5	0	8	15	500	4000	0.01	0	2	0
Hylocomium mosses	20	1	0.03	1	1000	0	0.07	150000	1050	0.05	0.15	0.35	-1	7	15	100	2750	0.02	0	3	0
Leucobryum glaucum	20	1	0.01	1	0.1	1	0.2	0	3000	-0.1	0.15	0.35	2	10	18	100	2750	0.02	0	3	0
Mnium mosses	20	1	0.3	2	1000	0	0.4	0	6000	0.15	0.25	0.6	0	8	16	100	2500	0.02	0	3	0
Polytrichum formosum	20	1	0.03	1	0.1	1	0.6	0	90000	-0.1	0.15	0.5	0	8	15	100	2500	0.03	0	2	0
Sphagnum mosses	20	1	0.03	1	0.1	3	0.01	150000	150	0.4	0.6	1	-1	7	15	100	2500	0.02	0	1	0
Calluna vulgaris	30	1.4	0.2	1	3	3	0.2	0	3000	-0.25	0.15	0.4	-1	7	15	500	5000	0.25	2	1	0.7
Rhododendron ferrugineum	10	1	0.03	2	1000	0	0.2	150000	3000	0.25	0.35	0.5	-1	5	9	1000	3500	0.5	2	1	0
Rubus fruticosus	10	1	1	2	1000	0	1	0	20800	0.15	0.25	0.4	3	11	19	100	3000	1	2	2	9
Rubus idaeus	5	1	1	2	1000	0	1	0	15000	0.15	0.25	0.4	2	10	18	1500	5000	0.8	2	3	9
Salix caprea	30	1	0.5	2	1000	0	0.5	0	9000	0.15	0.35	0.6	-1	5	11	1000	4000	1.2	3	1	9
Vaccinium myrtillus	10	1.6	0.1	1	0.1	3	0.1	0	1500	-0.1	0.15	0.5	-1	5	11	100	2000	0.3	1	1	2.3
Vaccinium vitis-idea	15	1.6	0.03	1	0.003	3	0.35	0	5250	-0.2	0.1	0.45	-1.5	4.5	10.5	500	4000	0.15	1	1	0.7
Agrostis capillaris	10	1	0.5	2	1000	0	0.2	0	3000	0.05	0.15	0.5	3	11	19	750	4000	0.25	2	3	2.3
Brachypodium pinnatum	5	1	20	2	1000	0	6	0	90000	0.1	0.2	0.35	3	11	19	1000	3500	0.5	1	3	9
Bromus benekenii	5	1	20	2	1000	0	12	0	180000	0.1	0.2	0.4	5	13	21	250	3000	0.6	2	30	9
Calamagrostis arundinacea	5	1	0.5	2	1000	0	1.8	0	20800	0.1	0.2	0.4	2	10	18	750	3500	0.5	2	3	0.7
Calamagrostis villosa	5	1	0.05	2	3	1	1	0	20800	0.15	0.25	0.5	1.5	9	16	750	3500	0.6	2	1	0.7
Carex pendula	5	1	1	2	10	1	6	0	90000	0.2	0.4	0.6	1	9	16	250	3000	0.5	2	1	2.3
Carex pilulifera	5	1	0.05	2	0.1	1	1	0	20800	0.05	0.15	0.5	-1	7	15	250	3000	0.1	1	1	2.3
Deschampsia cespitosa	5	1	0.5	2	1000	0	0.2	0	3000	0.15	0.35	0.6	3	11	19	1000	5000	0.35	2	3	0
Deschampsia flexuosa	5	1	0.05	2	1000	0	0.13	6	1950	0.05	0.15	0.3	-1	7	15	250	3000	0.2	2	3	2.3
Festuca ovina sl	10	1.4	0.02	2	10	1	0.1	0	1500	-0.25	0.05	0.25	3	11	19	1500	5000	0.1	1	30	0.7
Hordelymus europaeus	5	1	0.5	2	5	1	6	0	90000	0.15	0.25	0.5	3	11	19	100	2000	0.4	2	2	2.3
Milium effusum	5	1	20	2	1000	0	8	0	150000	0.15	0.45	0.6	5	15	20	250	3000	0.5	2	3	9
Molinia caerulea	5	1	1	2	1000	0	0.2	0	3000	0.2	0.3	0.45	5	13	21	1000	5500	0.4	2	30	2.3
Nardus stricta	10	1.2	0.05	2	10	1	0.2	150000	3000	0.15	0.25	0.4	0	8	16	1500	5000	0.15	2	1	0
Poa nemoralis	5	1	5	2	1000	0	8	0	120000	0.05	0.1	0.2	2	10	20	1250	5000	0.4	2	3	9
Athyrium filix-femina	20	1	0.05	2	5	1	1	0	20800	0.15	0.35	0.5	-1	7	15	150	2500	0.4	2	1	0
Blechnum spicant	20	1	0.05	2	3	1	0.6	0	9000	0.15	0.35	0.5	3	11	19	175	2000	0.15	1	1	0
Dryopteris dilatata coll	20	1	0.5	2	1000	0	2	0	30000	0.1	0.3	0.5	3	11	19	150	2500	0.4	2	1	2.3
Lycopodium annotinum	5	1	0.01	2	0.003	1	0.6	0	9000	0.15	0.35	0.6	-1	7	15	150	2500	0.15	1	1	0
Pteridium aquilinum	20	1	0.5	2	1000	0	12	0	180000	0.05	0.2	0.3	2	8	18	750	3250	0.5	2	1	0
Aconitum lycoctonum	20	1	5	2	1000	0	10	0	150000	0.25	0.55	0.9	2	6	10	1000	5000	1	2	1	0
Adenostylus alliaria	5	1	1	2	1000	0	6	0	200000	0.2	0.35	0.4	1	9	17	500	3000	0.5	2	1	9
Allium ursinum	2	1	20	2	1000	0	40	0	600000	0.25	0.2	0.6	4	12	20	250	5000	0.25	2	30	0
Anemone nemorosa	10	1	0.5	2	1000	0	0.8	0	12000	0.2	0.3	0.4	2	10	18	250	3500	0.15	1	3	2.3
Antennaria dioica	5	1	0.01	2	1000	0	0.1	0	1500	0.05	0.1	0.2	0	6	12	2000	5500	0.01	1	1	0
Arnica montana	5	1	0.01	2	1000	0	0.6	0	9000	0.05	0.1	0.2	7	15	20	2000	5500	0.01	1	1	0
Cicerbita alpina	5	1	1	2	1000	0	12	0	200000	0.2	0.3	0.5	1	9	17	1250	5500	0.4	1	1	2.3
Circaea lutetiana	5	1	1	2	10	1	12	0	200000	0.15	0.25	0.5	3	11	19	500	3000	0.2	1.5	1	0.7
Dentaria pentaphyllos	5	1	0.05	2	3	1	12	0	200000	0.15	0.3	0.5	3	11	19	375	3000	0.2	2	1	0
Epilobium angustifolium	5	1	1	2	1000	0	2	0	30000	0.15	0.2	0.3	0	8	20	1750	5500	0.8	2	3	32
Equisetum hyemale	15	1	0.05	2	3	1	12	0	200000	0.2	0.25	0.6	0	8	16	375	3000	0.3	2	1	0
Equisetum sylvaticum	15	1	0.05	2	3	1	0.3	0	3000	0.2	0.4	0.6	2	10	18	375	3000	0.3	2	1	0.7
Galium odoratum	3	1	5	2	1000	0	1.2	0	18000	0.15	0.25	0.4	3	11	19	250	3000	0.15	1	1	0.7
Geranium robertianum	3	1	1	2	1000	0	6	0	90000	0.15	0.25	0.4	-1	7	16	500	3000	0.15	1	2	9
Geranium sylvaticum	3	1	1	2	1000	0	1.8	0	27000	0.15	0.25	0.4	2	10	14	500	3000	0.5	2	3	9
Hedera helix	30	1	1	2	1000	0	6	0	90000	0.15	0.25	0.5	3	11	19	500	3000	1.2	3	1	0.7
Hepatica nobilis	20	1	1	2	1000	0	8	0	120000	0.15	0.25	0.4	2	10	18	375	3000	0.5	1	3	0
Impatiens glandulifera	5	1	1	2	10	1	12	0	200000	0.2	0.3	0.5	4	12	20	600	3500	1	1	1	0.7
Impatiens noli-tangere	5	1	0.5	2	5	1	6	0	90000	0.2	0.3	0.5	3	11	19	500	3000	0.6	1	1	0.7
Luzula luzuloides	5	1	0.03	2	0.1	1	0.3	0	3000	0.1	0.25	0.4	0	8	16	375	3000	0.2	1	1	0.7
Luzula sylvatica	5	1	0.05	2	3	1	0.3	0	3000	0.15	0.25	0.5	2	10	18	500	3000	0.3	1	1	0.7
Mercurialis perennis	5	1	5	2	1000	0	2	0	30000	0.1	0.25	0.4	5	15	20	500	3000	0.5	1	1	0
Origanum vulgare	20	1	0.5	2	30	1	10	0	150000	0.05	0.15	0.25	4	12	20	1500	6000	0.04	2	3	0.7
Oxalis acetosella	2	1	0.5	2	1000	0	0.2	0	3000	0.1	0.2	0.7	0	8	18	100	2500	0.05	1	1	0
Ranunculus lanuginosus	5	1	0.5	2	5	1	6	0	90000	0.15	0.25	0.5	4	12	20	375	3000	0.2	2	1	0.7
Sesleria coerulea	5	1	0.05	2	0.1	1	6	0	90000	0.1	0.25	0.5	3	11	19	1500	6000	0.2	2	1	0.7
Trifolium repens	5	1	1	0	1000	0	1.3	0	19500	0.2	0.35	0.4	5	15	25	1250	5500	0.3	2	1	32
Urtica doica	5	1	5	2	1000	0	10	0	150000	0.15	0.25	0.45	2	10	20	500	5000	0.8	1	3	0.7
Abies alba	60	1	0.05	2	3	1	0.36	0	5000	0.18	0.28	0.5	1	9	17	600	2000	0.1	3	1	0.7
Acer pseudoplatanus	80	1	0.5	2	5	1	0.25	0	3500	0.18	0.28	0.5	2	12	18	800	2800	0.1	3	1	9
Alnus glutinosa	30	1	0	0	1000	0	1.2	0	12000	0.2	0.3	1	2	10	18	500	3500	0.1	3	1	0.7
Alnus incana	30	1	0	0	1000	0	6	0	90000	0.2	0.3	1	0	8	16	500	3500	0.1	3	1	0.7
Alnus viridis	30	1	0	0	1000	0	1.2	0	12000	0.2	0.3	1	-1	7	17	1200	5000	0.1	3	1	0.7
Betula pendula	60	1	0.01	2	3	1	0.28	0	3750	0.15	0.25	0.5	-2	10	14	1000	2600	0.1	3	1	9
Carpinus betulus	100	1	0.05	2	3	1	0.4	0	6000	0.15	0.25	0.5	3	11	19	800	2500	0.1	3	1	2.3
Castanea sativa	90	1	0.05	2	3	1	0.25	0	3000	0.15	0.25	0.5	7	15	23	500	3500	0.1	3	2	0.7
Fagus sylvatica	100	1	0.05	2	3	1	0.3	0	4200	0.15	0.25	0.5	3	11	19	600	2600	0.1	3	1	9
Fraxinus excelsior	80	1	0.05	2	5	1	6	0	90000	0.15	0.25	0.6	4	12	20	1200	2600	0.1	3	2	9
Ilex aquifolium	70	1	0.05	2	3	1	1.2	0	12000	0.15	0.25	0.5	10	18	26	400	2400	0.1	3	1	0
Larix decidua	60	1	0.05	2	3	1	0.6	0	9000	0.15	0.25	0.5	-1	7	15	800	2700	0.1	3	1	9
Ostrya carpinifolia	30	1	0.05	2	0.1	1	6	0	90000	0.1	0.2	0.5	7	15	23	800	2500	0.1	3	2	9

Latin name	yrs	a0	k+	w+	k-	w-	kbc/al	kbc	kph	W min	W top	W max	T min	T top	T max	L min	L max	h(m)	height	k (P)	k (G)
Picea abies	60	1	0.01	2	3	1	0.32	0	4500	0.15	0.25	0.5	-1	7	15	400	1700	0.1	3	1	0.7
Pinus cembra	80	1	0.01	2	0.1	1	0.32	0	4500	0.15	0.25	0.5	4	12	20	1000	2600	0.1	3	1	0.7
Pinus sylvestris	80	1	0.01	2	0.1	1	0.28	0	3000	0.05	0.15	0.5	-1	7	15	600	2200	0.1	3	1	0.7
Populus tremula	40	1	0.01	2	3	1	0.6	0	9000	0.1	0.2	0.5	3	11	19	1200	3500	0.1	3	1	9
Prunus laurocerasus	20	1	0.05	2	3	1	0.25	0	3500	0.15	0.25	0.5	4	12	20	600	2600	0.1	3	2	32
Prunus serotina	20	1	0.05	2	3	1	6	0	90000	0.15	0.25	0.5	10	18	26	600	2600	0.1	3	2	32
Quercus pubescens	100	1	0.05	2	3	1	0.3	0	4000	0.1	0.2	0.5	6	14	22	1000	2800	0.1	3	1	0.7
Quercus robur	120	1	0.5	2	5	1	0.25	0	3000	0.15	0.25	0.5	4	12	20	1000	2800	0.1	3	1	2.3
Robina pseudoacacia	60	1	0	0	1000	0	1.2	0	12000	0.1	0.2	0.5	7	15	23	500	3500	0.1	3	2	0
Sambucus nigra	8	1	1	2	1000	0	0.4	0	6000	0.15	0.25	0.5	5	13	21	1200	5000	0.1	2	3	32
Sorbus aria	20	1	0.05	2	0.1	1	0.6	0	90000	0.15	0.25	0.5	4	12	20	800	4000	0.1	3	3	9
Sorbus aucuparia	30	1	0.05	2	3	1	0.35	0	5000	0.15	0.25	0.5	-2	6	14	1000	4000	0.1	3	2	32
Tilia platyphylla	100	1	0.05	2	3	1	1.2	0	12000	0.15	0.25	0.5	4	12	20	1400	4000	0.1	3	3	9
Trachyspermum fortunei	30	1	0.05	2	3	1	1.2	0	12000	0.15	0.25	0.5	8	16	24	800	3000	0.1	3	2	0
Ulmus glabra	80	1	0.5	2	5	1	0.5	0	7500	0.15	0.25	0.5	4	12	20	1200	2600	0.1	3	2	9

6. Demonstration at two Swiss and two Swedish sites

Four different sites have been chosen for taking the runs apart for interpretation and for iteration of a critical load. We have chosen to study several diagnostic parameters for this assessment: wood biomass, ground vegetation composition and the soil base saturation at 30 cm depth. This investigation has been applied at the following sites, selected from the regional databases of Switzerland and Sweden:

- Switzerland
  - Aeschau with fir, spruce and beech
  - Bachtel, with spruce
- Sweden
  - Högbränna, Lappland, Northern Sweden with spruce
  - Söstared, Götaland, Southern Sweden with pine

The sites make a transect across Europe in all the fundamental aspects of the problem, and ought to provide an adequate testing ground for the concept. The average temperature range from -1.5 to 11 ^{o}C, the nitrogen deposition from 2 to 35 kg ha^{-1} yr^{-1}, forest growth rates from 1.5 to 15 m^{3} ha^{-1} yr^{-1}.

6.1 Taking the runs apart

A set of investigative runs for evaluating the effect of different drivers involved with the pollution inputs, acidity input by sulfur alone, nutrient nitrogen input alone and the climate drivers water and temperature. These are shown in Table 2. One purpose of the investigative runs is to establish the **reference scenario**, the level from which all differences are measured. Then the set of scenarios composed to show how the different drivers have cooperated to create the result.

First of all the **standard run** is done and the model calibrated. The calibrated initial values from the standard run are then used for all other runs as initial starting values, and no calibration is done on the following scenarios. So, the runs start at the same base saturation and initial soil pH as we had in the calibrated standard run with normal pollution and climate change. Forest fires and wildlife management are been set with current history and continued at present level. No S or no N implies that these have been kept at natural background levels.

Run	Figure code	S	N	Climate
Reference	Sce-0	-	-	-
Scenario-1	Sce-1	-	-	C
Scenario 2	Sce-2	-	N	C
Scenario 3	Sce-3	S	-	C
Standard	Sce-4	S	N	C
Scenario 5	Sce-5	S	N	-

Table 2. *S means normal trajectory of sulfur, N, normal trajectory of nitrogen deposition to 2010, after that current legislation deposition, C means climate change, - means we have background deposition or no climate change.*

Field validation of vegetation simulations

The model system is only calibrated on the present base saturation by adjusting the initial base saturation at the starting time for these runs it was set to 1750. The Swedish runs were initiated in 1450. After calibration against the present base saturation, all other outputs follow from mechanistic rules, molecular biology and mass balances, and nothing else is adjusted to make the runs look right. Thus from one single calibration, all other like soil chemistry, nitrogen cycle, carbon cycle, tree growth, C/N ratios, decomposition as well as the ground vegetation follow.

	Number of species	
Item	Aeschau	Bachtel
Modelled and observed	8	8
Modelled but not observed	5	9
Observed but not modelled	2	6
Observed, but not yet assigned to any model plant group	*4*	*10*

Table 3. *Comparison of number of modelled and observed ground vegetation species at the two Swiss sites of Aeschau and Bachtel.*

At the sites we have observed field cover of plants, in Sweden (Sverdrup et al 2007) and in Switzerland. These were used for checking performance of the VEG submodel (see Table 3 for two Swiss sites). The ForSAFE-VEG model runs predict a sensitive reaction of *Rubus fructicosus* cover to N deposition. This is confirmed by observations from the forest plots. With N deposition of >25 kg N ha^{-1} yr^{-1}, cover by *Rubus* increases. In plots with repeated ground vegetation assessment, the cover by *Rubus* increased significantly from 1984 to 2003, especially where it had been low before. This cannot be explained only by management as e.g. in the plot Bachtel tree cover even increased during this time period. More attention is made to the validation of other aspects in a separate chapter of this report by Braun et al.

Aeschau, the Swiss beech and fir/spruce forest

The site is located in central Switzerland, near Bern. The vegetation response to nitrogen and climate for this site is significant. The responses have been plotted in Figure 5. Sce0 is the reference from which we always estimate the change.

- Comparing Sce0 --- (The reference run) and Sce1-C shows the difference between the no pollution without and with climate change. It can be seen that the effect of climate change alone, cause significant biodiversity changes after year 2000.

- Comparing Sce1-C and Sce2-NC (no sulfur, but N and climate change) shows that nitrogen introduces a very fundamental change to the site from already early dates for both forest growth and ground vegetation responses. Already at 1812 the changes in terms of vegetation shifts are large. This already suggests that if the reference scenario is the goal standard for setting the critical load, then this will be quite low. The nitrogen increases the oscillations in the system outside its usual envelope of variations, it destabilizes the ecosystem.

- Comparing Sce1-C and Sce3-SC shows the effect of quite modest acidification alone. At this site, sulfur pollution alone, does not change the biodiversity very much. However, the pH at this site does not really move below pH 5.5 and we should expect no great effect for this setup of plants. At this site, most of the acid comes from deposition of nitric acid and conversion of ammonium in the soil. The acidity impact on the biodiversity is significant, but difficult to cleanly separate from the nitrogen effects.

- Comparing Sce0 --- (The reference run) and Sce4-SNC (The standard run) shows the full effect of nitrogen and climate change and that taken together, the impact from the past to now has been very dramatic. The impacts are evident already 150 years ago, suggesting that the critical load for biodiversity is very low.

- Comparing Sce4-SNC (The standard run) and Sce5-SN shows that the system is made less stable by the addition of climate change to the scenario after year 2000.

Figure 6 shows the response in forest wood biomass and base saturation at the Aeschau site. It can be seen that the effect of nitrogen on the growth is profound, after 1930 the effect is really overwhelming. The base saturation at the Swiss Aeschau site shows a more complex pattern. The onset of climate change makes the weathering rate increase. However, the effect is off-set by the effects of pollution at the site. Thus with sulfur only, it acidifies, and it recovers partly because of decreased input and partly because of more weathering after 2000. In the nitrogen input scenarios, the acid input is by far more than the increase of weathering can compensate for. The coloured bands in Figure 5 represent each a plant group, whereas the colored lines in Figure 6 represent the scenarios.

