

A Multimedia Spatial Resolving Model for Mapping the Impact of Anthropogenic Depositions on High Elevated Alpine Forests.

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Abstract A multimedia approach is presented to evaluate the atmospheric impact on Alpine forests in Switzerland. The aim of this approach is the determination of anthropogenic air pollutants leading to wet and dry depositions in an area along the Sankt Gotthard transect crossing the Alps in the North-South direction and to evaluate the possible changes in the soil chemistry. This approach takes into account the historical development of the emissions in order to calculate the depositions back to the beginning of this century and is spatially resolving to realise the mapping of critical levels and loads. The deposition model is supplemented with a soil model in order to calculate the future development of the forest soil. It is shown, that a sustainable development of the Alpine ecosystems under consideration is only possible on condition of a 60 % reduction of nitrogen and sulfur deposition.

1. Introduction

The protection forest in the elevated regions of the Alps in Central Europe are known to be subjected to increased natural stresses such as sudden temperature decreases, dryness, short vegetation periods, frost and windfall. Therefore, the threshold values for harmful anthropogenic depositions, especially the critical loads for acidity and nitrogen, should be carefully observed in order to avoid exceedances. This impact of air pollutants on the Alpine forest ecosystems are of crucial importance from an economical point of view, since these forests protect the inhabitants and the important trade routes connecting Northern and Southern Europe against avalanches, falling rocks and land slide (see Nater et al. 1994).

A field measurement campaign during the years 1991 and 1992, followed by data analysis based on atmospheric deposition and soil models was carried out for one of the most important trade routes of Europe, the St. Gotthard pass along the upper Reuss Valley in Switzerland. The aim of this study was to evaluate the deposition of air pollutants and their possible impact on the forest soil over a region of 10x20 km with a resolution of 250 m and over a time period going back in history to the beginning of this century and looking 100 years into the future by means of selected deposition scenarios.

2. Atmospheric deposition modelling

Meteorological processes and the development of anthropogenic emissions since the year 1901 are used to evaluate the deposition of nitrogen and sulphur over various paths in dry and wet media. To illustrate the deposition mechanisms involved and the gases and ions deposited along the various deposition pathways, an example of the appropriate fluxes for a site at the bottom of the valley (Silenen) and at the valley slope (Waldiberg, values separated with a slash) for the annual mean values in 1992 are listed below:

- Dry deposition of gases
for ozone (2.94/3.85 kmol/hayr).
for ozone flux through the stomates of the needles ($O_{3,st} = 0.68/0.80$ kmol/hayr),
for NO_2 (9.7/3.5 kgN/hayr),
for HNO_3 (0.65/0.46 kgN/hayr).
for NH_3 (3.4/2.7 kgN/hayr) and
for SO_2 (10.4/6.0 kgS/hayr).
- Dry deposition of aerosols
(suffix *ae*)
for NH_4^+ (1.51/1.18 kgN/hayr).
for NO_3^- (0.057/0.037 kgN/hayr),
for SO_4^{2-} (1.57/0.91 kgS/hayr),
for H^+ (0.15/0.11 keq/hayr) and
for base cations (Ca^{++} and Mg^{++} abbreviated as BC^{++} , Na^+ and K^+ abbreviated as BC^+ , both abbreviated as BC , 0.23/0.16 keq/hayr).
- Wet deposition via cloud water and fog (suffix *cw*)
for NH_4^+ (0.47/0.93 kgN/hayr).
for NO_3^- (0.55/1.18 kgN/hayr).
for SO_4^{2-} (1.86/2.73 kgS/hayr).
for H^+ (0.054/0.034 keq/hayr).
for BC (0.38/0.63 keq/hayr).
- Wet deposition via precipitation (suffix *p*)
for NH_4^+ (1.58/1.45 kgN/hayr).

for NO_3^- (1.83/2.04 kgN/hayr),
 for SO_4^{2-} (3.62/2.45 kgS/hayr),
 for H^+ (0.053/0.039 keq/hayr),
 for BC (0.42/0.32 keq/hayr).