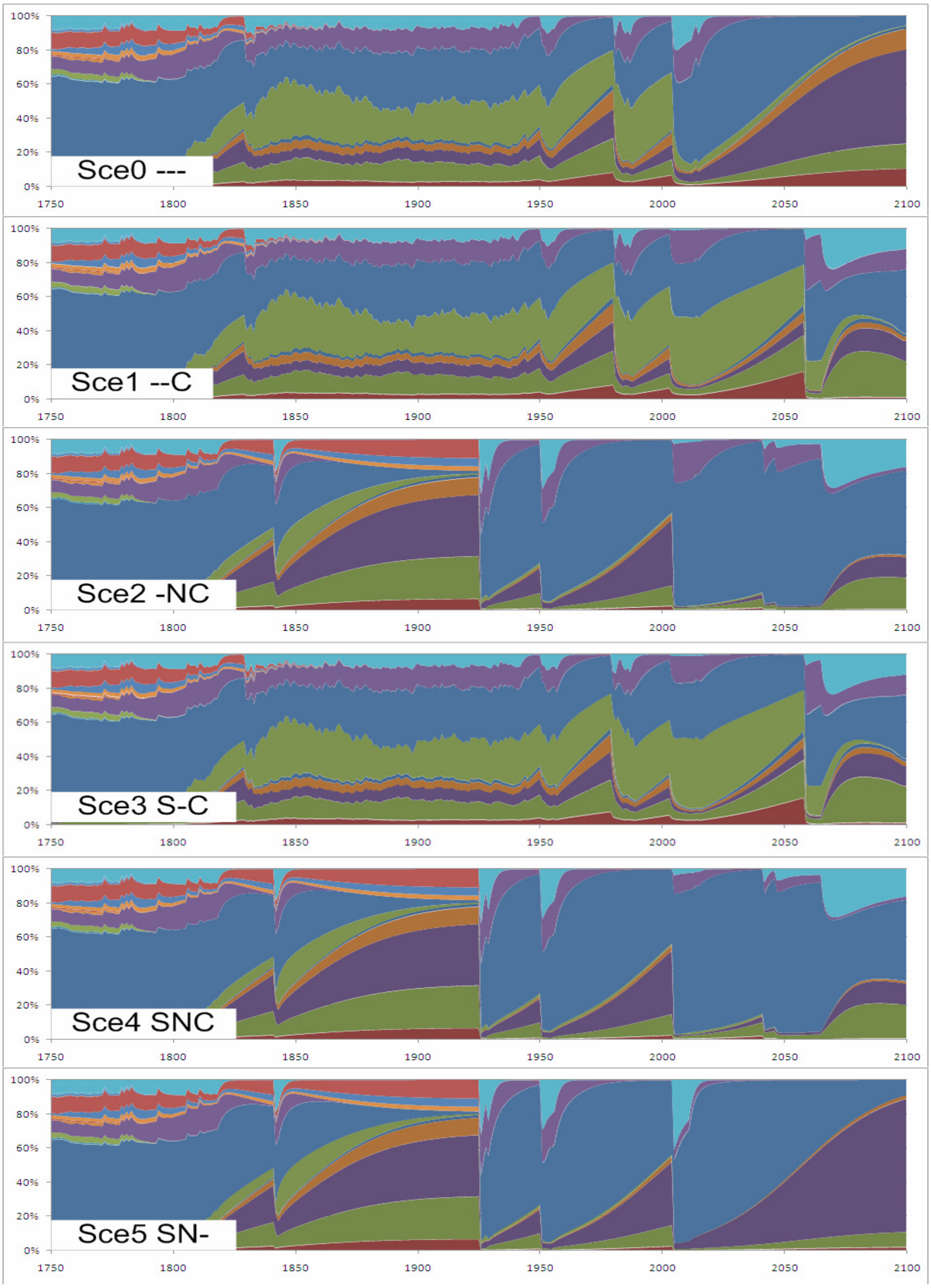
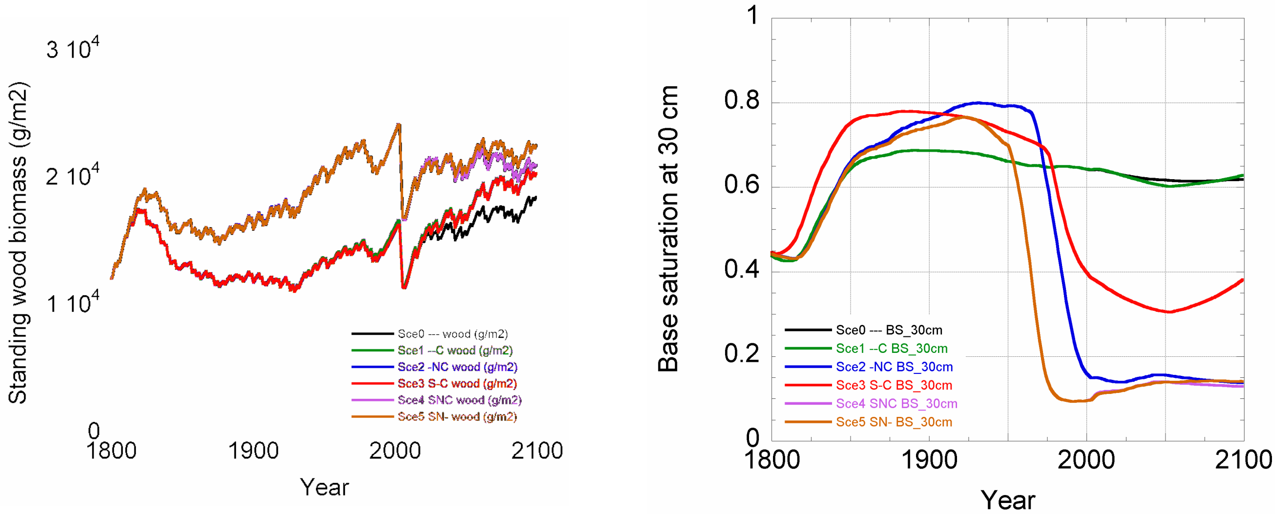


Figure 5. *Vegetation composition from 1750 to 2100 as predicted by the ForSAFE-VEG model at Aeschau. The colour bands represent different plant functional groups as defined in the plant legend for Switzerland (see Table 4).*



Run	Figure code	Color code	S	N	Climate
Reference	Sce-0		-	-	-
Scenario-1	Sce-1		-	-	C
Scenario 2	Sce-2		-	N	C
Scenario 3	Sce-3		S	-	C
Standard	Sce-4		S	N	C
Scenario 5	Sce-5		S	N	-

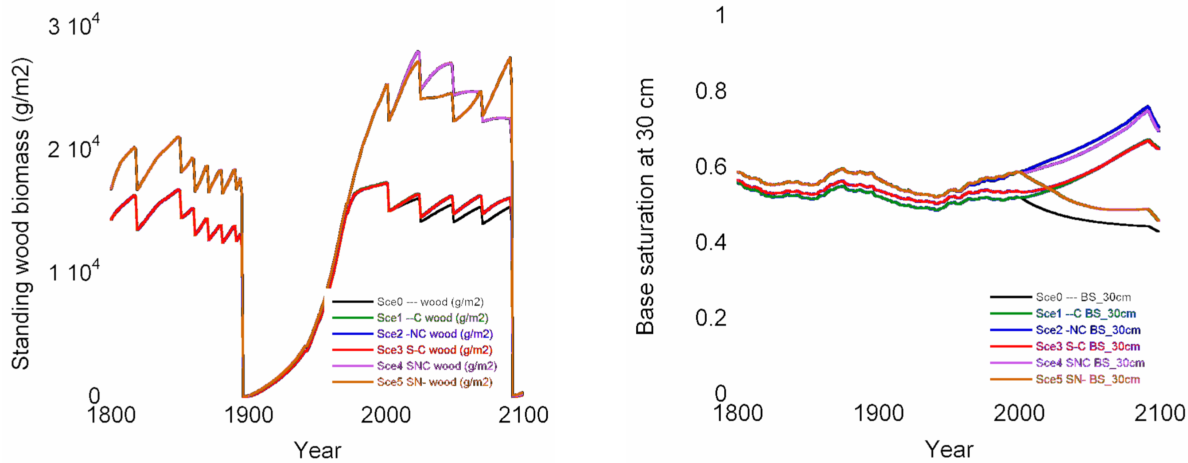


Figure 6. *The predicted wood biomass and the soil base saturation at 30 cm soil depth at Aeschau on top and Bachtel below. The Bachtel site does not get very acid in terms of pH, but the base saturation reach very low levels in some scenarios for Aeschau. In the middle, the key to read the scenarios.*

Bachtel, a Swiss spruce site

The Bachtel site near Zürich showed large responses. They are plotted in Figure 7. We may compare the runs as follows:

- Comparing Sce0 --- (the reference run) and Sce1--C, shows the difference between the no pollution without and with climate change. It can be seen that the effect of climate change alone, cause significant biodiversity changes after year 1970.

- Comparing Sce1--C and Sce2-NC (no sulfur, but N and climate change). It shows that nitrogen introduces a very fundamental change to the site from already early dates, 1840-1870, both for ground vegetation responses and for forest growth. This already suggests that if the reference scenario is the goal standard for setting the critical load, then this will be low for this site. The nitrogen makes the oscillations in the system pronounced already from the earliest moments (1850), and the amplitudes much larger, it destabilizes the ecosystem and lets it swing outside its usual envelope of variations. The addition of significant climate change after 2000 further increases the amplitude of the oscillations.

- Comparing Sce1--C and Sce3S-C shows the effect of sulfur alone. At this site, sulfur pollution acidity input alone is too small as compared to the weathering capacity for it to give any significant impact. The pH at this site does not really move below pH 6 and we should expect no great effect for this setup of plants. The total acidity input is much larger if S and N is considered and the site may possibly be exceeding the critical load for acidity based on biodiversity.

- Comparing Sce0 --- (the reference run) and Sce4SNC (the standard run) shows the full effect of nitrogen and climate change and that taken together, the impact from the past to now has been dramatic for this site. The biodiversity has been profoundly changed, the stability and variability in the system has fundamentally changed character. The impacts are evident already 150 years ago, suggesting that the critical load for biodiversity for preserving the original kind of biodiversity is very low.

- Comparing Sce4SNC (The standard run) and Sce5SN- shows that the system is made less stable by the addition of climate change to the scenario.

Only sulfur pollution alone will allow more forest growth by the setting free of more base cations in this time period. Adding climate change will help deplete the resources faster. The amount of wood biomass is also affected at this site as can be seen in Figure 6. The nitrogen determines the canopy size to a large degree, and there is an extra effect of climate change, albeit smaller. The effect on base saturation is less dramatic and the site is never really acidified. The two trajectories are caused by the onset of climate change and the positive change in base saturation shows the effect of more weathering caused by higher temperature.

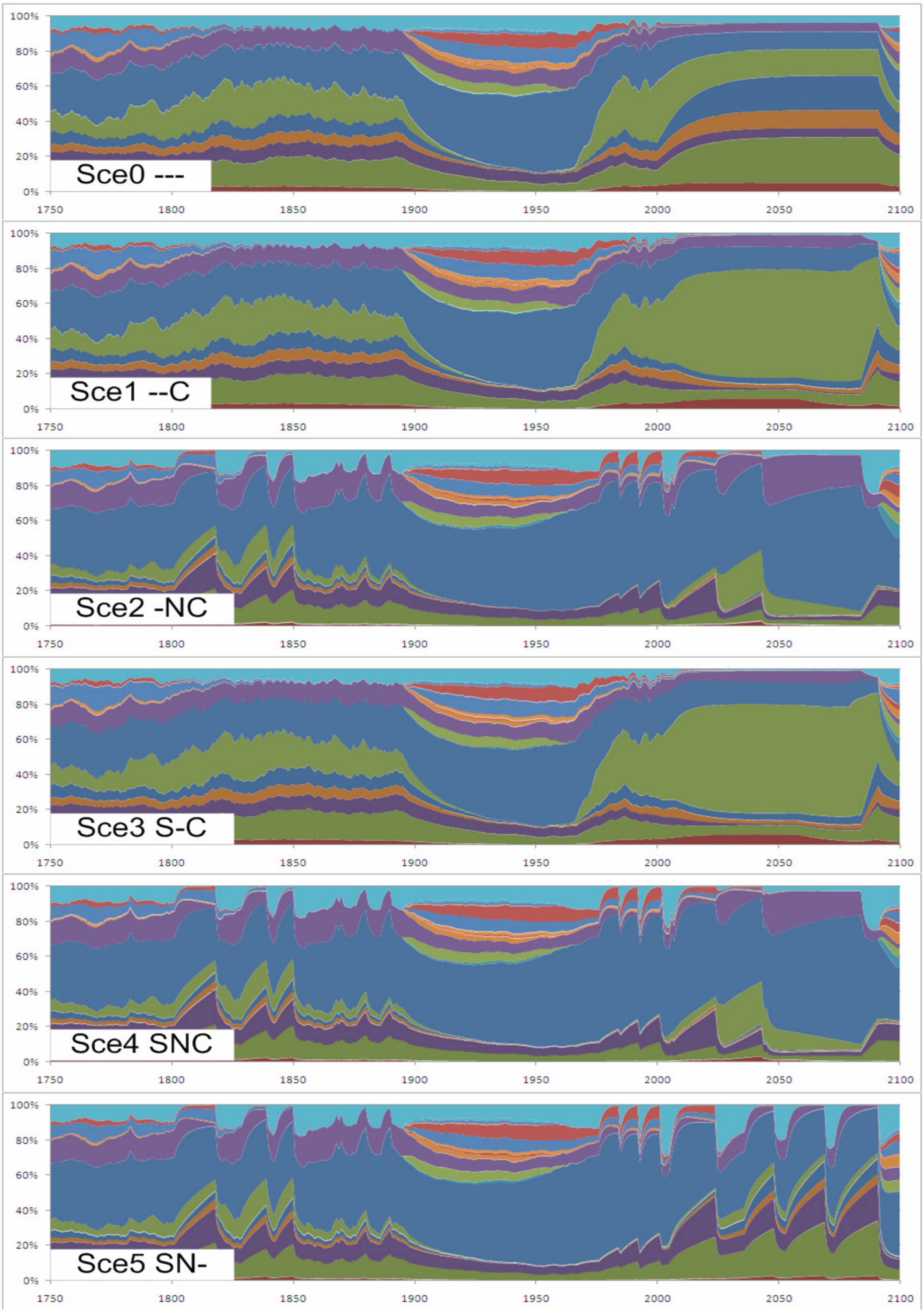


Figure 7. *Vegetation composition from 1750 to 2100 as predicted by the ForSAFE-VEG model at Bachtel site, with scenarios. The colour bands represent different plant functional groups as defined in the plant legend for Switzerland (see Table 4).*

Table 4. *Swiss functional plant group legend for the dynamic runs. For Switzerland we have 89 plant groups defined. The groups were determined in cooperation with Swiss plant ecologists. Each group represents plants with the exact same response function parameters for the drivers. Different species may inhabit the same group, only sharing driver parameter settings.*

Leucobryum_glaucum	Hylocomium_mosses	Mnium_mosses	Dicranella_heteromalla	Polytrichum_formosum
Sphagnum_mosses	Calluna_vulgaris	Vaccinium_myrtillus	Vaccinium_vitis-idea	Rhododendron_ferrugineum
Rubus_idaeus	Rubus_fruticosus	Salix_caprea	Agrostis_capillaris	Brachypodium_pinnatum
Bromus_benekenii	Calamagrostis_villosa	Calamagrostis_arundinacea	Carex_pilulifera	Carex_pendula
hordelymus	Deschampsia_cespitosa	Deschampsia_flexuosa	Festuca_ovina_sl	Milium_effusum
Molinia_caerulea	Nardus_stricta	Poa_nemoralis	Blechnum_spicant	Athyrium_filix-femina
Dryopteris_dilatata_coll	Lycopodium_annotinum	Pteridium_aquilinum	Aconitum_lycoctonum	Allium_ursinum
Anemone_nemorosa	Antennaria_dioica	Arnica_montana	Epilobium_angustifolium	Galium_odoratum
Geranium_robertianum	Geranium_sylvaticum	Hepatica_nobilis	Mercurialis_perennis	Origanum_vulgare
Oxalis_acetosella	Trifolium_repens	Adenostylus_alliaria	Luzula_luzuloides	Sesleria_coerulea
Dentaria_pentaphyllos	Equisetum_hyemale	Equisetum_sylvaticum	Circaea_lutetiana	Hedera_helix
Impatiens_glandulifera	Impatiens_noli-tangere	Luzula_sylvatica	Cicerbita_alpina	Ranunculus_lanuginosus
Urtica_doica	Tilia_platyphylla	Sambucus_nigra	Sorbus_aria	Sorbus_aucuparia
Alnus_glutinosa	Alnus_incana	Alnus_viridis	Betula_pendula	Carpinus_betulus
Fagus_sylvatica	Quercus_robur	Quercus_pubescens	Castanea_sativa	Prunus_serotina
Prunus_laurocerasus	Acer_pseudoplatanus	Ostrya_carpinifolia	Robina_pseudoacacia	Trachyspermum_fortunei
Populus_tremula	Ilex_aquifolium	Ulmus_glabra	Fraxinus_excelsior	Abies_alba
Picea_abies	Pinus_cembra	Pinus_sylvestris	Larix_decidua	

Söstared, a site in southern Sweden

The Söstared site showed large responses. They are plotted in Figure 9. We may compare the runs as follows

- Comparing Sce0 --- (The reference run) and Sce1--C shows the difference between the no pollution without and with climate change. In Sce0 we can see the strong effect of management at this site. The site is rich in biodiversity and this is changed, but not damaged by the management. And the changes appear to be reversible. Adding climate to the scenario introduce some permanent changes which are large and profound in their nature. There is a shift in dominant species and several new enter the scene.

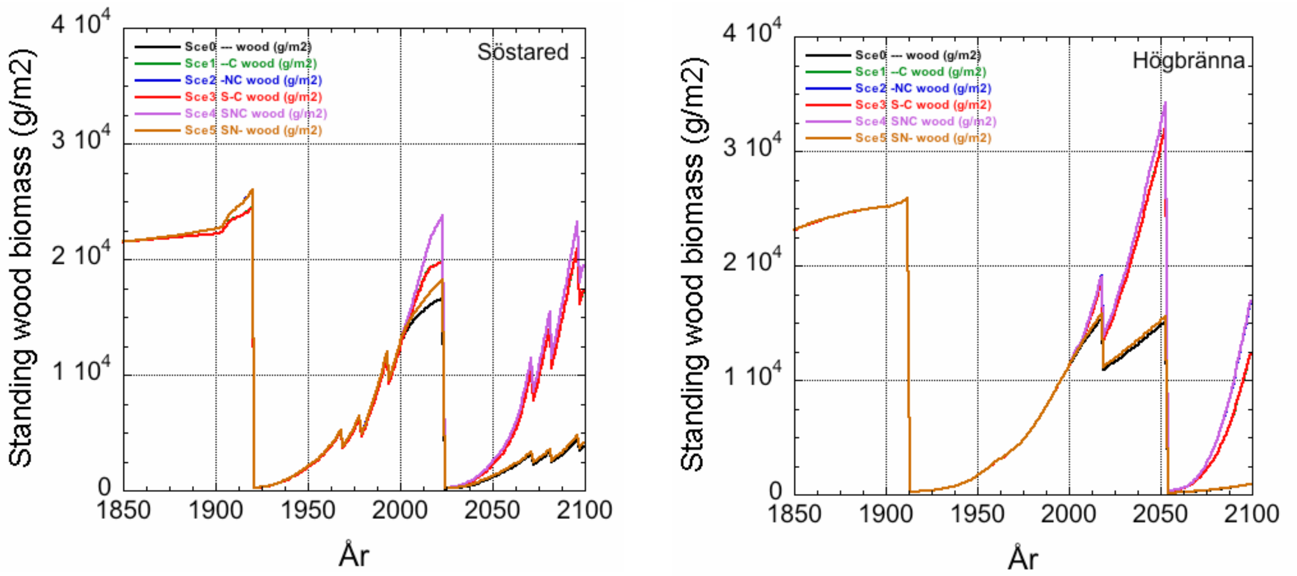
- Comparing Sce1--C and Sce2-NC (no sulfur, but N and climate change). This shows the effect of management and climate. The climate change introduce permanent changes to the system, and since climate change is here to stay. The output parameter variations in the system becomes larger, and the combination of climate change and nitrogen further increase this. Several plants with preference for nitrogen enter the scene.

- Comparing Sce1--C and Sce3S-C shows the effect of sulfur alone. This is not enough acidity to make much impact on biodiversity, and only when all the acidity from nitrogen and sulfur is considered do we see a significant effect on biodiversity. The critical load for acidity based on biodiversity is above the current legislation deposition for sulfur alone, but possibly at or below the acid input provided by both N and S. At Söstared, the nitrogen input has a profound effect on forest growth, far more than climate or management in itself. Acid input has also a significant impact, enhanced by the fact that the site has a modest weathering rate.

- Comparing Sce0 --- (The reference run) and Sce4SNC (The standard run) shows the full effect of nitrogen and climate change and that taken together, the impact from the past to now has been dramatic for this site. All the major drivers, acidity, nitrogen, climate change and management have had large and significant impact.

- Comparing Sce4SNC (The standard run) and Sce5SN- shows that the system is made less stable by the addition of climate change to the scenario. Without climate change, the temporal variations become smaller and the site seems to be able to reach a new steady state, different from the original.

The amount of wood biomass is also affected at this site as can be seen in Figure 8. It can be seen a large difference between the nitrogen and the non-nitrogen scenarios in wood biomass. The base saturation shows a pattern that is basically the same in all scenarios, but the amplitude change to larger with more nitrogen and when climate change is added.