Some relevant additional quantities are derived from these deposition values:

- present load of reduced nitrogen
 $\text{NH}_y = \text{NH}_3 + \text{NH}_4^+_{a,e} + \text{NH}_4^+_{c,w} + \text{NH}_4^+_{i,p}$
 (7.0/6.2 kgN/hayr)
- present load of oxidized nitrogen
 $\text{NO}_y = \text{NO}_2 + \text{HNO}_3 + \text{NO}_3^-_{a,e} + \text{NO}_3^-_{c,w} + \text{NO}_3^-_{i,p}$
 (14.1/8.1 kgN/hayr)
- present load of total nitrogen
 $\text{Ndep} = \text{NH}_y + \text{NO}_y$
 (21.1/14.3 kgN/hayr)
- present load of sulfur
 $\text{Sdep} = \text{SO}_2 + \text{SO}_4^{2-}_{a,e} + \text{SO}_4^{2-}_{c,w} + \text{SO}_4^{2-}_{i,p}$
 (17.5/12.0 kgS/hayr)
- present load of potential acidity
 $\text{ACdep} = \text{Ndep} + \text{Sdep}$ (1.82/0.87 keq/hayr)
- bulk deposition of BC
 $\text{BCdep} = \text{BC}_{a,e} + \text{BC}_{c,w} + \text{BC}_p$
 (1.02/1.11 keq/hayr)

For all processes described with the atmospheric deposition model, the numerical formulation is tested for the measurements during the field campaign in the year 1992. This calibration takes care of models, which require only parameters that are available or easily derivable from given measurements. Fortunately, the meteorological measurements at a site in the valley bottom and a few other sites in the Alpine region are known since 1901. For the historical development of the emissions, the values from known energy use such as fossil fuel burning, traffic intensity and so forth are used. After a split of the processes according to three different time scales (century, seasonal and diurnal variations) and two spatial scales (regional and local), the depositions are modelled spatially and temporally resolved, as described in Graber et al. (1994). The century variation of some depositions on the regional scale are taken from the literature and plotted in Fig. 1.

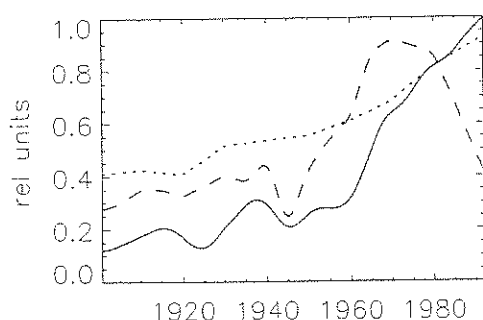


Figure 1: Trend of HNO_3 deposition (solid), ammonia deposition (dotted) and sulfur deposition (dashed) in rel-

ative units on a regional scale since 1901.

A more complete description of the model approaches is given in BUWAL, 1995. Fig. 2 shows the contributions of NO_y and NH_y , summing up to the present load of total nitrogen (Ndep). Fig. 3 shows the contributions of Sdep and Ndep, summing up to the present load of potential acidity.

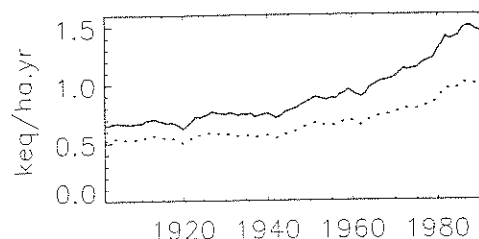


Figure 2: Present load of reduced nitrogen (NO_y , dotted) and present load of total nitrogen (Ndep, solid) for a site at the bottom of the valley (Silenen) from 1901 to 1992. (The difference of Ndep minus NO_y equals the present load of oxidized nitrogen (NH_y).)

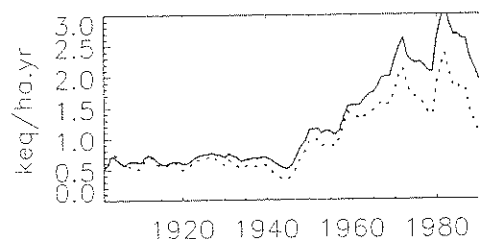


Figure 3: Present load of sulfur (Sdep, dotted) and present load of potential acidity (ACdep, solid) for a site at the bottom of the valley (Silenen) from 1901 to 1992. (The difference of ACdep minus Sdep equals the present load of nitrogen (Ndep).)

For further insight into the spatial distribution of the depositions, the topography and, as an example, the deposition of NO_3^- via cloud water ($\text{NO}_3^-_{c,w}$) are depicted in Fig. 4 and 5. Fig. 5 shows the predominant deposition of $\text{NO}_3^-_{c,w}$ along the slopes, where the clouds are most often located.

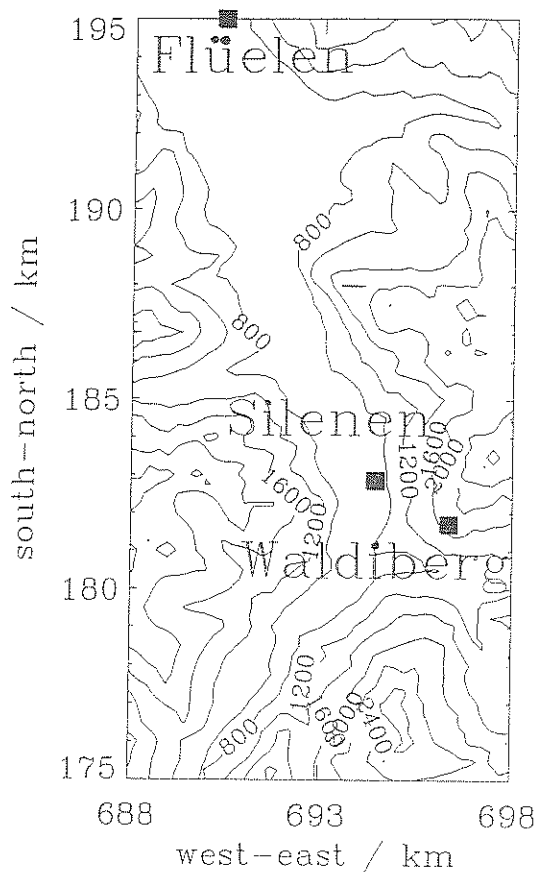


Figure 4: The topographical height in meter above sea level of the region St. Gotthard from Swiss-km 688 to 698 (West-East) and from 175 to 195 (South-North). Isolines are plotted every 400 mASL

3. Soil solution modelling

Increasing nitrogen and sulphur depositions can lead to serious nutrient imbalances in the soil. The soil acidification caused thereby is likely to be more important than direct effects of acid deposition on the forest canopy. The forest vitality based on deficiencies in cation nutrients is caused by increasing exchange of protons and Al^{+++} ions with the soil complex, leading to an increase of base cation leaching with percolating water leaving the soil root zone. The soil complex shows a higher affinity for H^+ and Al^{+++} compared to base cations, therefore higher values of H^+ and mobilized Al^{+++} from Aluminium hydroxids due to strong acid input loads, such as SO_4^{2-} and Cl^- , compete the base cation adsorbed at the soil complex.