Run	Figure code	Color code	S	N	Climate
Reference	Sce-0		-	-	-
Scenario-1	Sce-1		-	-	C
Scenario 2	Sce-2		-	N	C
Scenario 3	Sce-3		S	-	C
Standard	Sce-4		S	N	C
Scenario 5	Sce-5		S	N	-

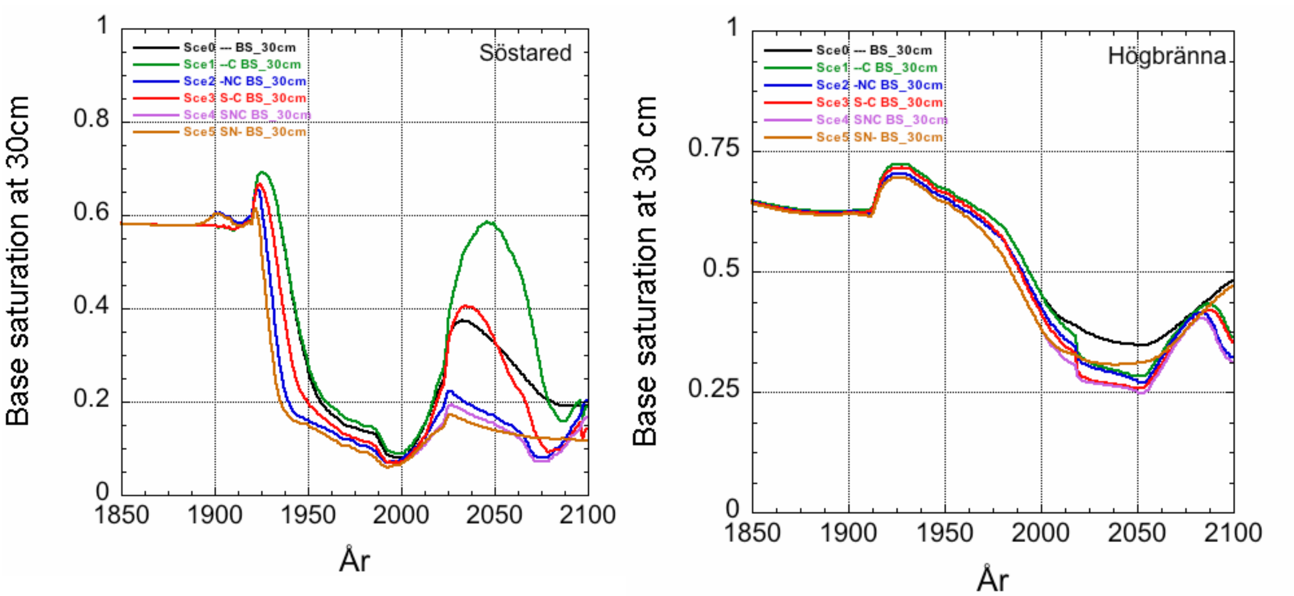


Figure 8. *Display of wood biomass and soil base saturation at the Swedish sites Söstared (South) and Högbränna (High north) for the period 1850-2100 for the different scenarios.*

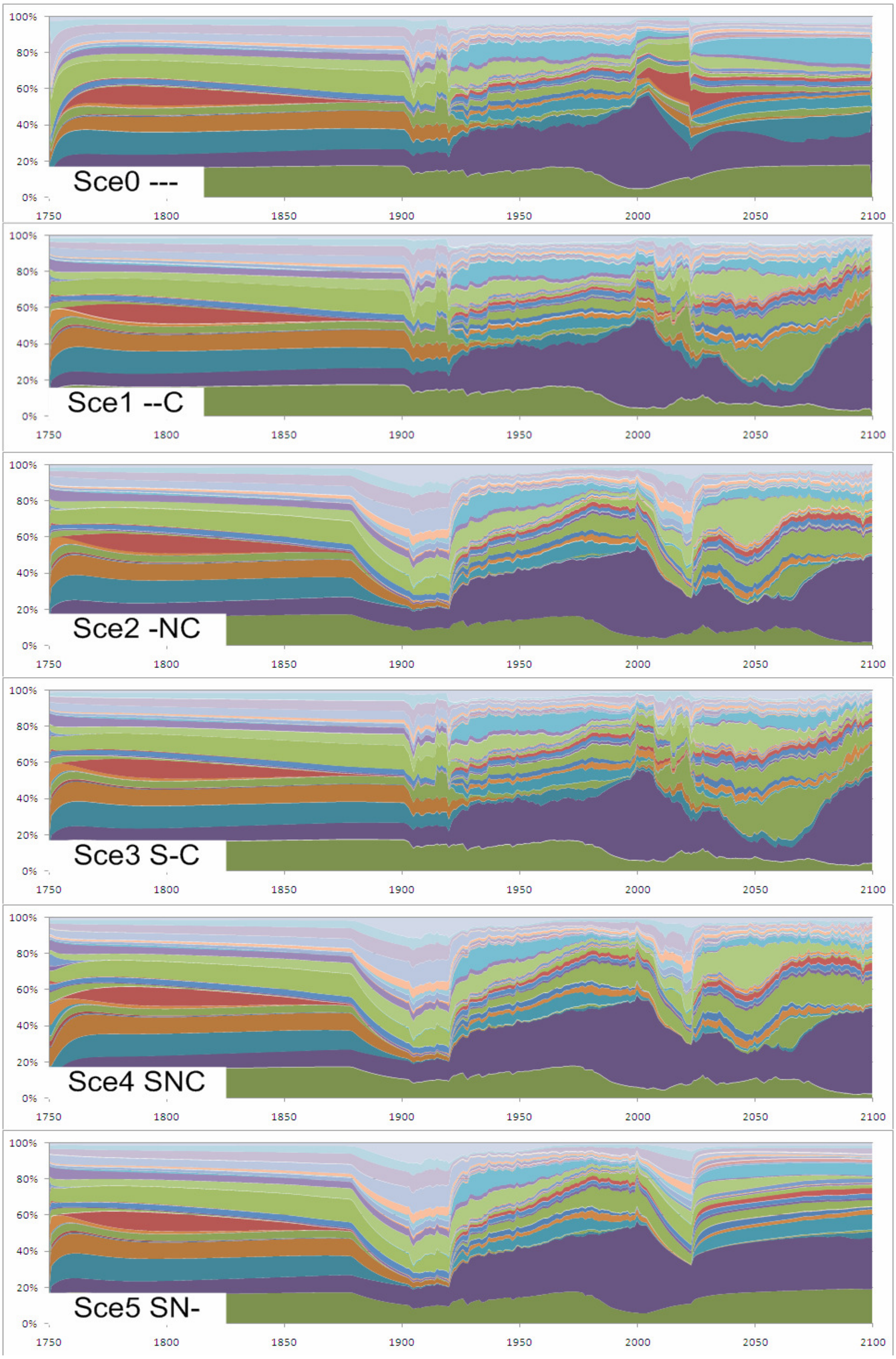


Figure 9. *The Söstared site 1750-2100. The colour bands represent different plant functional groups as defined in the plant legend for Sweden (see Table 5).*

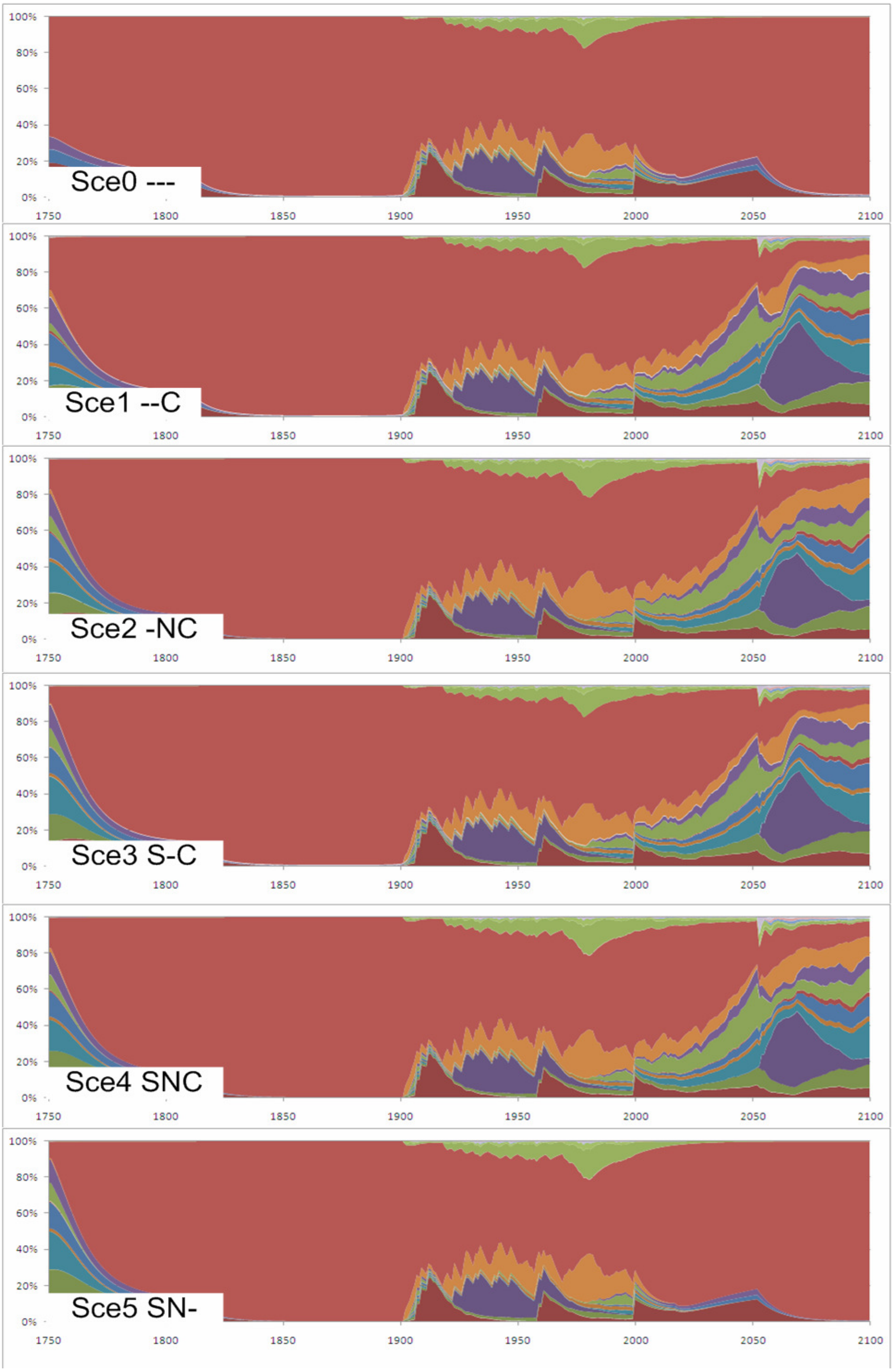


Figure 10. *The Högbränna site 1750-2100. The colour bands represent different plant functional groups as defined in the plant legend for Sweden (see Table 5).*

Högbränna, the polar site in the Swedish far north

The Högbränna site showed large responses that differed significantly from the other sites used so far. They are plotted in Figure 10. We may compare the runs as follows

- Comparing Sce0 --- (The reference run) and Sce1--C shows the difference between the no pollution without and with climate change. The SCe0 shows the effect of management on biodiversity. At Högbränna has management a large impact, but this is in itself all reversible and thus not a threat to the ecosystem. With the introduction of climate change the changes further increase and become permanent.

- Comparing Sce1--C and Sce2–NC (no sulfur, but N and climate change). The addition of nitrogen up to the current legislation at this site is not sufficient to create large changes, but minor changes are seen. The Current legislation deposition is not above what appears to be the critical load, but this is not fully evident here. Thus the change is visible, but rather modest.

- Comparing Sce1--C and Sce3S-C shows the effect of sulfur alone. The effect of climate change overshadows the effect of sulfur-related acidity, and no significant effects can be seen on biodiversity.

- Comparing Sce0 --- (The reference run) and Sce4SNC (The standard run) shows the full effect of nitrogen and climate change and that taken together, the impact from the past to now was dramatic for this site. Here the effect of acidity on biodiversity can be seen to be modest, counting all acidity that comes in from both nitrogen and sulfur. Thus the changes here arise from climate change, forest management and total acidity input. The site is probably above the critical load for acidity based on biodiversity. The impact of nitrogen on forest growth is very significant at this site, and probably essential for the long term viability commercial forestry in these regions. Without nitrogen input from pollution, forest growth would be very marginal.

- Comparing Sce4SNC (The standard run) and Sce5SN- shows that acidity and nitrogen has a modest effect in this system and that the major impact come from forest management and climate change. The critical load for acidity based on biodiversity is above the present acid input at this site.

The amount of wood biomass is also affected at this site as can be seen in Fig. 8. The base saturation is not much affected by any of the scenarios, illustrating that the acidity critical load is not exceeded at the moment and under current legislation. A comparison between the Swedish sites show that there are tremendous differences within Sweden and a study that involves significantly more sites from north to south is necessary for assessing the critical loads for nitrogen.

Table 5. *Swedish plant group legend: For Sweden we have 43 plant groups. Each group represents plants with the exact same response function parameters for the drivers. Different species may inhabit the same group, only sharing driver parameter settings.*

Cladonia_lichens	Hylocomium_mosses	Mnium_mosses	Sphagnum_mosses	
Calluna_vulgaris	Empetrum_nigrum	Erica_tetralix	Vaccinium_myrtillus	
Vaccinium_vitis-idea	Myrica_gale	Rhododendron_tomentosum	Rubus_idaeus	
Salix_lanata	Salix_myrsinifolia	Agrostis_capillaris	Brachypodium_pinnatum	
Bromus_benekenii	Calamagrostis_arundinacea	Deschampsia_cespitosa	Deschampsia_flexuosa	
Festuca_ovina	Milium_effusum	Molinia_caerulea	Nardus_stricta	
Poa_nemoralis	Dryopteris_dilatata_coll	Pteridium_aquilinum	Aconitum_lycoctonum	0
Allium_ursinum	Anemone_nemorosa	Antennaria_diocia	Arnica_montana	
Epilobium_augustifolium	Galium_odoratum	Geranium_sylvaticum	Hepatica_nobilis	
Mercurialis_perennis	Origanum_vulgare	Oxalis_acetocella	Trientalis_europaea	
Trifolium_repens	Urtica_dioica			

7. Estimating nitrogen critical loads based on biodiversity

The iteration runs are done, based on the initial values set from the calibrated standard run:

1. normal history S to 2010, then CuL S, no N, and climate change
2. normal history S to 2010, then CuL S, 33% of CuL N, and climate change
3. normal history S to 2010, then CuL S, 66% of CuL N and climate change
4. normal history S to 2010, then CuL S, 100% CuL N and climate change

The scheme was applied to the 2 sites in Switzerland and the 2 sites in Sweden. CuL is deposition according to current legislation after 2010.

The first results for 1750 to 2100 for the Swiss Aeschau site are shown in Fig. 5. We see that not much happens before 2100. The reason is that now the ecosystem is loaded with nitrogen that the turnover of the large internal pool is dominating the system. The system has become eutrophied to the degree where it has reached a new local self-sustaining stable zone. The system does not change until a major event strikes. This can be seen in the next set of graphs (Fig 11), where we have continued the calculations for another 400 years to 2500. In 2150 one large harvest of biomass is carried out as planned, and this is large enough to set the system again on a path of ecosystem change. After a transition period of approximately 150 years the system approaches a stable state, and we can see the results of the deposition reductions. In Fig. 11 we give the full overview from 1750 to 2500. We should note the following issues: within the span of 400 years from 2100 to 2500 the site does not fully recover. Some of the species never come back with respect to 1750. The site recovers to a state more resembling what it looked like in 1880's, but some of the mosses are on the verge of extinction. At 33% of the nitrogen deposition, some significant as well as marginal species are lost with no recovery. Thus, the critical load will be well below 33% of current deposition. For very long after the reductions, memory effects play around in the system, also being expressed as clear effects on the ground vegetation. Just for clarity, we repeat the reduction scenarios below in Tables 6 and 7.

Site	Sulfur	Nitrogen				Temperature
	Kg N/ha yr					°C
		100%	66%	33%	Background	
Aeschau	10	35	23	11	6	10
Bachtel	10	31	20	10	6	8
Söstared	18	20	15	7	3.5	6
Högbränna	1.7	1.5	0.9	0.45	0.3	-0.5

Table 6. *Deposition levels used in the assessment for critical loads in Switzerland and Sweden, covering a distance of more than 3,000 km across Europe.*

In Fig. 12 we have the similar scenario for the Swiss Bachtel site. It responds differently from the Swiss Aeschau site. Changes break through in the system much faster. The delays are shorter in this system, also causing partial recovery to occur faster. The site already early showed a lot of dynamic behavior in the reference run. It has shorter delays and faster response times. A close study of the run shows that there is not much difference between the reference run and the 33% run. This suggests that the critical load is perhaps in this range. Here also the clear-cut initiates a large change in dynamics and allows the recovery to start.

Söstared is a pine forest site that is more open than a spruce forest, and it lets more light penetrate to the ground through the canopy, providing opportunity for biodiversity. It is therefore the site in this test with the largest biodiversity. A large part of the site had open land from 1620 to 1820, but a part of the site was permanently with a pine cover. The scenario runs are seen in Figure 13, for 1750-2500. At Söstared, permanent vegetation composition change will remain, because of climate change. The site seems to have small changes at the 33% level but significant at the 66% level.

At Swiss Aeschau and Swedish Söstared sites the irreversible changes occur because of the climate change. Recovery is not complete, unless climate change is undone. This is not likely to happen in the next millennia.

Site	Site	Nitrogen deposition				Critical load
	150 %	100%	66%	33%	Background	
	Ecological effect					
Aeschau	Extreme	Extreme	Very large	Small	Reference	25%
Bachtel	Extreme	Very large	Some	Some	Reference	40%
Söstared	Extreme	Large	Some	Small	Reference	30%
Högbränna	Large	Small	None	None	Reference	125%

Table 7. *Effects assessment for setting critical loads for selected sites in in Switzerland and Sweden, covering a distance of more than 3,000 km across Europe.*