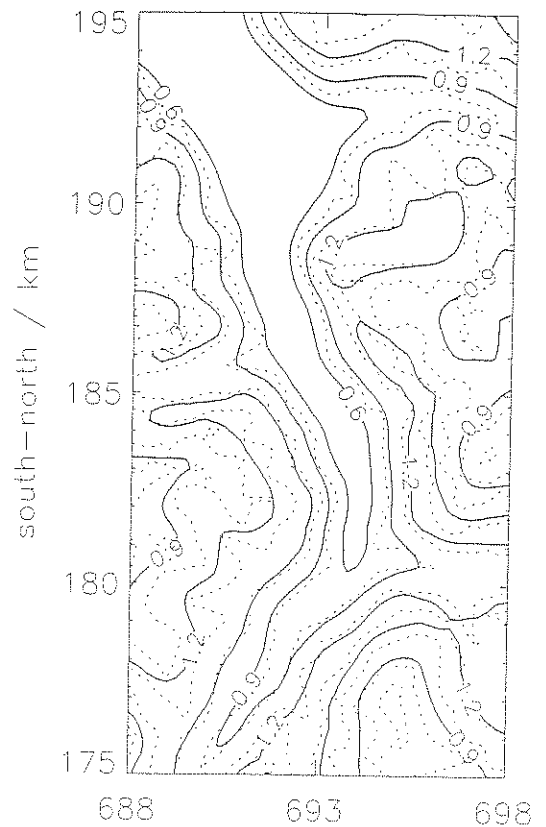


Figure 5: Deposition of NO_3^- via cloud water ($NO_{3,cl}^-$) over the region of Fig. 4. (dotted lines mark the topography).

The soil model SMART (see de Vries et al., 1989) is used to evaluate dynamically the processes in the soil and to calculate and predict the concentrations of the ions H^+ , Al^{+++} , BC^{++} , NH_4^+ , NO_3^- , SO_4^{2-} and HCO_3^- in the soil solution. SMART includes and describes the following key processes:

- The atmospheric deposition is input to the model and controls mainly the behaviour of the soil solution.
- The charge balance for the above mentioned ions in the soil solution is fulfilled.
- HCO_3^- is in equilibrium with the CO_2 pressure in the soil air and depends on pH.
- *Carbonate buffer range:* In calcareous soils with $pH \geq 5$, the H^+ produced from dissolved CO_2 reacting with water (the naturally acidifying process) is neutralized by dissolution of calcite ($CaCO_3$), described with an equilibrium reaction.
- *exchange buffer range:* In non-calcareous soils or after the calciumcarbonate is exhausted ($4.5 \leq pH \leq 5$), the adsorbed BCs are exchanged with H^+ , since the organic matter of the soil complex has a high affinity to H^+ . The exchange rate

is controlled by the Gaines-Thomas equilibrium equations, which state, that the ratio of the concentrations ($c_{BC^{++}}$ to $c_{H^+}^2$) is proportional to the ratio of the exchangeable fractions ($f_{BC^{++}}$ to $f_{H^+}^2$), similar for Aluminium exchange.

- At low acid loads in non-calcareous soils $pH \geq 5.5$ remains and H^+ is consumed by BC from weathering of minerals (BC_{we}), therefore the H-BC exchange is unimportant and the pH is determined by CO_2 equilibrium.
- *Al buffer range:* At $pH \leq 4.5$ organic matter has a high affinity to Al^{+++} , which is mobilized with strong acids from $Al(OH)_3$.
- For the ions Al^{+++} , BC^{++} , NH_4^+ , NO_3^- and SO_4^{--} in the soil solution a mass balance equation is solved to calculate the time developments, balancing the input from atmospheric deposition, the soil interaction processes (including ion uptake from vegetation) and the leaching with the water outflux (runoff with precipitation surplus, defined as precipitation minus evaporation minus interception). These equations contain the ability to use the model as a predicting tool.
- Nitrogen immobilization (N_{imm} : N bound to solid soil), NH_4^+ nitrification (N_{ni}) and NO_3^- denitrification (N_{de}) are described by means of rate limited equations.
- The cation exchange capacity (CEC), the precipitation surplus (Q), the weathering input fluxes for BC and the uptake of nitrogen (N_{upt} and BC (BC_{upt}) with harvesting are inputs to the model.

Starting with a relatively small set of input variables for the description of the soil state (taken from BUWAL 1995) and the atmospheric depositions described in the previous chapter, the model is used to calculate the behaviour of the Alpine forest soils over the last 92 years and over the area under consideration. In Fig. 6 the exchangeable fraction $f_{BC^{++}}$, f_{H^+} and $f_{Al^{+++}}$ are plotted in cumulative form for the site Flüelen at the bottom of the valley. Due to the charge balance condition, these fractions sum up to 1. It is obvious, that the exchange of BC with H^+ and Al^{+++} took place since the beginning of the time period and increased rapidly since 1960. The exchangeable fraction $f_{BC^{++}}$, defined as the *base saturation*, is an indicator for the buffer capacity of the soil. Compared to other European sites, e.g. South England or the Netherlands (see de Vries et al. 1994), the soil is not yet in a critical state, since the Al mobilisation started only slightly. Nevertheless, the soil shifted to the exchange buffer range and serious problems will arise, if the exceedance of nitrogen and acidity deposition (see next chapter) will not be brought under control.

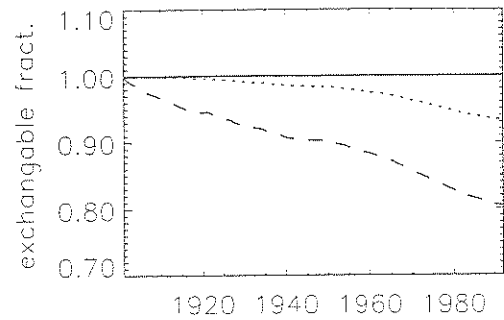


Figure 6: Cumulative exchangeable fractions of BC^{++} (dashed), plus H^+ (dotted) and plus Al^{+++} (solid) versus time. Due to the charge balance condition, the fractions sum up to 1.

Additional time evolutions are shown in chapter 5. The nitrogen immobilization is a considerable quantity in the context of establishing the critical load for nitrogen as presented in the next chapter. The map of N_{imm} in Fig. 7. shows higher values at the bottom of the valley, where the ratio of carbon to nitrogen is also higher.

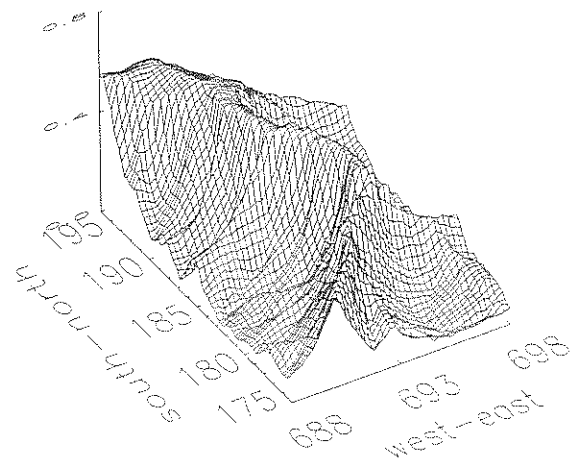


Figure 7: Nitrogen immobilization (N_{imm}) in keq/hayr mapped over the region of Fig. 4.

4. Present and critical loads and exceedances

The deposition model presented in chapter 2 and the soil model presented in chapter 3 enables us to estimate the present and critical loads of nitrogen and acidity and their exceedances.

In a first step, the critical load of nitrogen was estimated with the assumption that deposited nitrogen from the atmosphere can be balanced by means of 4 terms in the soil and vegetation compartments: The nitrogen taken up by the vegetation (N_{upt}), the part of NO_3^- which is denitrified (N_{de}), the nitrogen immobilized by means of bounding in solid soil particles (N_{imm}) and NO_3^- leached with the runoff water at the critical level ($NO_{3,le,cr}$). These four variables are plotted cumulatively over a selected west-east transection in the test region in Fig. 8.

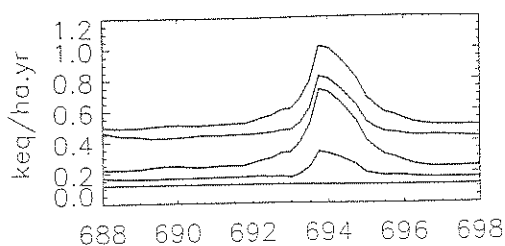


Figure 8: Cumulative cross-sections (West-East at km 182) of the contributions to the critical load of nitrogen (top curve). From bottom up: N uptake by harvesting (constant), plus N denitrification, plus N immobilization, plus critical leaching flux of NO_3^- at critical load.