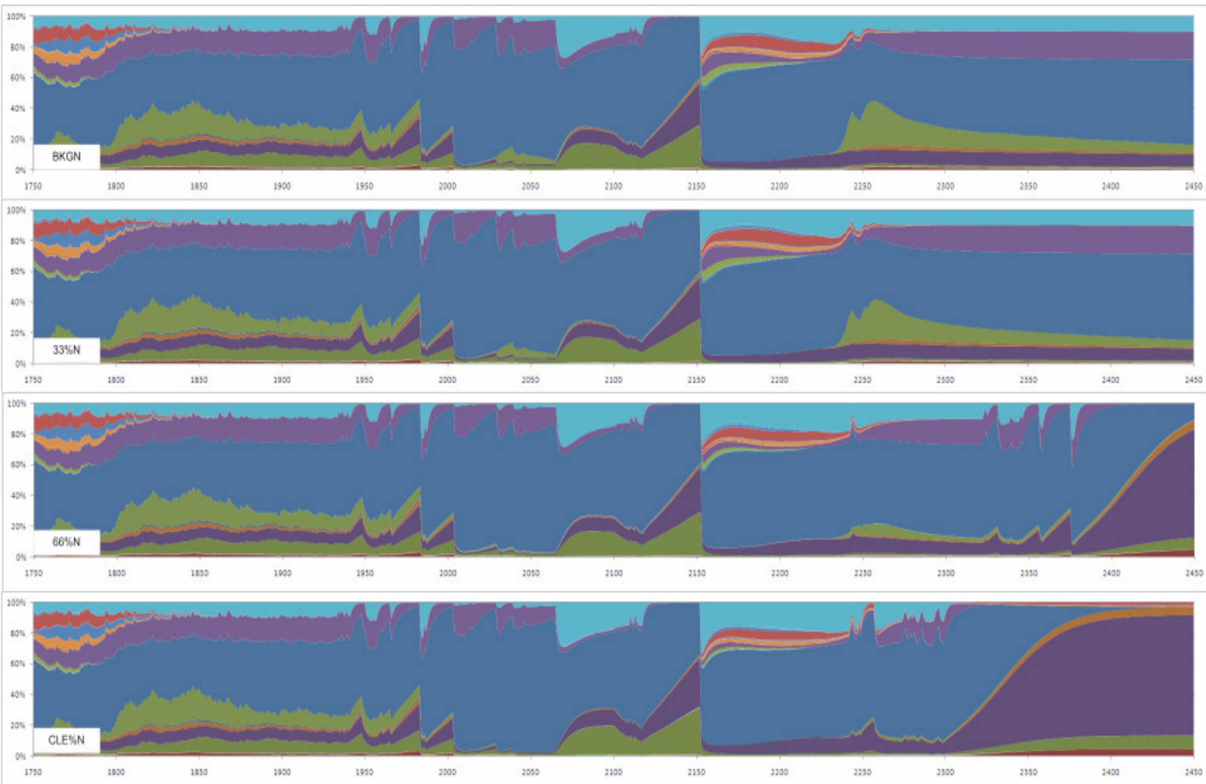


Figure 11. *Vegetation scenarios for Aeschau 1750-2500.*

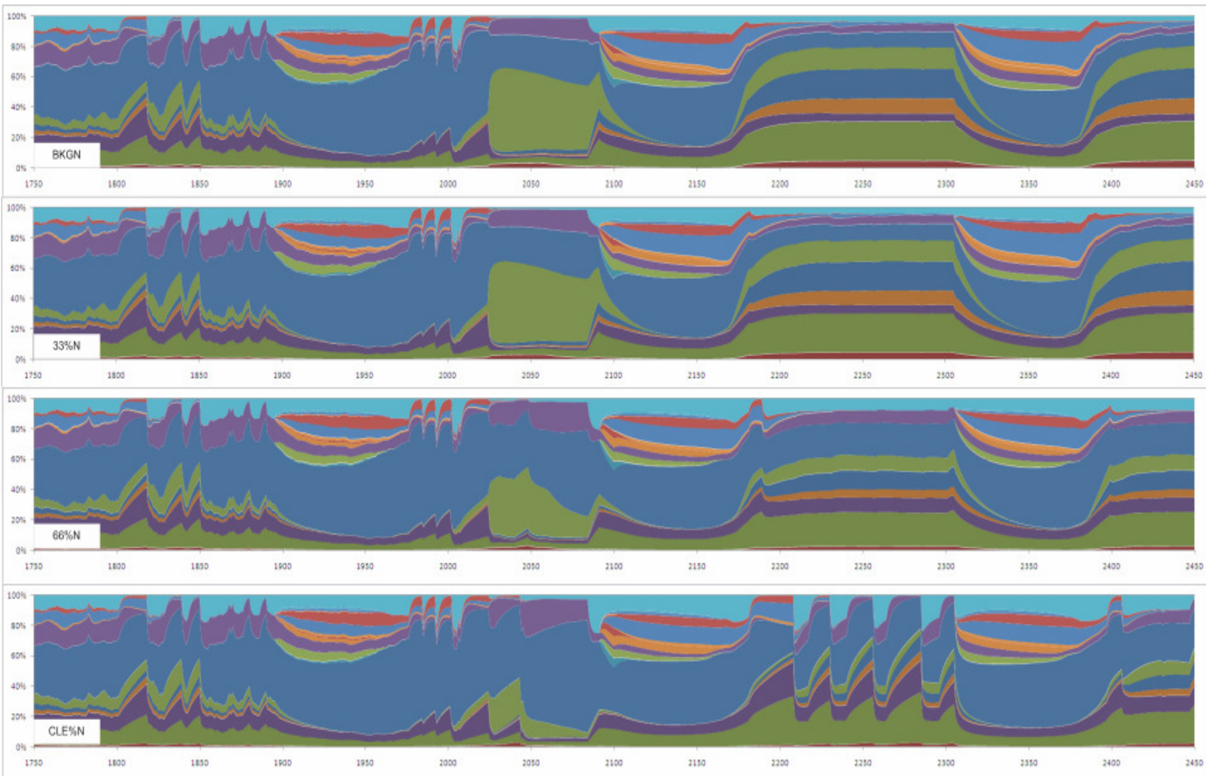


Figure 12. *Vegetation scenarios for Bachtel 1750-2500.*

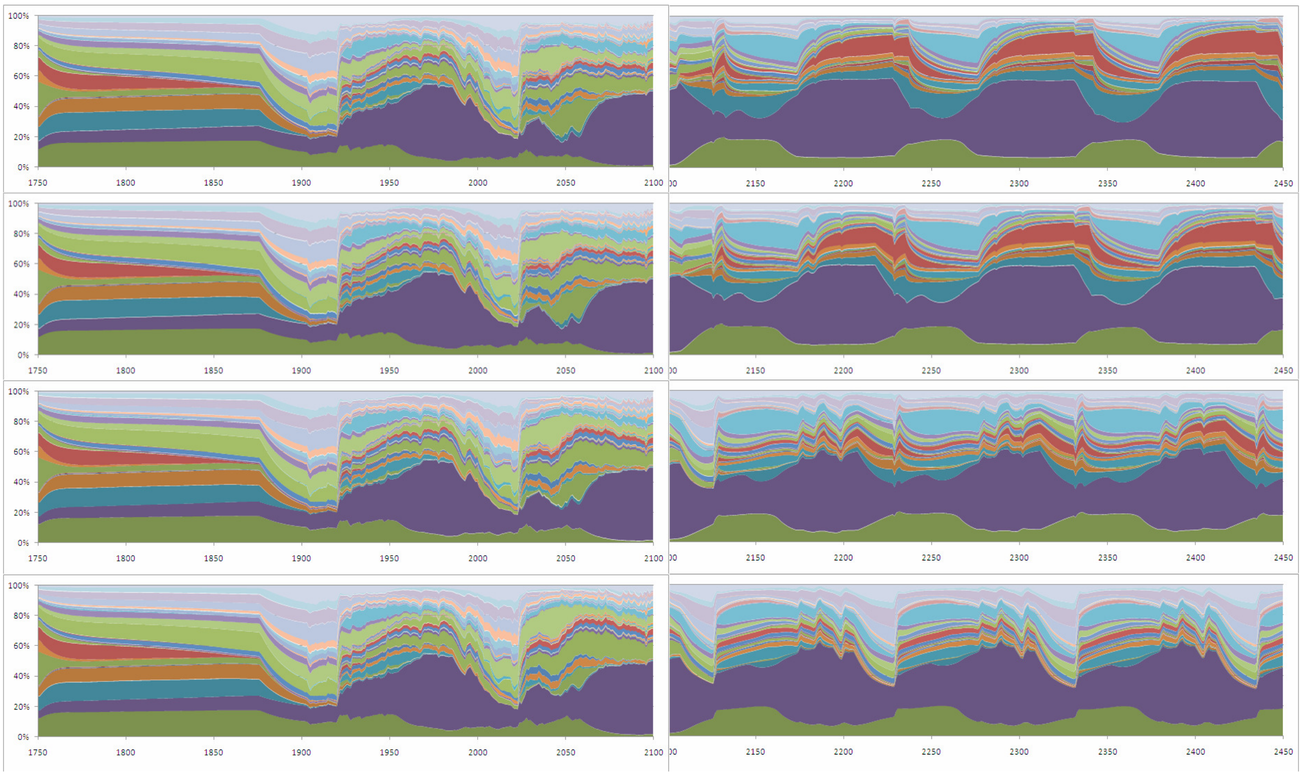


Figure 13. *Vegetation scenarios for Söstared in Sweden 1750-2500*

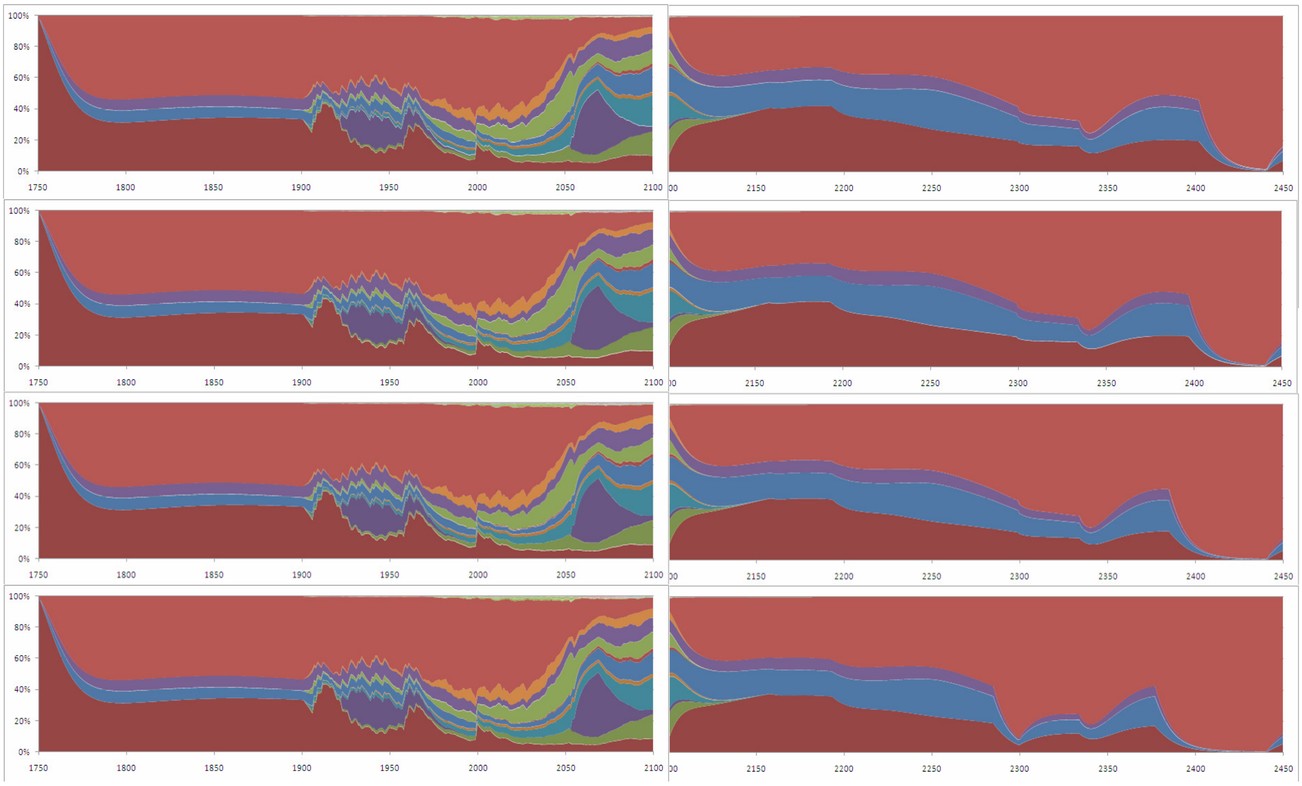


Figure 14. *Vegetation scenarios for Högbränna, Sweden 1750-2500*

Högbränna is a site in northern Sweden, in the province of Lappland. It is far to the north in a polar environment, with long cold winters and small amounts of pollution deposition. Here the nitrogen deposition has been above the current legislation deposition for the site during 1980-2020, and the model runs tell that the site exceeded the critical load during those years. However, the site was loaded up by sufficient nitrogen to eutrophy the soil and to start a cycle where the eutrophied state is made permanent by the internal cycle. Whereas the deposition applied according to current legislation is about 1.5 kg N/ha yr, the maximum N deposition was in the range 3.0-3.5 kg N/ha yr. According to Figure 14, the site will be heavily affected and the recovery will not take place until after 2100, when the site is clear-cut, and this pushes the system towards a recovery. The load is in 2020 at or slightly below the critical load.

In Table 8 we have summarized the assessment of critical loads, exceedance and policy. We can see that at the sites chosen for this study, the present nitrogen pollution policies do not provide adequate protection for vegetation biodiversity.

Site	Current legislation deposition in 2010	Estimated critical load	Approximate exceedance in 2010	% reduction required
	kg N/ha yr			
Aeschau	35	5-11	24-30	65-90%
Bachtel	31	10-16	15-21	50-65%
Söstared	20	4-6	14-16	70-80%
Högbränna	1.5	1-2	-0.5-0.5	increase 15%

Table 8. *Assessment of critical loads, exceedance and policy requirements*

8. Discussion

This was a study with the focus to suggest a method for calculating the critical load for nitrogen based on biodiversity. The issue is the method, and not the numerical values. At this stage, we do not really care about the exactitude of the numerical values of the critical loads, they are just examples and not representative for anything in Switzerland nor Sweden at present. However, we are able to create reasonable estimates and vegetation predictions across a large gradient in climate and pollution across Europe, from central Europe to the polar regions in the north, more than 3,000 km apart.

The model output diagrams are not trivial to interpret and there is certainly a lot of room for improvement in our critical loads proposal. However, it allows now for exploratory studies and attempts to come up with good estimates of a critical load based on biodiversity. This in turn now puts pressure on having a real discussion about what is the proper reference, and how much change is damage? In the end this boils down to become a principal question of protection perspective and environmental goals for the long term.

There may be an issue with the existence of a critical load for acidity from S and N based on biodiversity. However, this was outside the scope of this study to investigate, and the results for this issue are just indicative, but no more. Further work needs to be done to address this issue and calculate the values, in order to assess to what degree they are covered by the Gothenburg protocol now in force, and if this also should affect the planned revision.

One important observation from the runs is that soils have the ability to become self-sustained in an eutrophied state if the stock of nutrients is large enough. The requirement is that when the internal recycling becomes so large that the external supply or removal becomes insignificant, then the system may keep itself in an eutrophied state for a prolonged period of time. Then the system needs a strong disturbance in order to shift its state. This is parallel to what happens with phosphorus in an eutrophied lake (Sverdrup et al. 1991).

9. Conclusions

As a result of this study we may make some conclusions concerning methods for deriving critical loads for nitrogen based on biodiversity:

1. We have a method that can make critical loads for nitrogen based on biodiversity.
2. There appears to be necessary to assess critical loads for acidity input, based on biodiversity. The present study was not designed to separate out a critical load for acidity alone, and further work will be needed. This issue should be properly addressed at a number of test sites.
3. An automatic model tool for regional assessment of critical loads for nitrogen based on biodiversity can be ready in the near future.
4. A mapping manual for regional critical loads for nitrogen based on biodiversity, can be ready in the near future.

Concerning what we learned from the actual runs, we may conclude:

1. Recovery from nitrogen pollution effects on biodiversity is slow (50-300 years) and sometimes the system seems to need a push from management measures to start full or partial recovery.
2. Some changes are irreversible, mostly because of long-term climate change that cannot be removed.
3. The results are sensitive to the limits for ecological change used.
4. The tool of management holds large threats but also some very good opportunities for helping mitigation and adaptation.
5. Earlier modeling of biodiversity without the feedbacks between the nutrient cycles and the cross-feedbacks between climate change, acidity input, nitrogen cycle and nutrient use mass balances with links to growth are rendered invalid, and all assessments made on such assumptions need to be scrapped and redone.

The take-home policy messages are:

1. The present European N pollution mitigation policy does not provide adequate protection for vegetation biodiversity, and the existing policy needs a substantial revision to be able to do so.
2. The present study also shows that the present policy of nature conservation for biodiversity in the hope of return to a historical state or to preserve the present is a total failure and cannot provide what it is intended for. The sooner this policy is revised the better.

3. Much damage can be done to ground vegetation biodiversity by the wrong type and timing of forest management. At the same time forest management is one of the important tools for helping mitigation, adaptation and recovery.

The present runs with the ForSAFE-VEG model have convinced us that the ForSAFE model is superior to the SAFE model in its overall and particular performances, also with respect to soil chemistry and forest growth modeling. This because many of the assumptions in SAFE have been replaced by proper mechanistic formulations, the ForSAFE model is thus far more general. Another fact is that because of its more generic nature, ForSAFE requires less input data than SAFE.

Modeling two sites in each two countries cannot make a map, but the indication from this study is that it is justified to make a larger assessment covering many sites and different regions of both Switzerland and Sweden to assess stock at risk and help devise adequate mitigation and adaptation strategies. This would provide the first steps towards a fully integrated regional assessment.

10. Acknowledgments

This study would not have been possible without the generous support of the Swiss Federal Office for the Environment (FOEN) and the Swiss National Focal Centre for modeling and mapping activities under the Convention on Long-range Transboundary Air Pollution (UNECE). The Swedish critical loads effort has profited significantly from the Swiss cooperation and support. The study used models and datasets developed within the Swedish long term research programs ASTA 1997-2006 and SUFOR 1996-2005, supported by the MISTRA research foundation in Sweden.

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Input preparation for dynamic modelling with ForSAFE-VEG in Switzerland – deposition of nitrogen, sulfur and base cations and climate related parameters

Beat Rihm[6] and Daniel Kurz[7],

The climate inputs

Data requirements

For dynamic modelling of soil and vegetation changes with ForSAFE-VEG (Sverdrup et al. 2007a and 2007b) the following climatic parameters are required with a monthly temporal resolution:

- Year. The data should span the period from approximately 1700 to 2100.
- Day of year (doy), middle of each month, January to December.
- Monthly mean air temperature (TT), in °C, 2 m above ground.
- Air temperature - monthly average of daily minima (TD_{min}), in °C.
- Air temperature - monthly average of daily maxima (TD_{max}), in °C.
- Monthly minimum of air temperature (TT_{min}), in °C.
- Number of frost days in the month.
- Monthly sum of precipitation (RR), in mm.
- Photosynthetically active radiation (PAR), monthly average between sunrise and sunset, in $\mu E\ m^{-2}\ s^{-1}$.
- (planned) Monthly mean CO2 concentration in the air, in ppm.
- (planned) Monthly mean ozone concentration in the air, in ppm.

In future releases of the model, it is planned to include the effects of atmospheric CO_2- and ozone-concentration. Therefore, also input data related to CO_2 were prepared. For ozone, no input data are available, so far. Regarding air temperature, earlier releases of the model calculated TT as the average of TD_{min} and TD_{max}. Now, TT is given as a separate input parameter. TT_{min} and frost days are also new input parameters. They refer to the bud break problem, which is relevant for the competitiveness of several relevant plant species. Input data were prepared for 260 forest sites in Switzerland. As there are no meteorological on-site measurements, the data had to be spatially interpolated to those locations as precisely as possible, i.e. local climatic influences such as altitude, high horizon and terrain were integrated in the interpolation. The challenge consists of preparing a data set that fairly reproduces local conditions and spans a period of several centuries as well.

Methods and Data Sources

For solar radiation (PAR), the annual cycle is assumed to be constant, as neither historical data nor projections were available. The mean monthly PAR values are calculated on the basis of measurements of solar radiation in the reference period.

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The CO_2-concentrations are hemispheric averages (measured and projected). For temperature (TT) and precipitation (RR) monthly resolved time-series are calculated for the period 1659-2100 by combining (1) results of local meteorological measurements for a reference period, (2) monthly temperature and precipitation reconstructions back to 1659 as well as (3) climate change projections for the period 2000-2100. The statistically reconstructed fields of monthly temperature and precipitation (1659- 1800 in case of precipitation; 1659-1900 in case of temperature) were prepared by Luterbacher and collaborators (2007) as grid data with a spatial resolution of 0.5°x0.5° (in case of temperature) and 0.1°x0.1° (in case of precipitation), respectively. For the post 1800 (precipitation) and post 1900 (temperature) we used station based grid analysis of the Climatic Research Unit (Mitchell and Jones, 2005; Efthimiadis et al. 2006). Climate change projections are available as global raster data, e.g. from Met Office (2005) or IPCC (2007). Thus, the main work steps for preparing the required temperature and precipitation inputs can be summarized as follows:

a) Determine a *reference period* for which climatological measurements are available. In this study we use 1961-1990 as the reference period. For any climatological application a period of at least 30 years is recommended by the World Meteorological Organisation (WMO).

b) Calculate the *reference period means* of TT and RR for each modelling site on the basis of the grid reconstructed TT and RR data.

c) Calculate the monthly *anomalies* of TT and RR 1659-2000 with respect to the reference period means. This is done on the basis of the reconstructed raster data set. The climate change projections of the Met Office (2005) provide anomalies for 2070-2100 relative to the reference period 1960-1990.

d) Spatially interpolate meteorological *measurements* to the modelling sites and use them to calculate base period means of TT and RR. While the raster data only show averages of a larger area, the (interpolated) measurements reflect the local conditions at the modelling sites.

e) Construct the time-series of TT and RR 1659-2000 at each modelling site by *adding* the monthly anomalies to the 'measured' reference period means.

f) Calculate TD_{min}, TD_{max}, TT_{min} and frost days as a *function of TT*. This was done assuming that the monthly variability of temperature, which was analyzed for a reference period, is constant during the whole modelling period (1659-2100).

For calculating the mean monthly values of TT, RR and radiation in the reference period at the modelling sites, the software-tool METEONORM (Remund et al. 2007) was used. This tool includes both, a worldwide database of meteorological measurements as well as interpolation models to calculate mean values at any desired location. METEONORM offers two reference periods (1961-90 and 1996-2005) and includes also the climate change projections calculated by the Hadley CM3 model (Met Office 2005) based on the IPCC emission scenario IS92a. The software also comprises routines to derive TD_{min} and TD_{max} from the monthly mean temperature (TT). In the present version of the software, it is assumed that the relation between monthly average temperature and the extremes is stable over time, although there is some evidence that this is not strictly the case. This point could be improved in future studies.

For this study, the METEONORM software was extended by routines to calculate TT_{min}, frost days and PAR. Furthermore, the software was extended by a batch-mode for (1) running several sites in one run and for (2) reading the monthly anomalies and calculating the output parameters for each month of the modelling period (1659-2100).

Temperature and Precipitation

The statistically reconstructed grid temperature and precipitation data compiled by Luterbacher et al. (2007) include the following data sources:

- Mean monthly temperature (TT) 1659-1900: Luterbacher et al. (2004) and Xoplaki et al. (2005); the data were recalculated and fitted to the Greater Alpine Region (GAR) using more monitoring station series as predictors.
- Mean monthly temperature (TT) 1901-2002: Mitchell and Jones (2005).
- Monthly precipitation sum (RR) 1659-1800: Luterbacher et al. (2007).
- Monthly precipitation sum (RR) 1801-2002: Efthymiadis et al. (2006).

The historical TT data have a resolution of 0.5°x0.5° as shown in the example of Figure 1. The historical RR data were prepared at a resolution of 0.1°x0.1° (Figure 2). The reconstructions are based on a combination of instrumental station data and documentary proxy evidence applying principal component regression analysis. The statistical model is fitted within the 20th century (1901-1995) between each single grid point and available temperature and precipitation measurements. The statistical relationship obtained within the instrumental period is then applied to the available data back in time. It is the same methodology as applied by Luterbacher et al. (2004) and Xoplaki et al. (2005), however fitting on the new temperature dataset of Mitchell and Jones (2005) and precipitation data of Efthymiadis et al. (2006) and reconstructing monthly values. Due to the decrease in climate data back in time the uncertainty of the reconstructions increases and the variability for each grid-point decreases.

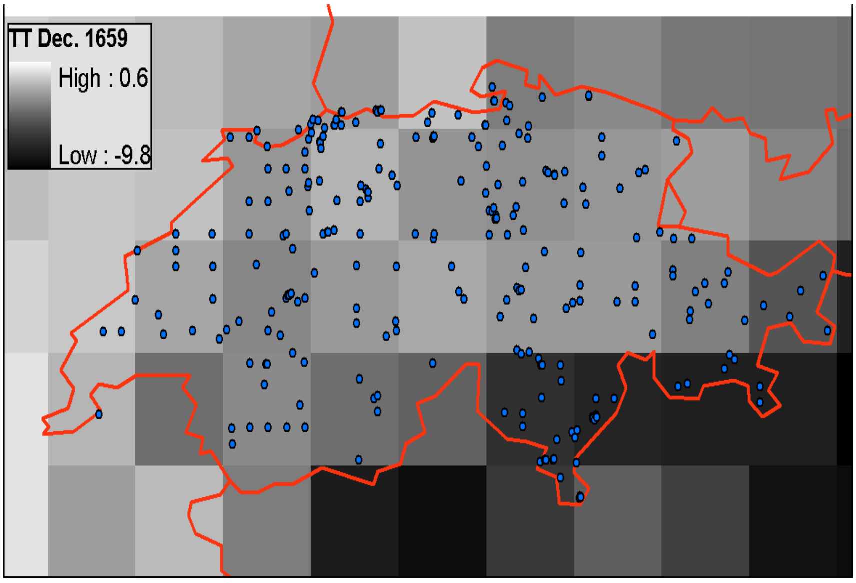


Figure 1. *Mean temperature in December 1659 reconstructed on a 0.5°x0.5° raster (Luterbacher et al. 2007). The locations of the 260 modelling sites are marked by black dots.*

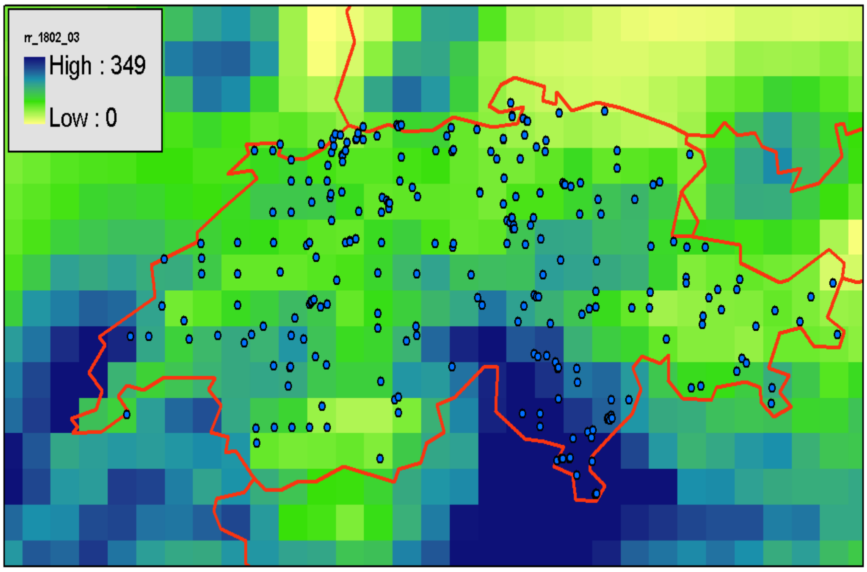


Figure 2. *Precipitation sum in March 1802 reconstructed on a 0.1°x0.1° raster (Luterbacher et al. 2007). The locations of the 260 modelling sites are marked by a black dot.*

Figure 3 shows the monthly temperature anomalies for a selected site (temperature of a month minus the reference period mean of that month). The anomalies were calculated on the raster-cells shown in Figure 1 and then interpolated to the modelling sites. The precipitation anomalies were calculated in the same manner. The selected site Beatenberg is situated in the pre-Alps at 1510 m a.s.l. (7.762°E 46.700°N).

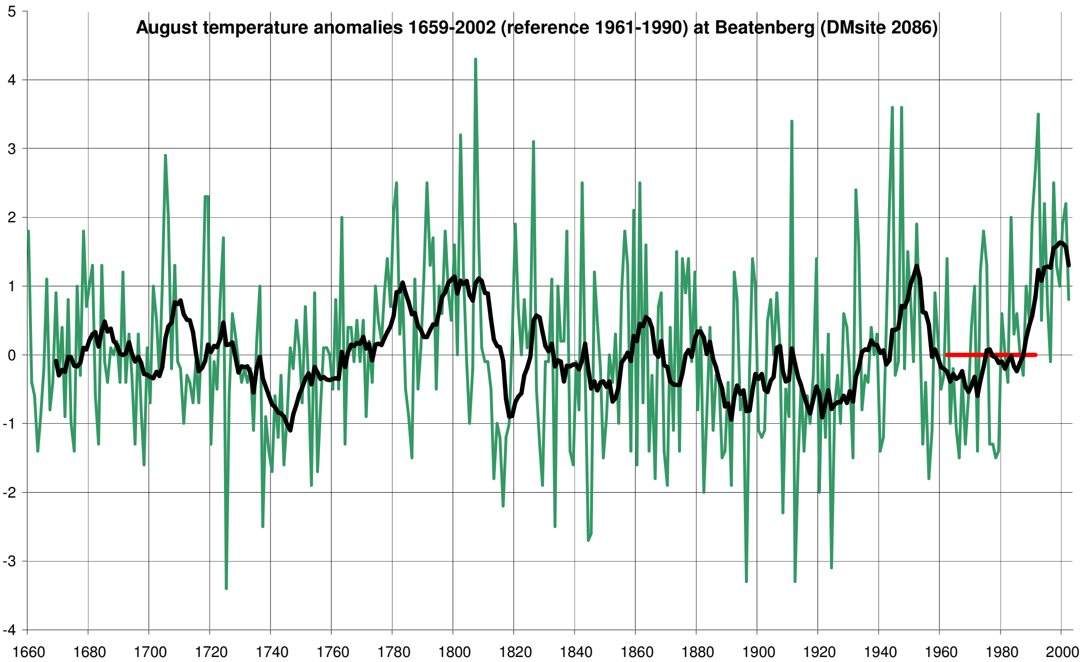


Figure 3. *August temperature anomalies 1659-2002 relative to the reference period (1961-1990, see red bar) at the pre-Alpine site Beatenberg (1510 m a.s.l). Units: °C. The black line is the moving average over 10 years.*

Results from climate-change experiments conducted using Met Office Hadley Centre computer models (Met Office 2005) are used for predicting trends of precipitation and temperature between 2003 and 2100. The experiments assume that future emissions of greenhouse gases will follow the IS92a scenario, in which the atmospheric concentration of carbon dioxide more than doubles over the course of the 21st century. This is a 'business as usual' scenario, which assumes mid-range economic growth but no measures to reduce greenhouse-gas emissions. The scenario is integrated in the standard version of the METEONORM software.

The reconstructed anomalies and the climate projection until 2100, as well as the site-specific interpolated monitoring data of the base period are used for calculating the monthly precipitation sums (RR) and mean air temperatures (TT). Furthermore, METEONORM applies local corrections for sites on southern slopes and sites close to large lakes (Remund et al. 2007). As an example, Figures 4 and 5 show the resulting values for January and July at the pre-Alpine site 'Beatenberg'. The main characteristics and trends at this site can be considered as representative for large parts of Switzerland. E.g., increasing temperatures in the last decades can be seen in Figures 3 and 4 (mainly in winter). Until 2050 (Figure 4) a substantial temperature increase of approximately 3 °C is expected for summer. The winter temperatures are rising as well.

So far, there is no inter-annual variability of TT (and RR) implemented for the post 2002 period. In a next step, it is important to introduce variation of TT and RR also for this period, because the extremes will change vegetation first, not the averages.

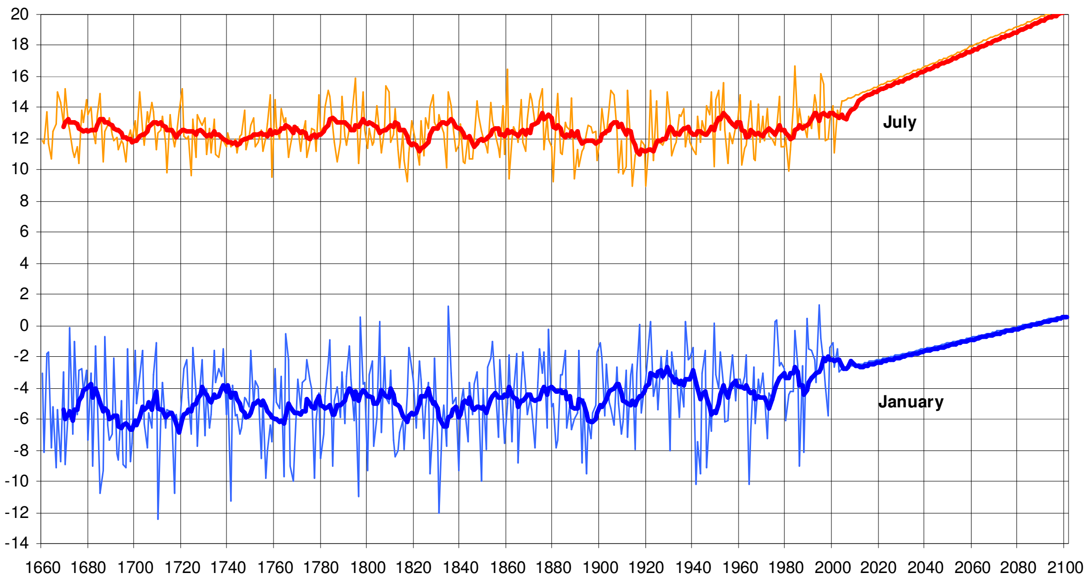


Figure 4. *Mean January (blue) and July (red) air temperature (TT) 1659-2100 at the site Beatenberg (1510 m a.s.l). Units: °C. The thick lines are moving averages over 10 years.*

Stochastic models are implemented in METEONORM to calculate TD_{min}, TD_{max}, TT_{min} and frost days (Remund et al. 2007). The stochastic models generate intermediate data (hourly values) having the same statistical properties as the measured data, i.e. average value, variance, and characteristic sequence (autocorrelation). The generated data approximates the natural characteristics as far as possible. The statistical properties rely on measurements of the period 1996-2005.

At the site Beatenberg, precipitation in winter used to be lower than in summer most of time since 1659 (Figure 5). However, this is expected to turn around in the future: the climate projections of the Hadley Centre (Met Office 2005) as well as regional scenarios of ICPP 2007 show this trend towards drier summers and wetter winters. The annual precipitation amounts are expected to remain more or less at the present level.

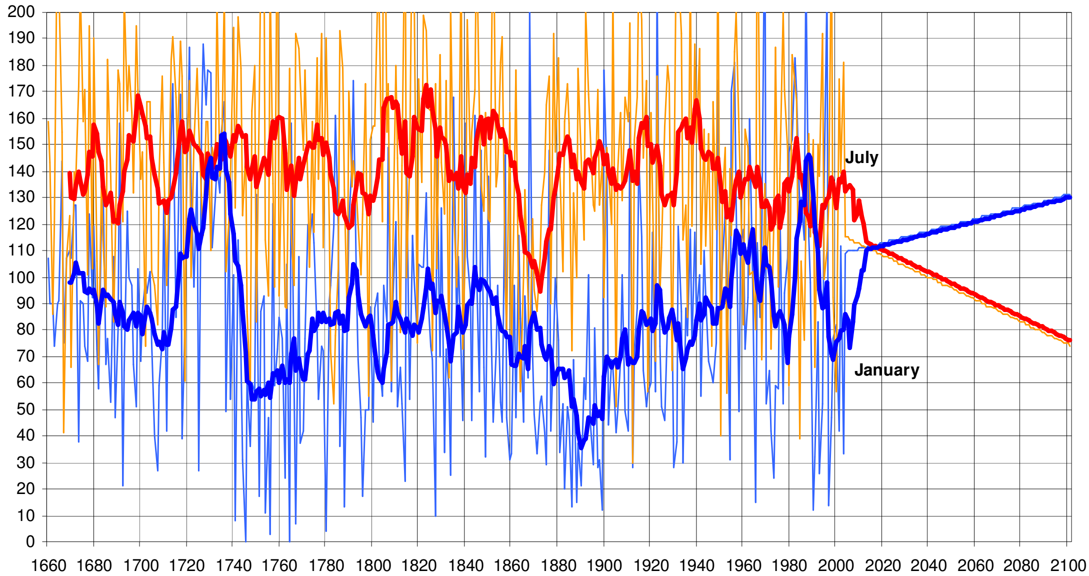


Figure 5. *Precipitation sum in January (blue) and July (red) 1659-2100 at the pre-Alpine site Beatenberg (1510 m a.s.l). Units: mm/month. The thick lines are moving averages over 10 years.*

Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) is the part of global solar radiation in the 400–700 nm waveband. It is the general radiation term that covers both photon terms and energy terms. The vegetation module of ForSAFE-VEG requires the photosynthetic photon flux density expressed in µE m^{-2} s^{-1} (1 µE = 1 µmol photons = 6.022 10^{17} photons). Furthermore, PAR must be calculated as monthly mean between sunrise and sunset. There are very few stations world-wide measuring PAR. PAR can be estimated from measurements of global solar radiation to a reasonable degree of accuracy. A straight forward approach for calculating hourly PAR from global solar radiation (G), the clearness index (k_t) and the solar zenith angle θ_z was proposed by Rubio et al. (2005) based on an empirical model developed by Alados-Arboledas et al. (2000):

$$PAR = G \cdot (1.832 - 0.191 \cdot \ln k_t + 0.099 \cdot \cos \theta_z)$$

The solar zenith angle is the most important factor in cloudless conditions and the clearness index allows the model to take into account the effect of clouds. This model was implemented in the METEONORM software, where the stochastic models generate hourly values of the required input data (Remund et al. 2007). As an example, Figure 6 shows the mean annual cycle of PAR over the 1961-1990 period calculated for the site Beatenberg. This result is used for all years in the modelling period 1659-2100, as no information on the long-term development of PAR was available.

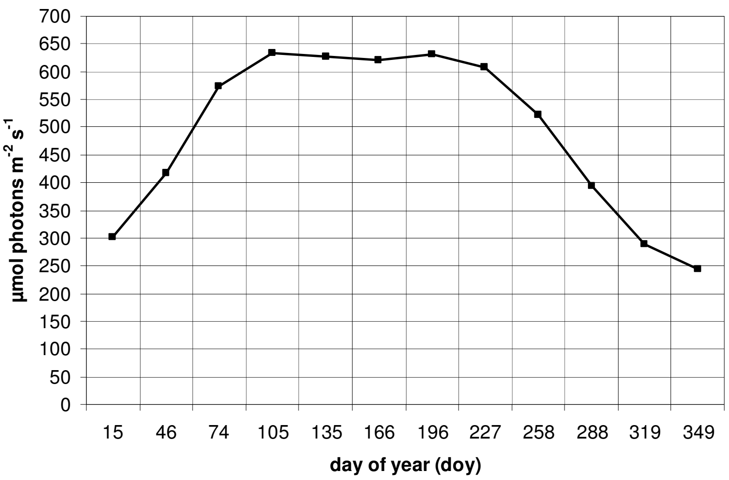
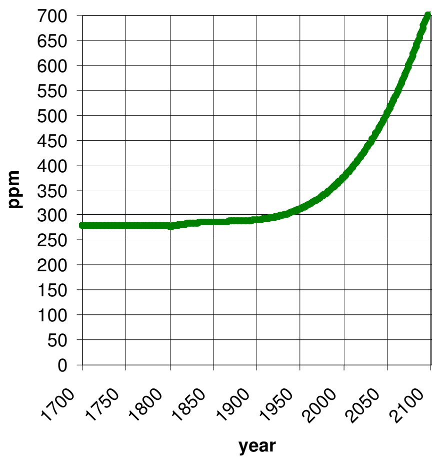


Figure 6. *Photosynthetically active radiation (PAR) from January to December, average over the period 1961-1990, at the pre-Alpine site Beatenberg (1510 m a.s.l).*



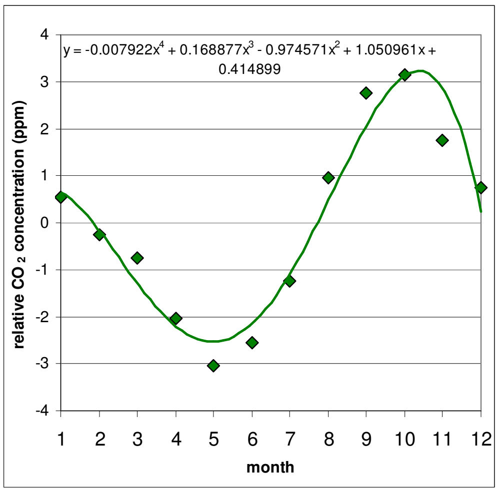


Figure 7. *(a) Global CO_2 concentration in the atmosphere over the period 1700-2100 (future values according to IPCC IS92a scenario). Units: ppm. (b) Annual cycle of the relative CO_2 concentration. The values are relative to the annual mean concentration in 1959. Units: ppm.*

CO_2 Concentration

In the pre-industrial era of the 17th and 18th centuries, the global concentration of CO_2 in the atmosphere was at a constant level of about 280 ppm. Since 1800 an accelerating increase of the concentration is observed reaching today a level of 380 ppm in 2006 (see IPCC 2007 for a compilation of monitoring results). The future development of the CO_2 concentration following the IS92a emission scenario (which was used for the temperature and precipitation projections) is documented in IPCC (2001): until 2100 it is supposed to reach around 700 ppm. Figure 7 (a) shows the resulting CO_2 concentrations for the period 1700-2100. The CO_2 concentrations follow a typical annual cycle caused by the activities of the vegetation. Figure 7 (b) shows the monthly deviation of the concentrations from the annual mean concentration as observed in the Northern hemisphere (Tans 2007). This information was also included in the preparation of the input-files for ForSAFE-VEG.

Deposition inputs

Data requirements

The dynamic modelling of soil and vegetation changes with ForSAFE-VEG requires annual deposition rates for a specified reference year as well as (relative) trend curves of the deposition over the modelling period. ForSAFE calculates the temporal evolution of dry deposition as a function of the vegetation status. Therefore, wet and dry deposition must be supplied separately. Furthermore, oxidized and reduced nitrogen have to be distinguished in the deposition input files for the reference year, which contain the following parameters:

- Wet and dry deposition of oxidized nitrogen: WD_{NOy}, DD_{NOy}
- Wet and dry deposition of reduced nitrogen: WD_{NHx}, DD_{NHx}.
- Wet and dry deposition of sulphur: WD_{SOx}, DD_{SOx}
- Wet and dry deposition of base cations (= Bc = Ca + Mg + K): WD_{Bc}, DD_{Bc}
- Wet and dry deposition of Na: WD_{Na}, DD_{Na}
- Wet and dry deposition of Cl: WD_{Cl}, DD_{Cl}

DD_{NOy} is the sum of gaseous NO_2, gaseous HNO_3 and particulate NO_3^-. DD_{NHx} is the sum of gaseous NH_3 and particulate NH_4^+.

Methods and Data Sources – a Summary

Deposition in the Reference Year (2000)

Input data were prepared for 260 forest sites in Switzerland. As there were in general no on-site measurements, wet and dry deposition rates were modeled or interpolated on the basis of results from various monitoring sites. The deposition of N, S, Bc, Na and Cl was calculated with a generalized combined approach for the reference year 2000. Thimonier et al. (2004) give a description of the methods related to N and S deposition. In short, wet deposition is calculated by combining the concentration field of sulfate, nitrate and ammonium compounds in rain water with a precipitation map. Results of wet concentration measurements are relatively homogenous below an altitude of 1000m. At higher altitudes concentrations decrease. In Southern Switzerland, a detailed study on wet deposition patterns was carried out (SAEFL, 2001). Resistance analogue models are used for assessing the dry deposition of NH_3 and NO_2 gas and aerosols. For these compounds, the concentration fields are calculated from emission inventories with a resolution of 200m (NH_3 100m) by applying statistical dispersion models as presented by Thoeni et al. (2004) for NH_3, by SAEFL (2004) for NO_2 and by SAEFL 2003 for aerosols (PM10). For HNO_3, the concentration field is calculated as a function of altitude. For SO_2, the concentration field is determined by geo-statistical interpolation of monitoring results. For BC, grid bulk deposition data from CCE are used in combination with filtering factors for forests and average ratios of individual base cations in bulk deposition measurements. The concentration fields are multiplied by deposition velocities, which depend on the reactivity of the pollutant, surface roughness and climatic parameters. Deposition velocity values were taken from literature. As an example, Figure 8 shows the resulting spatial pattern of total nitrogen deposition, characterized by a general decrease with altitude, relatively low deposition in inner-Alpine valleys and areas with high depositions due to local ammonia emissions (e.g. in central Switzerland) or by import (in Southern Switzerland).

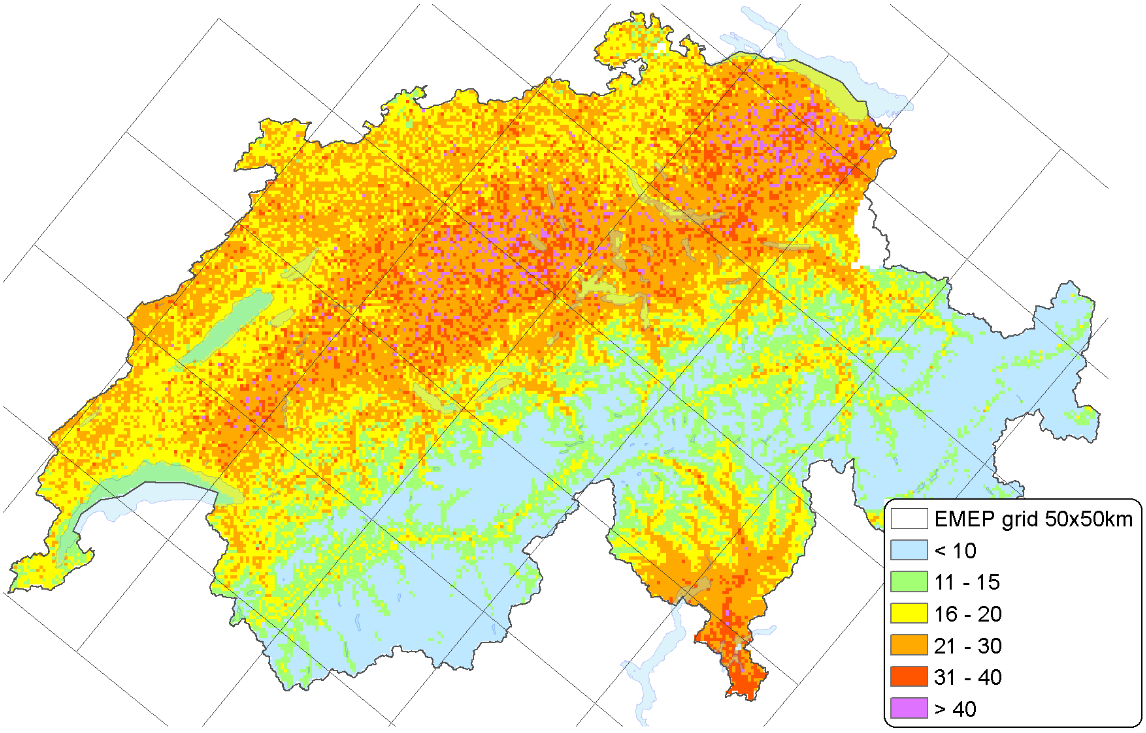


Figure 8. *Nitrogen deposition for Switzerland (kg N ha^{-1} a^{-1})*

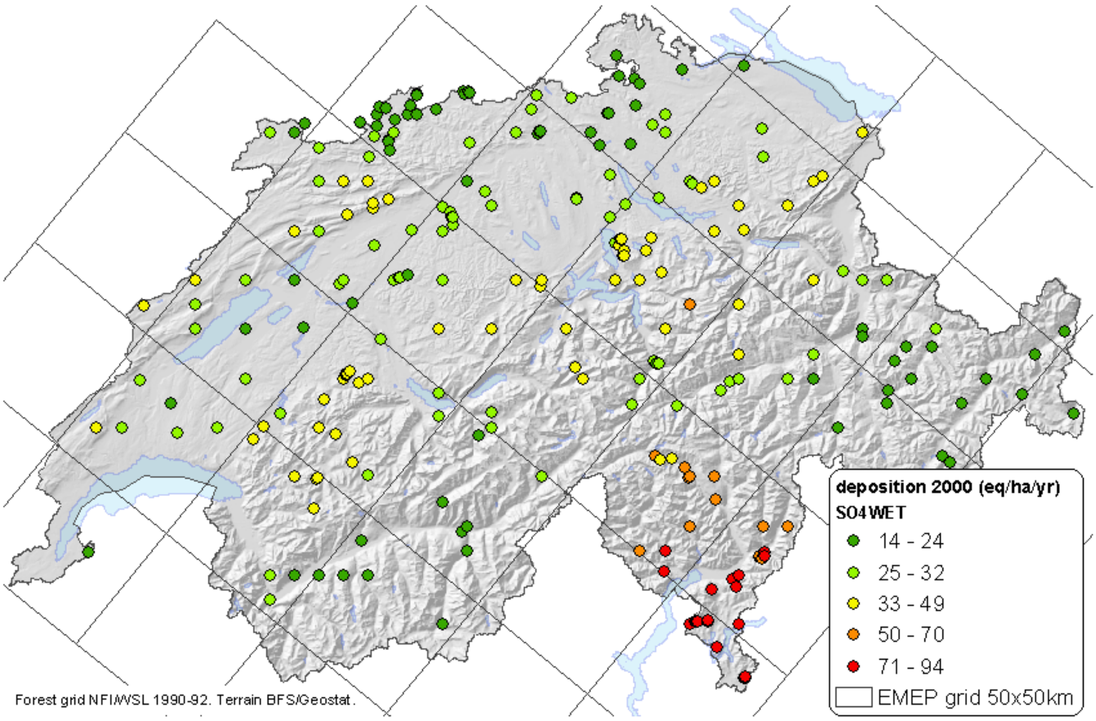


Figure 9. *Wet sulfur deposition at modelling sites, year 2000.*

Figure 9 shows the wet deposition of sulfur for the 260 modeling sites: the highest deposition rates are found in the South, where high precipitation amounts occur along with relatively high sulfate concentrations in rain water.