In the next step the exceedance of the critical load was evaluated as the difference of the critical load and the total nitrogen deposited. Fig. 9 shows the result for the same transect. It is obvious, that the exceedance is considerable. The amount of reduction as a fraction of the total load is also shown in Fig. 9, a mean value of 20 to 30 % as a reduction is recommended.

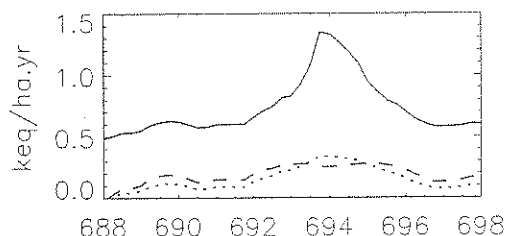


Figure 9: Cross-sections (West-East at km 182) of the total N deposition in keq/ha.yr (solid), the exceedance (dotted, keq/ha.yr) of N above the critical load from Fig. 8 (N_{dep} minus exceedance equals this critical load) and the needed reduction of deposited nitrogen to avoid an exceedance (dashed, fraction of deposited nitrogen).

Furtheron, the critical load of acidity (CL_{ac}) was calculated. The critical load of acidity is defined in accordance with deposition and soil property values, above which harmful deficiencies in the vegetation under consideration are likely to occur. The approach of a critical ratio of Al to BC meets this requirement (Hettelingh and de Vries, 1992). This approach is based on the acid neutralizing capacity (ANC) from weathering minus a critical maximum leaching rate of this ANC, depending on the limiting Al^{+++} and H^+ leaching at critical load. The calculation leads to the following equation:

$$CL_{ac} = BC_{wc} + \left(1.5 \frac{0.8BC_{wc} + BC_{dep} - BC_{upt} - 0.015Q}{200} \right)^{1/3} Q^{2/3} + 1.5(0.8BC_{wc} + BC_{dep} - BC_{upt} - 0.015Q)(1)$$

The evaluation of the term in this equation is transparent from Fig. 10 for the same transect as in Figs. 8 and 9.

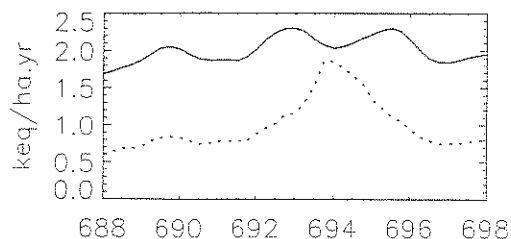


Figure 10: Cross-sections (West-East at km 182) of the base cation input from weathering of minerals (solid, keq/ha.yr), BC uptake by harvesting (dotted), the term $1.5 \cdot Q$ (runoff water in m/yr, dashed) and the deposited base cations (dot-dashed in keq/ha.yr).

Similar to the exceedance of nitrogen, an exceedance for acidity can be calculated. It is obvious from the relation between the critical load and the present deposition load depicted in Fig. 11, that this value is never positive in the region under consideration.

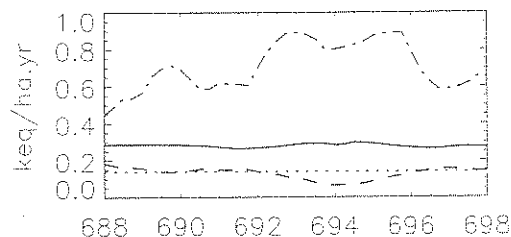


Figure 11: Cross-sections (West-East at km 182) of the critical load of acidity (solid, keq/ha.yr) and the potential acid deposition (dotted, keq/ha.yr), showing no exceedance at present time.