Trend Curves of Deposition

The trend curves used to construct time-series of deposition of SO_x, NO_y and NH_y are shown in Figure 10. They are based on data compiled by Schöpp et al. (2003) for 1880-2030. In the time span before 1880, deposition trends of SO_x and NO_y were obtained from scaling the Rothamsted sulfur deposition trend (C. Walse, Lund University, pers. comm., 1996, based on Sverdrup et al. 1996) to the given 1880 SO_x and NO_y depositions. Resulting grid average background loads of the early 18th century, 27 to 40 $mol_c\ ha^{-1}\ a^{-1}$ for sulfate and 7 to 11 $mol_c\ ha^{-1}\ a^{-1}$ for nitrate (natural backgrounds according to EMEP 25 to 79 and 0 to 9 $mol_c\ ha^{-1}a^{-1}$, respectively), were finally extended into the past as far as needed. The ammonia depositions were extended unchanged to the beginning of the simulation period. Regarding dynamic acidification modeling, we have assumed for all three compounds deposition trends for years beyond 2020 to be constant until the end of the simulation period. Finally, values for years between the five-year intervals were obtained by linear interpolation.

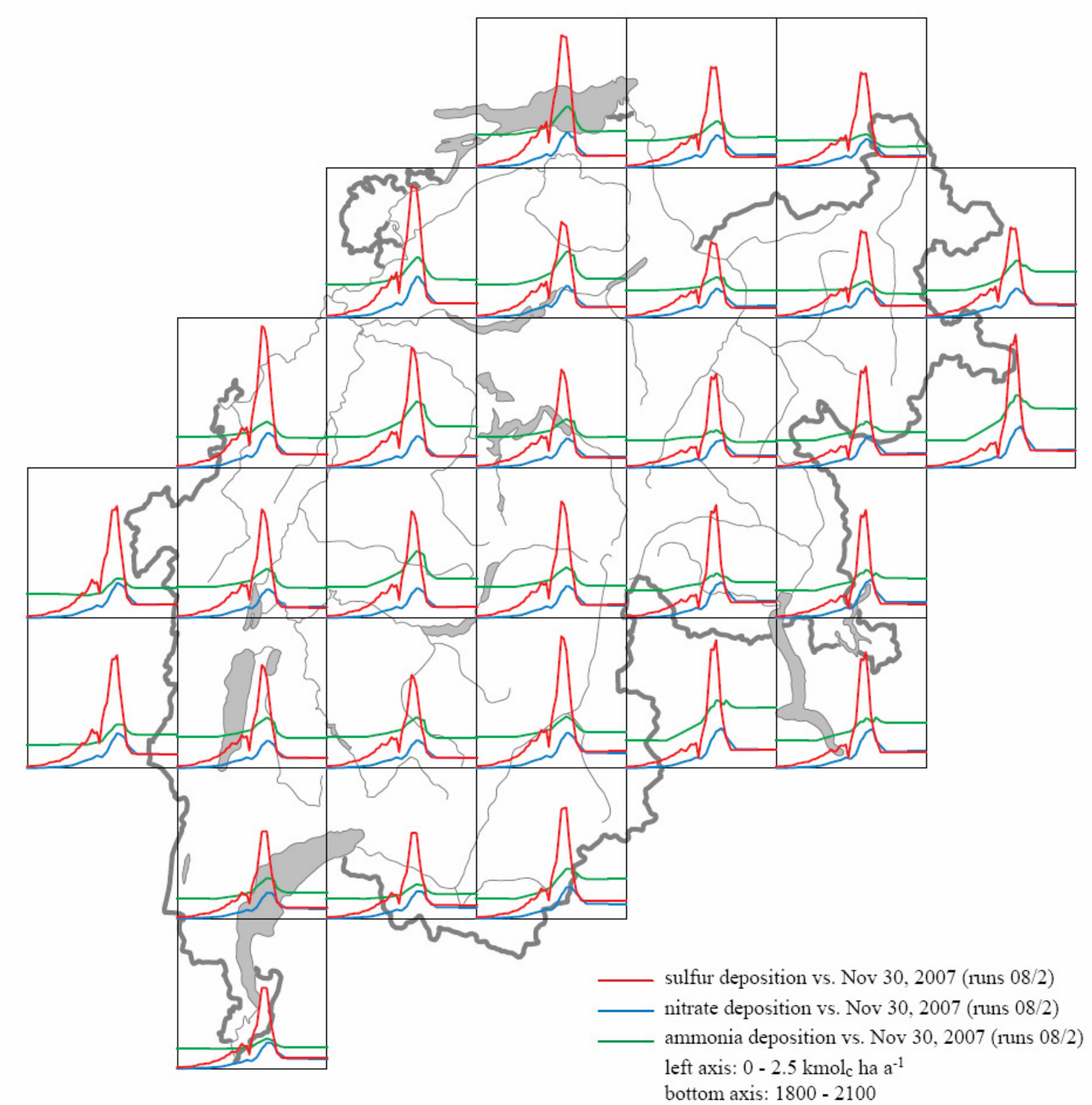


Figure 10. *Deposition trend curves of sulfur (red), oxidzed nitrogen (blue) and reduced nitrogen (green) for the period 1800-2100, shown as diagrams for each EMEP grid (50km) covering Switzerland.*

Chloride and base cation deposition trends are (not yet) provided. We have therefore adopted, as earlier, national deposition trends (Fig. 11) from the initial national dynamic modeling exercise (SAEFL, 1998). Chloride deposition trends are entirely based on the Swiss national hydrochloric acid emission evolution compiled by the BUWAL (1995). Before 1900, chloride depositions were scaled down more or less along the sulfur trend to a background value of ca. 25 mol_c ha^{-1} a^{-1} in 1800. Deposition after 2000 was slightly reduced to 40 mol_c ha^{-1} a^{-1} by 2050 and kept constant until the end of the simulation period. The evolution of base cation (Ca^{2+}, Mg^{2+}, K^+ and Na^+) emission and deposition trends still is subject to controversy, mainly due to an almost complete lack of data. For this study, we have tentatively scaled 20% of the originally constant base cation deposition with the trends of dust emissions in Switzerland (BUWAL 1995). This leads to steadily increasing base cation deposition prior to 1960 and rather strongly decreasing base cation deposition after 1960. From 2030 onwards, values were kept constant until the end of the simulation period.

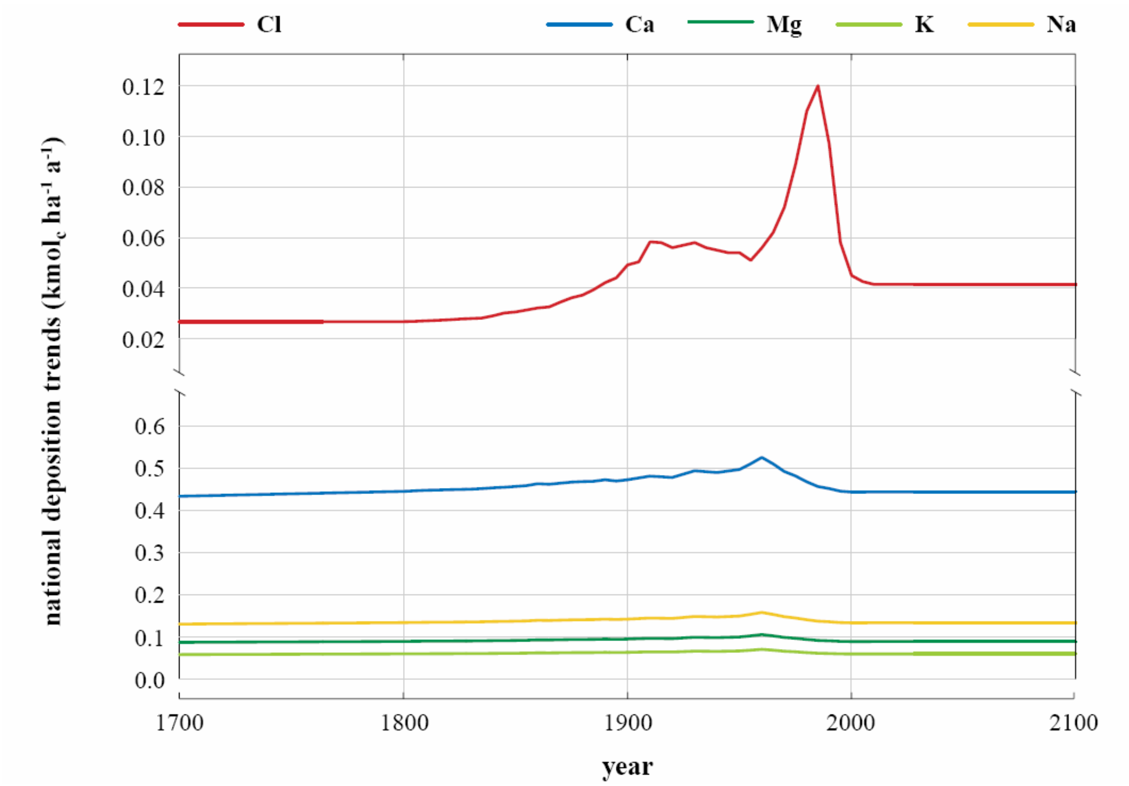


Figure 11. *National chloride and base cation deposition trends used to extrapolate current site-specific deposition in time.*

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Glossary

Bc	base cations (Ca + Mg + K)
DD	dry deposition (gas or aerosols)
WD	wet depositon
doy	day of year (1..365/366)
E	Einstein = 1 mol photons = 6.022 $*10^{23}$ photons
IPCC	United Nations Intergovernmental Panel on Climate Change
k_t	clearness index, ratio of global radiation on earth's surface and extraterrestrial radiation
PAR	photosynthetically active radiation
TT	monthly mean air temperature (°C), 2 m above ground
TD_{max}	air temperature - monthly average of daily maxima (°C)
TD_{min}	air temperature - monthly average of daily minima (°C)
TT_{min}	monthly minimum of air temperature (°C)
RR	monthly sum of precipitation, above canopy (mm)

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Monitoring, experimental data and geochemical evaluations related to the modelling sites

Sabine Braun[8], Salim Belyazid[9], Dani Kurz[10] and Harald Sverdrup[11]

Parameterisation of the vegetation table

An expert meeting was held with B. Nihlgård (Nihlgård, 1972; Nihlgård and Lindgren, 1977) and E. Landolt (Landolt, 1977) to parameterise a vegetation table with representative plant species. 89 species were selected (see annex), namely 6 mosses, 7 dwarf shrubs, 15 grasses, 5 brackens, 28 herbs as well as 28 trees and shrubs. Indicator values were assigned by expert knowledge for acidity, water, temperature, light, plant height, root depth, life time and grazing preference.

Sites used for comparison with model output

From a network of 133 forest observation plots (Flückiger and Braun, 1998, Braun et al., 1999), 32 plots were selected for model work (Fig. 1). The selected plots are all equipped with suction cups for collection of soil solution, and most of them have soils that are poor in base cations. Information on soil morphology and soil chemistry, tree biomass, stem increment (Fig. 2) and ground vegetation is available for all plots as well. In 10 plots also soil moisture is monitored which allows some validate of the hydrology outputs from ForSAFE.

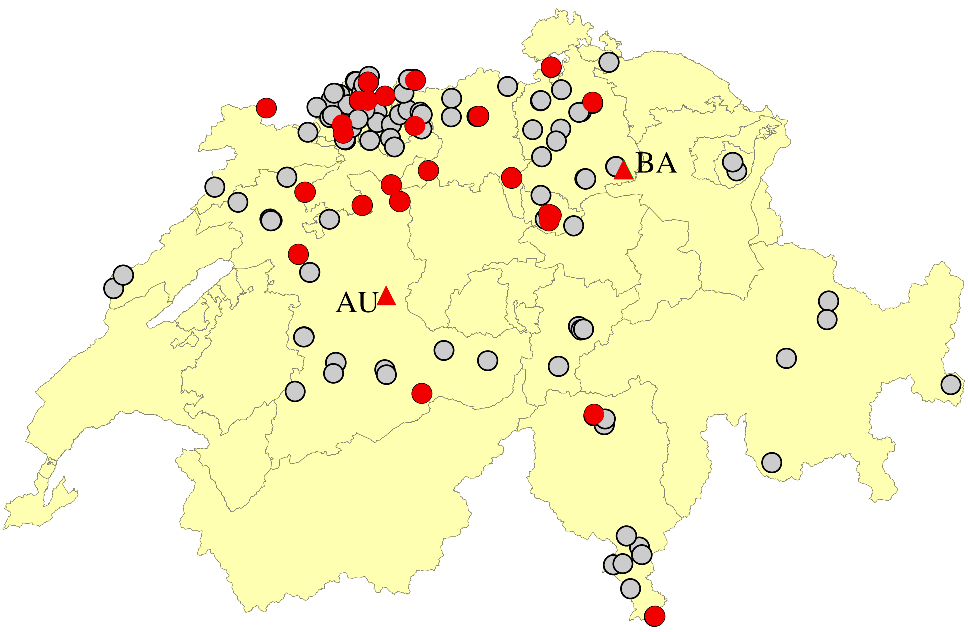

Fig. 1: *Network of forest observation plots (grey) and plots selected for model work (red). The plots Aeschau (AU) and Bachtel (BA) are highlighted.*

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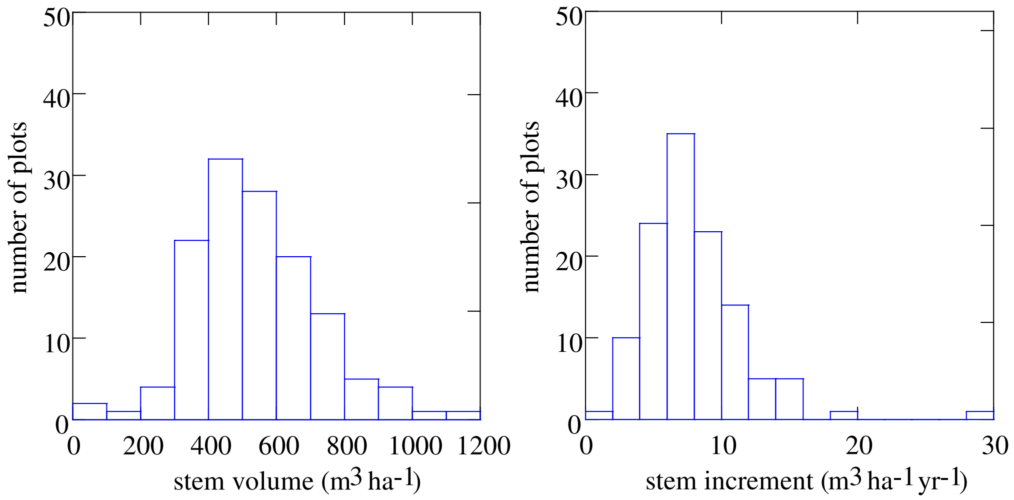

Fig. 2: *Density distribution of biomass of 133 plots (left) and of stem increment between 2002 and 2006 of 119 plots (right).*

Input data to the model

Site history

Stand age is available for all forest plots. For some of them, site history was traced back as far as possible. In most cases, this was possible back to at least 1876 when a forest law was enacted in Switzerland to maintain sustainability which demanded detailed records. In some cases it was possible to follow the forest history back to 1770. For Bachtel no detailed information is available except stand age. The plot Aeschau has been recorded as selection forest already in 1865, i.e. as a forest stand with removal of single trees, without clear-cut. After attempts to transform into a high forest it is managed today again as selection forest. Other former management systems include coppice or coppices with standards, with high forest in higher elevations. The utilization of branches was a common practice till about 1950.

Soil parameters

Soil morphology was evaluated from a soil pit following the classification system of Benzler et al. (1982). Samples were collected by layer and analysed for exchangeable cations according to Trüby and Aldinger (1984) using an unbuffered NH_4Cl extract as well as for total nitrogen and carbon. The mineral composition of the soil of a site was quantified from the bulk chemical analysis (XRFA) of each individual soil layer using the algorithm A2M (Posch and Kurz, 2007). The site-specific qualitative mineralogy was identified by means of optical microscopy of the fraction >63 µm of at least one sample per site. Furthermore, conventional X-Ray diffraction analysis was used to determine the clay mineralogy of the samples' fraction <2 µm. Stoichiometries for the minerals identified were drawn from the literature. To remain internally consistent, stoichiometries used for the quantification of the mineralogy were also introduced into the MineralData file (i.e. site specific MineralData file) which contains kinetic data and stoichiometries both being used by ForSAFE to calculate weathering rates. As suggested by Jönsson et al. (1995), we have area weighted the quantitative mineralogy.

Comparison of model output with field data

Vegetation table

The model output of the test sites Aeschau and Bachtel was compared to ground vegetation assessment (Tab. 1). A quite large proportion of the species present at these two sites were modelled correctly although improvements are still possible. *Rubus fruticosus* and *Oxalis acetosella* were predicted even with a correct estimate of the cover degree. The presence of *Vaccinium myrtillus*, *Blechnum spicant*, *Dryopteris dilatata* and *Polytrichum formosum* was also forecasted correctly in both sites.

	Number of species	
	Aeschau	Bachtel
modelled and observed	8	8
modelled but not observed	5	9
observed but not modelled	2	6
observed, but not assigned to any plant group	4	10

Tab. 1: *Comparison of number of modelled and observed ground vegetation species at the two Swiss sites Aeschau and Bachtel.*

The ForSAFE-VEG model runs (see contribution by Sverdrup et al.) predict a sensitive reaction of *Rubus fructicosus* cover to N deposition. This is confirmed by observations from the forest plots. With N deposition of >25 kg N ha^{-1} yr^{-1}, cover by *Rubus* increases exponentially (Fig. 3). In plots with repeated ground vegetation assessment, the cover by *Rubus* increased significantly from 1984 to 2003, especially where it had been low before (Fig. 5). This cannot be explained only by management as e.g. in the plot Bachtel tree cover even increased during this time period. Simultaneously, the average Ellenberg score class in the plots was significantly higher in 2003 than in 1984 (Fig. 4).

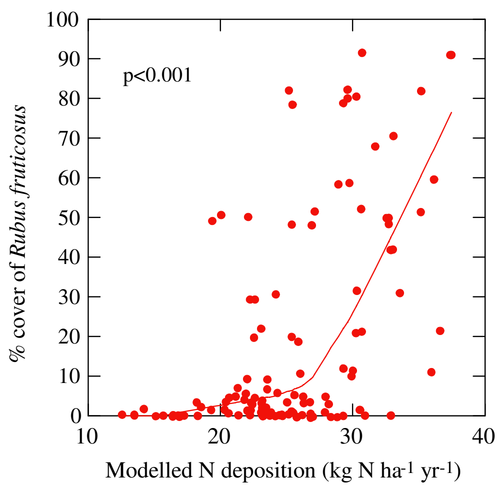

Fig. 3: *Cover of Rubus fruticosus in all forest observation plots in relation to modelled N deposition. The line is a smoother through local median values (SYSTAT function LOWESS).*

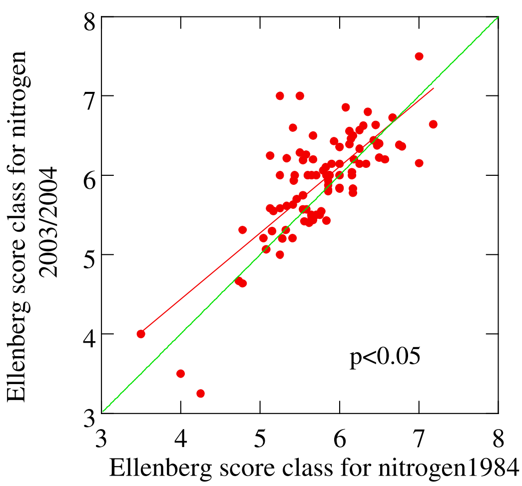

Fig. 4: *Average Ellenberg score class for nitrogen in 1984 und 2003 (48 relevés in 23 observation plots). The red line is the regression through the points, the green line is the 1:1 line.*

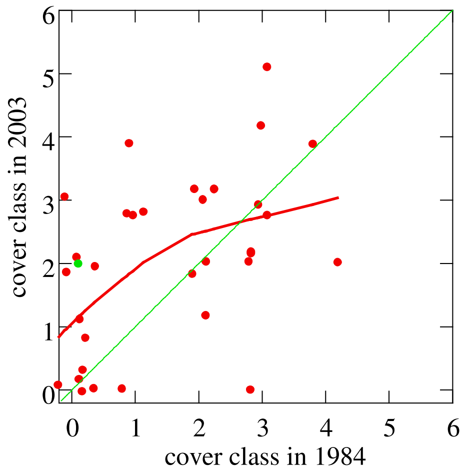

Fig. 5: *Braun-Blanquet cover class of Rubus fruticosus in 1984 and 2003 (35 relevés in 22 plots). The red line is a smoother through local median values, the green line is the 1:1 line. The increase from 1984 to 2003 is significant at p<0.05. Green point: Bachtel.*

Biomass data

Biomass was predicted well for the two Swiss test sites (Fig. 6). The difference in the lines for Aeschau and Bachtel reflect the different management system (selection forest in Aeschau, high forest in Bachtel).

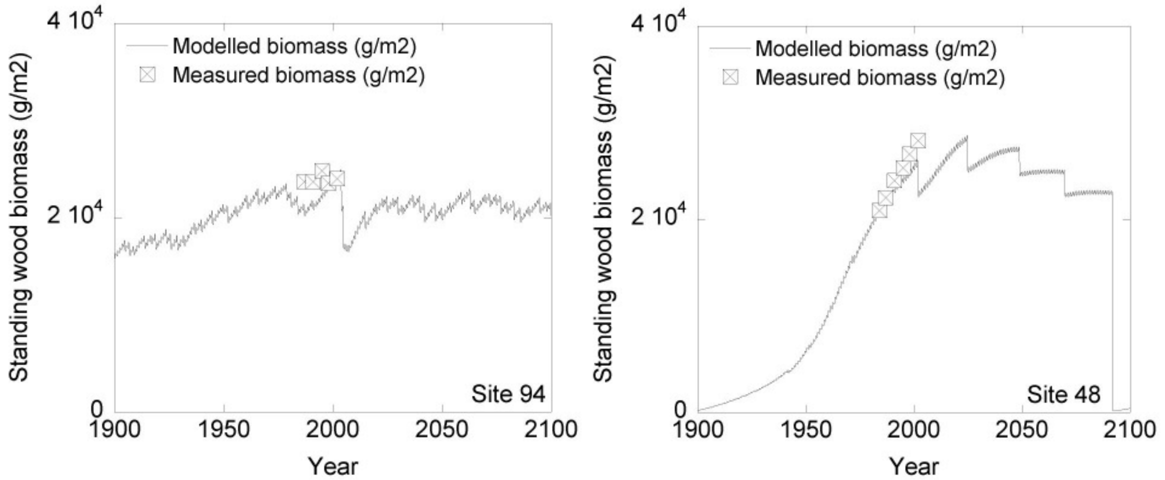

Fig. 6: *Comparison between measured biomass (squares) and biomass modelled using ForSAFE (line) for the plots Aeschau (left) and Bachtel (right).*

Litterfall

Litterfall was measured in 8 plots. Four of them include comparisons between adjacent beech and spruce plots (BA, BR: spruce, BAB, BRB: beech). The wood fraction collected consists of dropped branches, it does not include decaying wood debris. For comparison with model calculation, data are available for Bachtel. From Tab. 2 it can be seen that measured litterfall was higher than the modelled numbers. The measured loads for N, Ca and Mg are correspondingly higher, for K the modelled value is higher which suggests that the K concentration in leaf litter is overestimated.

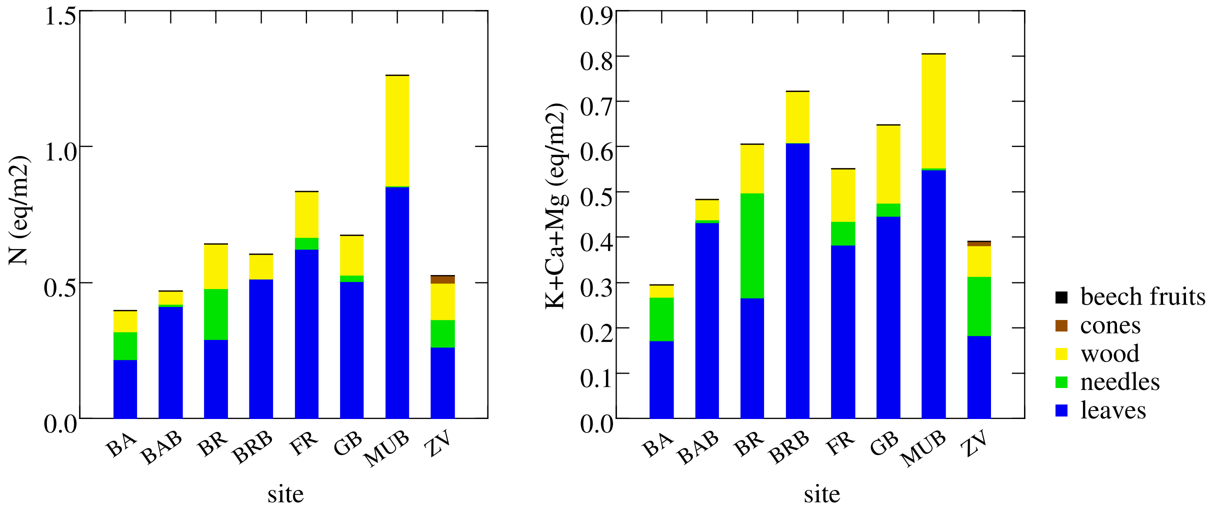

Fig. 7: *Litterfall of N and Ca+Mg+K in 8 forest observation plots. BAB (Bachtel), BRB (Brislach) and MUB (Muri) are beech plots, BA (Bachtel), BR (Brislach) and ZV (Zugerberg Vordergeissboden) spruce plots and FR (Frienisberg) and GB (Grenchenberg) are mixed stands.*

	Measured	Modelled
dry matter	425	300
N	4.47	2.67
Ca	4.09	1.27
Mg	0.55	0.25
K	0.70	2.70

Tab. 2: *Litterfall in Bachtel in the year 2005 (excluding branches collected in the litterfall traps). Units are g/m^2.*

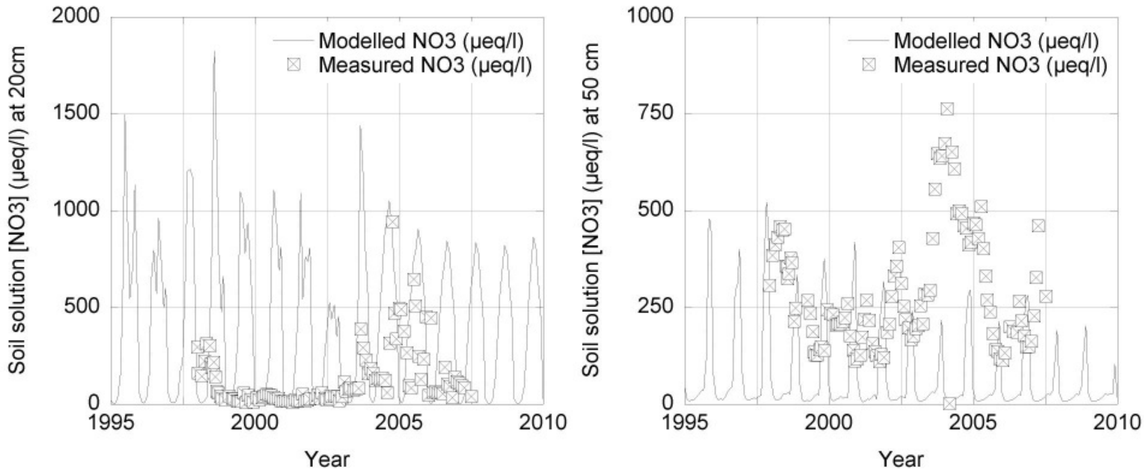

Fig. 8: *Comparison between measured (squares) and modelled nitrate concentration (line) for the plots Aeschau (left) and Bachtel (right).*

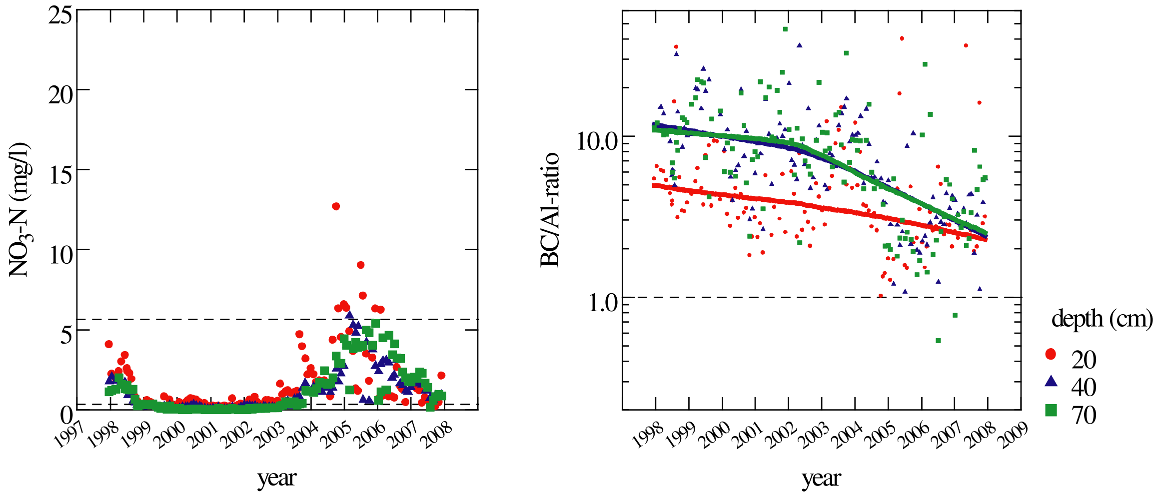

Fig. 9: *Measured nitrate concentrations (left) and BC/Al ratio (right) in different depths of the observation plot Aeschau. The lower dashed line in the left graph is the concentration which corresponds to the maximum tolerated nitrate leaching for non-polluted ecosystems (UN/ECE, 1992), the higher the Swiss limit for drinking water quality. The dashed line in the right graph is the critical BC/Al limit.*

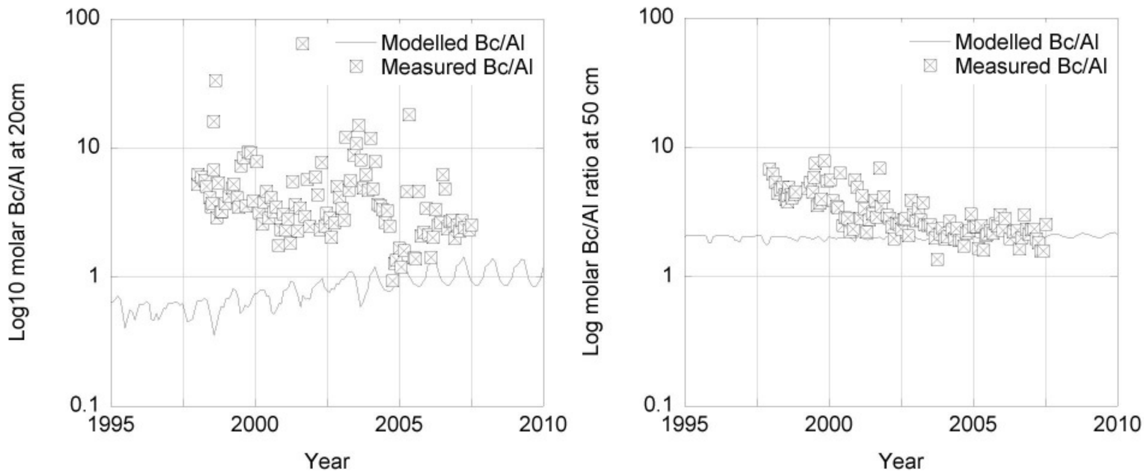

Fig. 10: *Comparison between measured (squares) and modelled BC/Al ratio (line) for the plots Aeschau (left) and Bachtel (right).*

Soil solution chemistry

The modelled nitrate concentration in the soil solution show a large seasonal variation which is not reflected by the measurements (Fig. 8). In the site Bachtel the measured concentrations never reach the lower end of the predicted variation which means that uptake in summer is overestimated by the model. However, the peak value agree reasonably well at this site. In Aeschau, nitrate concentrations are overestimated. The measured nitrate peak in the soil solution of Aeschau is caused by a management event (see also Fig. 6). It is paralleled by a decrease in BC/Al ratio especially in the lower soil layers (Fig. 9). The BC/Al ratio is underestimated by the model, more in Aeschau than in Bachtel (Fig. 10). The hydrology as reflected by the Cl concentration is modelled well (Fig. 11).

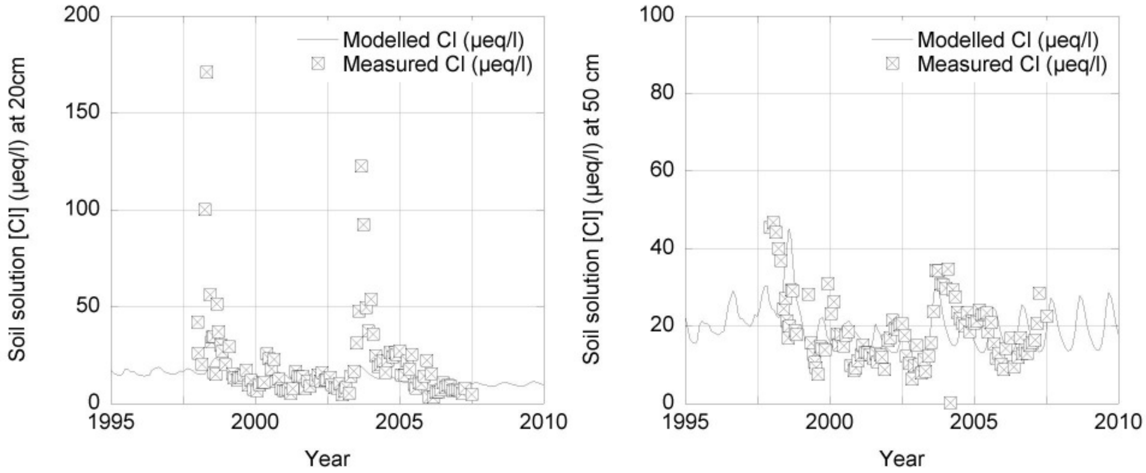

Fig. 11: *Comparison between measured (squares) and modelled chloride concentration (line) for the plots Aeschau (left) and Bachtel (right).*

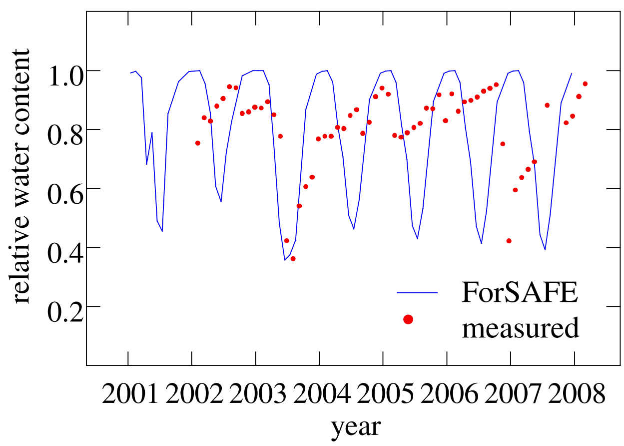

Fig. 12: *Soil moisture data modelled with ForSAFE in comparison to measured data (monthly averages) at 20 cm depth.*

Soil moisture

Volumetric soil moisture data are available for the site Bachtel. They were compared to the modelled data. Although the chloride concentrations of the soil solution indicate that the hydrology is about correct, the seasonal variation modelled by ForSAFE is much greater than in the measured values, and the difference between years is much smaller (Fig. 12). The differences seen in Fig. 12 may be caused by the deviation of the microscale hydrology at the site from the stand-generalized hydrology used in the model. We have observed that the accumulated water flux fits well, implying that the water is slightly dislocated in time.

Room for improvement in the present model

The ForSAFE-VEG is in a state of steady development and we have seen after the present runs that some changes are desired to the model.

1. ***Change of tree species*:** The model will be complemented with a routine that will allow for gradual or abrupt change of tree species in the model. Tree species composition is a result of forest management and may change during time. Often this is not the naturally dominating species. Up to now, it was not possible to change the species composition during a model run. This should be kept in mind for future versions of the model.
2. ***Phosphorus*** We need to complement the model with a simple phosphorus availability sub-model. The will be based on a simple concept focusing on tree nutrient cycling, weathering and decomposition. This will utilize existing driving engines already present inside the model. In the forest observation plots, a striking increase of P deficiency was observed between 1984 and 2007 (Tab. 3). This P deficiency has consequences for growth (Tab. 4) and may be the reason why the stem increment of beech has decreased since 1987 (Fig. 13). N addition experiments suggest that this P deficiency may result from increased N deposition (Fig. 14). Thus, the P nutrition has to be taken into account when growth is modelled from climate data and nutrient availability. We also have reason to suspect that some plants, for example Urtica, are affected in their competition abilities by the availability of phosphorus in small or large amounts. Thus for biodiversity assessments this is also desirable.

	Year	Number of plots	Strongly deficient ≤0.8	Slightly deficient >0.8-1	Normal >1 mg
Fagus sylvatica	1984	51	0	11.8	88.2
	1987	57	5.3	8.8	86
	1991	55	5.5	27.3	67.3
	1995	52	5.8	17.3	76.9
	1999	53	26.4	30.2	43.4
	2003	53	13.2	52.8	34.0
	2007	52	25.0	46.2	28.8
Picea abies	1984	18	5.6	5.6	88.9
	1987	27	7.4	40.7	51.9
	1991	35	40	25.7	34.3
	1995	38	18.4	44.7	36.8
	1999	52	30.8	28.8	40.4
	2003	50	20.0	28.0	52.0
	2007	48	33.3	33.3	33.3

Tab. 3: *Development of the proportion of forest observation plots with P deficiency (%). P concentrations in mg P/g d.m.*

	P mg/g d.m.	Number of trees	Increment (cm^2/year)	95% confidence interval
Fagus sylvatica	≤0.8	57	27.7	25.4 - 29.9
	>0.8-1	97	33.3	31.3 - 35.2
	>1	200	34.3	32.9 - 35.7
Picea abies	≤0.8	67	26.9	25.0 - 28.8
	>0.8-1	50	28.8	26.3 - 31.2
	>1	53	31.2	28.7 - 33.6

Tab. 4: *Growth of cross section area of beech and Norway spruce in relation to P concentration in the foliage (assessment on the basis of individual trees). In both tree species the relation is significant at p<0.01.*

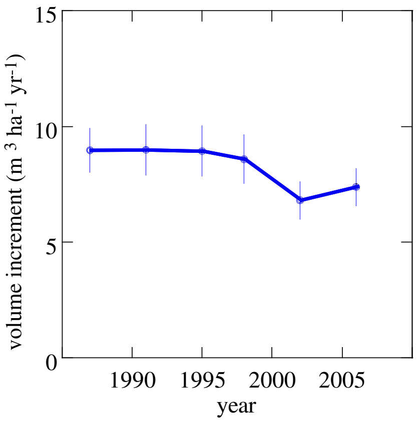

Fig. 13: *Development of biomass increment in beech plots between 1984 and 2007 (41 plots). Bars: 95% confidence interval.*

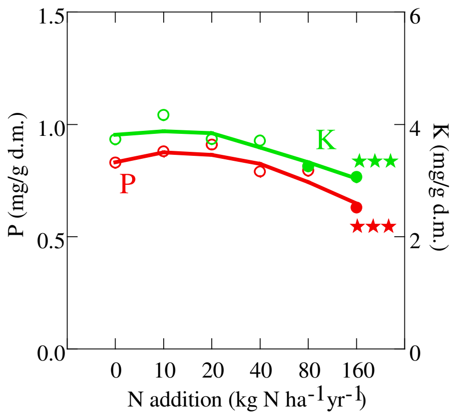

Fig. 14: *Effect of N addition on the concentration of P (red) and K(green) in leaves of young beech. The asterisks indicate a significant linear trend with increasing N addition, filled data points significant differences to the control (n=9-12).*

3. ***Adaptation of the ForSAFE-VEG model to open land conditions.*** The adaptation of the model to model open land is needed for above tree-line areas, montane meadows, coastal land, tundra and grasslands. This would require two main items to be fixed permanently:
   a. The inclusion of a proper carbon and nitrogen mass balance for each plant group, in order to have a proper carbon and nitrogen cycle without the presence of trees and forest cover. The model also needs uptake of N to ground vegetation for being able to better predict N leaching from clear-cut areas in the forest. At present the N leaching is somewhat over-predicted in intensity and temporal length.
   b. The inclusion of the effect of wind on the ground vegetation through wind chill that decrease the temperature and the effect of mechanical stress on plants by the force of the wind.

Adaptation of the model to open land conditions would put the model in reach of many important biodiversity sites outside the traditional forested ecosystems.

4. Potassium nutrition and drought resistance

In a N addition experiment on calcareous soil, a serious K deficiency developed during the experiment which was aggravated by N addition (Fig. 14). This K deficiency was correlated with drought necroses (Fig. 15). A relation between N deposition and K concentration in the foliage was also observed in mature forest stands during the dry year 2003 (Fig. 16). As K is involved in the control of the stomatal opening, these observations suggest that its deficiency results in increased water loss. Such scenarios should be included into the models as climate change is expected to increase drought.