Modeling of scenarios

In order to evaluate the further fate of the soil under various assumptions concerning the deposition of anthropogenic pollutants 7 scenarios are assumed. All scenarios start with the calculated relations of the previous paragraph for the first 92 years. The input of acid and nitrogen load was then varied up to the year 2100. The following 7 different scenarios were calculated:

1. A 60% reduction of nitrogen and sulfur realized linearly decreasing during the years 1993 to 2013, continuation with that values until 2100.
2. A 30% reduction of nitrogen and sulfur realized linearly decreasing during the years 1993 to 2013, continuation with that values until 2100.

3. Continuation of the present load until 2100.
4. Linear increase of 30% during the years 1993 to 2013, continuation with that values until 2100.
5. Linear increase up to a factor of 4 from the present loads of sulfur and nitrogen until the year 2100.
6. A 60% reduction of oxidized (NO_y) nitrogen only realized linearly decreasing during the years 1993 to 2013, continuation with that values until 2100.
7. A 60% reduction of reduced (NH_y) nitrogen only realized linearly decreasing during the years 1993 to 2013, continuation with that values until 2100.

It is evident from the 3 Figs. 12, 13 and 14, that a sustainable continuation of the ecosystems under consideration are only possible with a 60 % reduction of nitrogen and sulphur load. Otherwise a critical situation with an increasing Al/BC ratio up to the value of 1.0, which is known to be harmful, may arise. In the case of scenario 5, this state will be reached within the next hundred years, the value (exceeding by far the scale in Fig. 12) reaches 1.1 in the year 2100. The base saturation in Fig. 13 indicates, that the buffering with exchangeable base cations will end for scenario 5 and the pH value (Fig. 14) decreases to harmful low values.

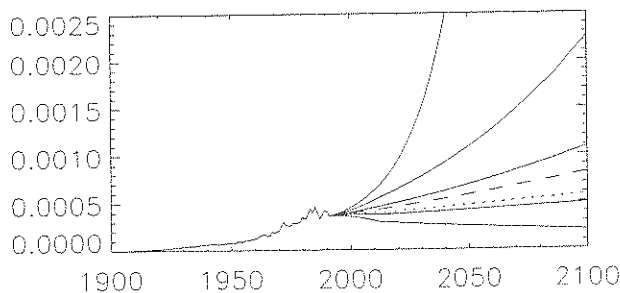


Figure 12: Al/BC ratio for 7 scenarios (see text) calculated over 200 years for the site Flüelen: scenarios 1 to 5 (solid lines from bottom up), scenario 6 (dotted), scenario 7 (dashed).

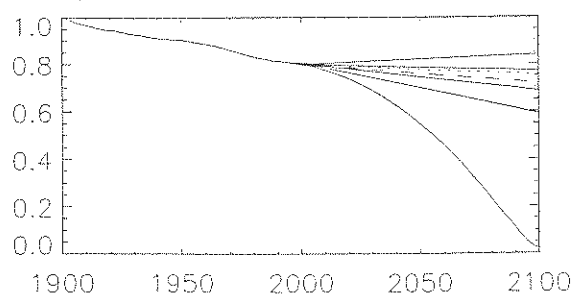


Figure 13: Base saturation for the same 7 scenarios for the site Flüelen: scenarios 1 to 5 (solid lines from top down), scenario 6 (dotted), scenario 7 (dashed).

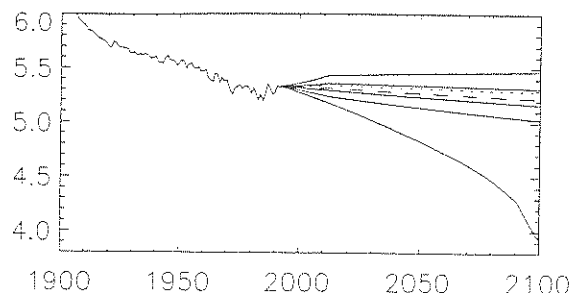


Figure 14: Acidity (pH) of the soil solution for the same 7 scenarios for the site Flüelen: scenarios 1 to 5 (solid lines from top down), scenario 6 (dotted), scenario 7 (dashed).

Acknowledgements

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