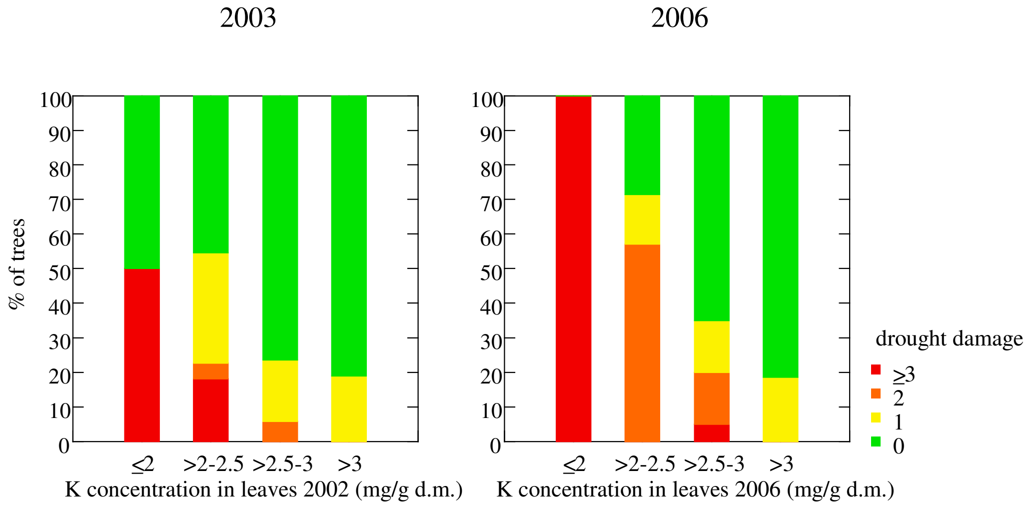

Fig. 15: *Drought necroses in beech leaves in relation to K concentration in the leaves. Both relations are significant at p<0.001.*

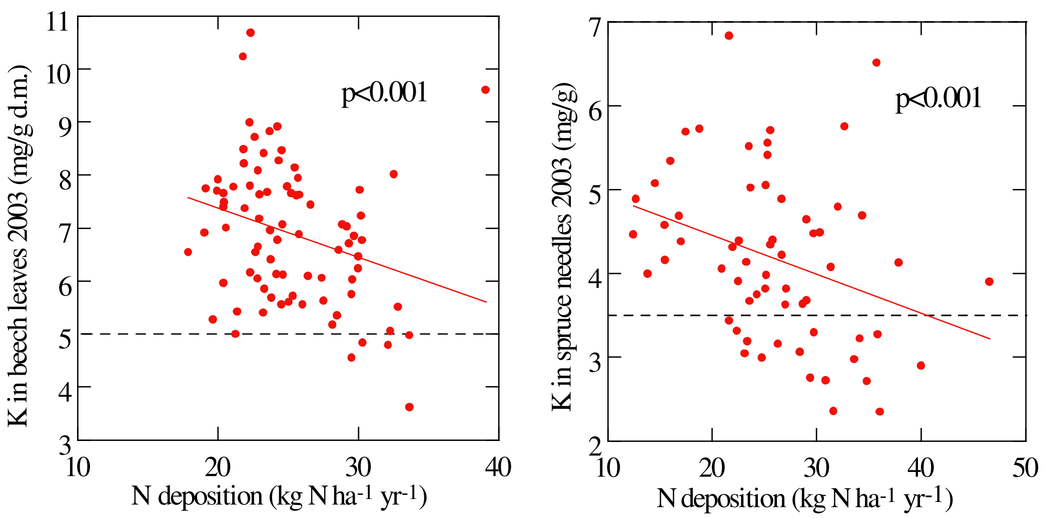

Fig. 16: *Relation between K concentration in the foliage of beech (left) and Norway spruce (right) in relation to modelled N deposition. Samples collected in summer 2003, during the drought. The dashed line marks the lower end of the optimal range.*

Conclusions

The comparison of the output of ForSAFE-VEG with field data shows encouraging results. We must conclude that ForSAFE-VEG is a strong tool for risk assessment both for the past and the future.

Acknowledgments

The model work, the N experiments and the analysis of soil solution were supported by the Federal Office for Environment, the forest observation by the Swiss cantons of Aragau, Bern, Basel Land, Basel Stadt, Fribourg, Solothurn, Toggenburg, Zug and Zürich. We thank all our supporters for their interest in our work.

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Forecasting Air Pollution Impacts on Biodiversity and Habitat Quality: A British Study[1]

Ed C. Rowe[2], Chris D. Evans[2], Simon Smart[3] and Bridget A. Emmett[2]

1. INTRODUCTION

The Convention on Long-Range Trans-boundary Air Pollution (CLRTAP) of the UNECE is an effective international policy instrument that uses evidence of actual or potential damage from pollutants to set emissions limits. The CLRTAP has been particularly successful in regulating emissions of the acidifying pollutants nitrogen (N) and sulfur (S). Damage indicators and thresholds are currently defined in terms of soil chemical criteria such as pH or Ca/Al ratio. This approach is being reconsidered due to two pressures. Firstly, a large reduction in S emissions has shifted the emphasis from acidification damage towards eutrophication, i.e. a damaging increase in ecosystem productivity driven by N pollution. Secondly, EU conservation legislation uses habitat quality indicators that are largely based on species occurrence, not soil properties. Hence, we have developed a model chain that predicts the effects of pollution emissions scenarios on species-based habitat quality indicators, by linking models of pollutant deposition, soil chemistry, species occurrence and habitat quality. This requires much trans-disciplinary communication, so there is a clear requirement for transparency in model description, in particular the definition of model inputs and outputs.

2. SIMULATING SPECIES OCCURRENCE

2. 1 Introduction

A two-stage process was used to simulate the effects of different N and S deposition scenarios on plant species. Firstly, a dynamic model [Cosby et al., 2001] which is currently used by the UNECE Coordination Centre for Effects to simulate effects of pollution on soil [de Vries et al., 2007] was used to predict changes in soil pH and carbon (C) to N ratio. These variables were used as inputs into a set of static regression models [Smart et al., in prep.] which predict species' probabilities of occurrence under a given set of environmental conditions.

2.2 Soil chemistry

The MAGIC model focuses on acid-base dynamics, solving at each time-step a system of linear equations that describe ionic competition for exchange sites. This model also simulates N dynamics using a simple saturation function. Nitrogen pollution affects habitats mainly through effects on competition. With a decrease in N limitation, low-growing, light-demanding species are shaded out by increased growth of faster-growing and taller species. However, the soil micro-flora competes strongly with plants for N additions, and initial inputs of N into a pristine ecosystem are mainly immobilized by interaction with the soil carbon (C)

[1] *A version of this document was presented to iEMSs 2008: International Congress on Environmental Modelling and Software, Barcelona, under the title "Predicting Winners and Losers:Translating Air Pollution Policy Initiatives into Indicators of Habitat Quality."*

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pool, resulting in a decrease in soil C/N ratio [Gundersen et al., 1998]. Because of the large organic matter pool in most soils, C/N ratio changes only slowly with typical levels of atmospheric inputs. In the absence of historic soil measurements, N addition experiments allow predictions of soil C/N change to be assessed (Fig. 1).

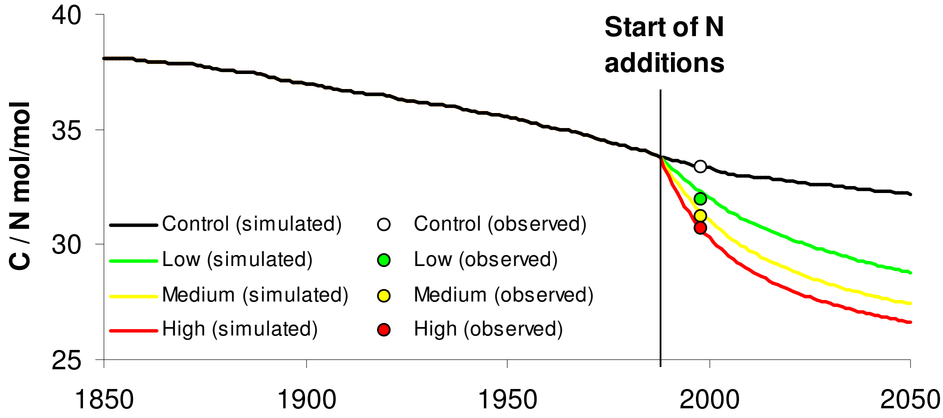

Figure 1. *Measured soil C/N ratio in an upland dry heathland (Ruabon, N Wales, UK) receiving 0, 40, 80 and 120 kg N ha^{-1} y^{-1} since 1988, and MAGIC simulations of this site [Evans et al., 2006]. Initial C/N was obtained by calibrating the model to measured C/N in the zero additions treatment.*

2.3 Plant niches

Plant species occur within specific ranges of environmental conditions, determined by their autecology, competition with other plants, and susceptibility to pests and diseases. This ‘realised niche’ is a hyper-volume within the space defined by a set of environmental factors. Maximum probabilities of occurrence exist for many species in relation to these factors, although some species have broad tolerance or bimodal distributions when plotted against individual factors. Ellenberg [1992] and subsequent authors defined optima scores for European plant species on arbitrary scales related to the availability of nutrients, water and light, and acid reactivity. We modelled the occurrence of plant species in two stages, to make use of datasets where environmental factors were measured alongside occurrence as well as the far larger datasets where only species were recorded. For the former dataset, multiple regression was used to calibrate mean scores for present species against five soil variables: total C and N content, pH, % soil moisture, and bicarbonate-extractable phosphorus. Minimum adequate models were determined by first rejecting factors with no significant effect on mean Ellenberg score and then using deviance reduction tests to accept or reject interactions and quadratic terms for the remaining factors. Next, multiple logistic regression was used to relate probability of occurrence within the larger dataset to the mean Ellenberg score, by stepwise elimination from the set of significant effects, interactions and quadratic effects. This results in a set of per-species models (Fig. 2), collectively known as GBMOVE, which can predict the probability of a species occurring under a given set of environmental conditions [Smart et al., in prep.].

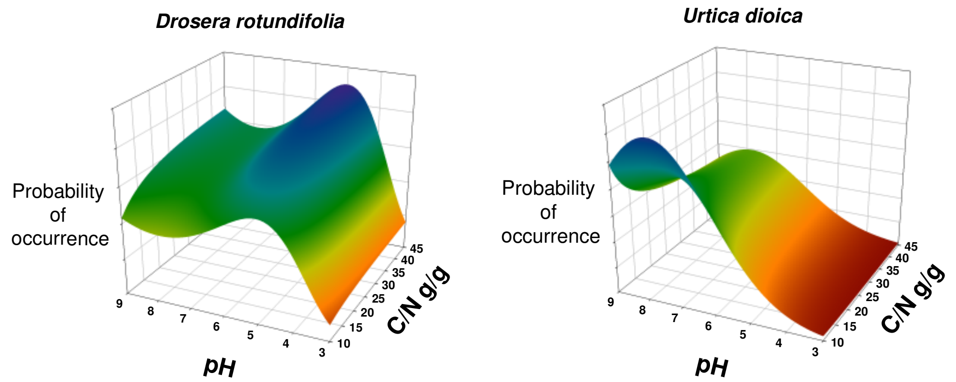

Figure 2. *GBMOVE niche models for Drosera rotundifolia and Urtica dioica (plants typical of infertile and fertile habitats, respectively) in relation to soil pH and soil carbon/nitrogen ratio, at fixed levels of canopy height (0.8 m), soil moisture content (35%) and soil carbon content (5%).*

2.4 Species dynamics

Coupling the MAGIC dynamic soil chemistry model with the GBMOVE static species niche model allows the dynamics of plant species occurrence to be simulated. Testing this model chain is difficult due to the scarcity of long-term datasets covering both soil chemistry and plant species occurrence. However, the model chain proved fairly successful in simulating the rates of change in probability of occurrence in a floristic dataset extending from 1973 to 2001 (Fig. 3).

3. FROM SPECIES OCCURRENCE TO BIODIVERSITY INDICATORS

Predictions of changes in probability of occurrence for a large number of individual species are of limited value in themselves for assessing habitat quality, which is assessed according to criteria such as rarity, typicality and fragility [Ratcliffe, 1977]. The Habitats Directive of the European Union [EEC, 1992] has lead in the UK to the development of Common Standards Monitoring (CSM) protocols [JNCC, 2006] which list species for each habitat, grouped into positive and negative indicators. We have used this categorisation to interpret predictions of species change, by calculating an overall habitat-specific quality score Q as

$$Q = \sum_{i=1}^{p} \frac{\left(\frac{P_i}{P\max_i}\right)}{p} - \sum_{j=1}^{n} \frac{\left(\frac{P_j}{P\max_j}\right)}{n} \qquad (1)$$

where P_i and P_j are the probabilities of occurrence of the p positive indicators and n negative indicators for a habitat, respectively, and *P*max is the maximum probability of occurrence for the species within the parameter space. Re-scaling to *P*max is necessary because the large variation in abundance of individual species within large survey datasets and in maximum occupancy of suitable sites means that absolute probabilities of occurrence vary widely. Rescaling to p and n allows for the variable numbers of positive and negative indicator species listed for different habitats. Species not included in the CSM indicator lists are not used in this calculation. The approach is illustrated using simulations of C/N and pH change due to atmospheric S and N deposition (Fig. 4). Whilst with more N pollution the probability of occurrence increases for some positive indicators, and decreases for some negative indicators, the overall pattern of response is for N pollution to favour negative over positive indicators and so there is a clear decline in the overall quality score.

4. MODEL IMPROVEMENT

4. 1 Uncertainty

Linking models increases uncertainty related to both parameterisation and model structure. A major source of uncertainty in the MAGIC-GBMOVE model chain relates to the prediction of mean Ellenberg fertility score from soil biophysical measurements. Between-habitat variation in the inert proportion of soil organic matter [Rowe et al., 2006] results in a poor correlation between total soil C and N pools and mean Ellenberg fertility score. We are currently measuring a set of soil properties including mineralisable N alongside floristic data in a large national survey, to identify more accurate predictors. This reduction in parameter-uncertainty will however lead to a requirement for more structural complexity in the soil organic matter model.

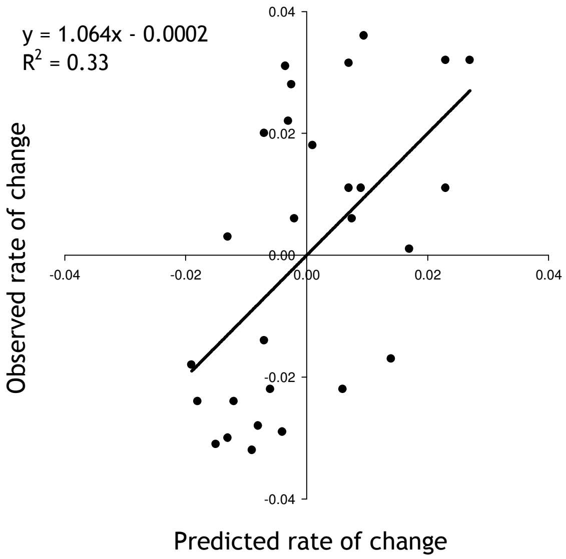

Figure 3. *Predicted versus observed change for individual species in blanket bog (Moor House long-term monitoring site, Cumbria, UK). Predicted change is the slope coefficient of a linear regression on occurrence probabilities predicted by the MAGIC-GBMOVE model chain for each year between 1973 and 2001. Observed change is the slope coefficient of a linear regression on % frequency in sample plots in each survey year. Pearson correlation coefficient = 0.568, p=0.002. [Smart et al., 2005]*

4. 2 Additional drivers

The inclusion of multiple environmental gradients in the GBMOVE niche models offers the potential to link to other dynamic biophysical models. Canopy height is used in the niche models as a surrogate for ground-level light availability, which has a profound effect on environmental suitability for plant species. We are currently using this mechanism to link GBMOVE to the SUMO vegetation model [Wamelink, 2007] to simulate the effects of vegetation succession on plant species occurrence. The effects of changes to rainfall pattern could be represented via effects on mean soil moisture content. We have also developed an extended version of GBMOVE that includes other climatic variables, allowing simulations of climate change. Since the niche models are based on empirical data that includes the effects of multiple drivers, we have some confidence that this approach can be applied to simulations of several interacting biophysical drivers.

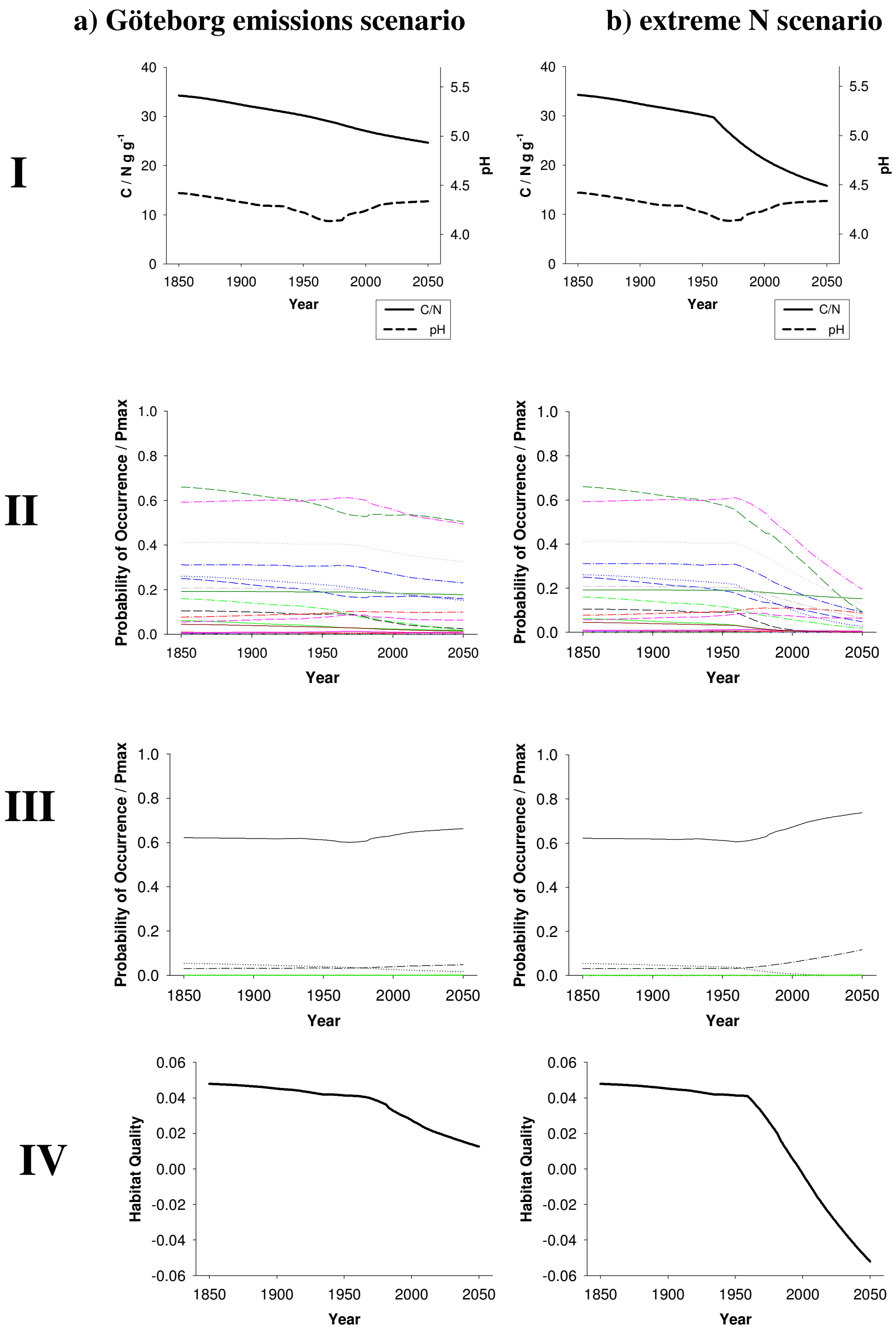

Figure 4. *Simulated changes in blanket bog at Moor House long-term monitoring site, Cumbria, UK, under a) Göteborg emission scenario, and b) an extreme N addition scenario with an additional 50 kg N ha^{-1} yr^{-1} from 1960. (I) Soil pH and C/N ratio simulated using the MAGIC soil chemistry model. Soil water content and canopy height were assumed to be constant. (II) Probabilities of occurrence of positive Common Standards Monitoring indicator species for blanket bog, rescaled to Pmax. (III) Probabilities of occurrence of negative CSM indicator species for blanket bog, rescaled to Pmax. (IV) Overall habitat quality Q (see equation 1).*

4. 3 Open model development

The model development process has historically been monopolised by the subset of scientists who are also programmers. We are using several methods to open this process to wider scrutiny and discussion. Static niche models related to measurable factors are easily understood and checked by plant ecologists, compared with dynamic models of species populations or of cover proportion. Dynamic soil chemistry models written in FORTRAN are being re-implemented in SIMILE graphical modelling software [Muetzelfeldt and Massheder, 2003], which can be understood and assessed by non-programming modellers. This also makes it easy to see submodel boundaries, eliminating the danger of double representation of processes when combining models. Lastly, the use of CSM indicators to assess habitat quality allows discussion with habitat specialists in the UK nature conservation agencies using familiar terms.

5. CONCLUSIONS

By linking a dynamic soil chemistry model to static plant niche models, we have obtained positive correlations between predicted and measured change in the abundance of individual plant species. This approach could be applied to a variety of other problems in nature conservation, which urgently requires methods for predicting the effects of a changing environment on species abundance. The proposed one-dimensional habitat quality summary statistic is based on indicators used by conservationists and policymakers, yet allows definition of a simple damage threshold that could be used to define acceptable pollutant loads.

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