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Soil Chemistry as Indicator in Forest Ecology

Bodenchemie als Indikator in der Forstökologie

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Contents

Soil Chemistry as Indicator in Forest Ecology

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Abstract. Since soil chemistry is used as a tool in forest ecology, the suite of requested answers and leads has changed. Initially, a small set of available soil chemical parameters supported the findings of fertilizer experiments, but the major target variable was the growth response of the respective forest stands. Geochemical monitoring relied on the chemistry of surface waters, which *per* se allowed to draw conclusions on the soil chemistry in the investigated watershed. The harmonization of lab methods and big steps forward in lab technology facilitated the generation of large and reliable datasets of soil chemical parameters, that are sensitive to short term changes. Soil chemistry was employed in large scale monitoring projects, often in order to pin down the anthropogenic impact on forests. The wide array of simultaneously operating processes in field experiments and the great resilience of mature forests often impairs the identification of the sought cause-response relationship. Therefore short-term experiments in an artificial, yet controllable, lab environment help to test hypotheses on specific processes and consequently contribute to the interpretation of field studies. The rapid increase in computing power and the availability of geochemical models has further widened the options of forecasting and the chemical system analysis. - This habilitation thesis gives a brief overview on the indiviudal subjects and describes the authors contribution in each of the field. The format is an auto-report, *i.e.* the authors papers are cited and the main parts of abstracts of reviewed papers are displayed in framed boxes.

Keywords: Forest ecology, soil science, soil chemistry, monitoring, modelling, habilitation

Kurzfassung. [Bodenchemie als Indikator in der Forstökologie.] Seit die Bodenchemie als forstökologisches Werkzeug verwendet wird, haben sich die forstlichen Fragestellungen stark verändert. Vor wenigen Jahrzehnten dienten bodenchemische Untersuchungen der Absicherung der Ergebnisse von Düngungsversuchen, wobei die wichtigste Zielgrösse stets die Beeinflussbarkeit der Wachstumsrate des Waldes war. Geochemisches Monitoring bezog sich auf die Chemie von Oberflächengewässern, von der Rückschlüsse auf die Böden des jeweiligen Einzugsgebiets gezogen wurden. Die Vereinheitlichung von Labormethoden und die Entwicklung der Labortechnik waren die Voraussetzung der Erstellung grosser und verlässlicher Datensätze von sensitiven Bodenparametern. Die Bodenchemie wurde in grossen Monitoring-Projekten verwendet, wobei oft das Ziel war, den menschlichen Einfluss auf Wälder belegen zu können. Die Vielzahl gleichzeitig wirkender Prozesse und die Resilienz von Wäldern erschweren stets die Ableitung von Ursache-Wirkung-Beziehungen in Feldstudien. Versuche unter künstlichen, jedoch kontrollierbaren Laborbedingungen helfen innerhalb kurzer Zeit die Bedeutung einzelner Prozesse zu untersuchen. Diese Ergebnisse helfen bei der Interpretation von Geländestudien. Die Zunahme der Computerleistung und die Verfügbarkeit geochemischer Simulationsmodelle haben die Möglichkeiten der Vorhersage und der chemischen Systemanalyse weiter verbessert. In dieser Habilitationsschrift wird eine kurze Einführung in die einzelnen Fachbereiche gegeben und danach der Beitrag des Autors zum jeweiligen Feld beschrieben. Als Auto-Referat wird auf die Publikationen des Autors Bezug genommen. Die Schlüsselpassagen der Zusammenfassungen sind jeweils in gerahmten Boxen dargestellt.

Schlüsselworte: Forstökologie, Bodenkunde, Bodenchemie, Monitoring, Modelle, Habilitation

1 Introduction

Soil chemistry offers insights in the functioning of terrestrial ecosystems. The major biogeochemical processes affect the chemical composition of the liquid and solid phase of the soil. The interpretability of soil chemical data is enhanced when information on soil physics and soil microbiology is included. This text focuses on soil chemistry, but physical and biological soil properties are also taken into account.

Soil chemical data are used as ”indicators & criteria” in environmental monitoring and as response variables for forest treatments. It is recognized that the *homo polluens* affects the geochemistry of ecosystems on a large scale. A thorough quantitative understanding of the human impact on ecosystems as ”lateral damage” of a industrial society is sought. Besides environmental change there are more traditional goals of soil chemical studies in forestry, such as fertilizer experiments and silvicultural treatments, where soil chemical data serve as benchmark for the success of the treatment.

Investigations of the following topics often have a soil chemistry module:

- Field experiments
  - Fertilization
  - Stand management
- Laboratory experiments
  - Greenhouse experiments
  - Soil percolation experiments
  - Incubation studies
- Soil monitoring
- Biogeochemical experiments
  - Watershed Studies
  - Input/Output Studies

Field experiments have a defined experimental design. A treated plot is compared with an untreated or differently treated plot. The treatment effect can be evaluated by comparison. The contributions of the author are presented in chapters 2.1.2, 2.1.3, and 3.3. *Watershed studies* and *Monitoring Programs* are field experiments with a similar set of investigated soil parameters. For this text I draw the line along the purpose of the respective studies.

In **watershed studies** processes in the ecosystem are investigated. They are conducted at carefully selected sites and the temporal resolution of measurements is usually high. The significance for larger land units is not necessarily clear. Contributions of the author are presented in chapter 2.2.3. We assessed the consequence of high loads of N deposition on a mountain forest on calcareous bedrock. In the Vienna Woods we investigated forests that receive unusually high amounts of nutrients due to specific site conditions. The research projects are described in chapters 2.4.3 and 2.4.4.

Monitoring Programs aim at the measurement of ecosystem properties with a high spatial resolution. The term ”monitoring” is used in two different ways, (i) the measurement of data in relation to key variables which etermine whether or not objectives and standards have been met, (ii) the collection of data with the aim to detect trends and to understand how a system is functioning. The location of the individual site is defined by the overall design of the study, *e.g.* a grid position. The temporal resolution of the measurements is lower and less parameters are assessed. The problem is that time may interact with factors, that are not monitored. Monitoring is a key issue in ”Global Change Research”. This term has assumed many meanings: climate, air pollution, soil acidification, N eutrophication, and C sequestration. The author’s contributions to the Austrian Forest Monitoring Program (Level I/Level II) are described in chapters 2.3.3 and 2.3.4. The statistical difficulties in the evaluation are described in chapter 2.3.2.

In this manuscript a range of applications of soil chemical investigations in forest ecology is presented. The first and longest part (chapter 2) deals with **field experiments**, that have been conducted in several research projects and locations (figure 1). The second part (chapter 3) describes **laboratory experiments**. Here the focus is the investigation of a certain soil behavior at controlled experimental conditions. A third part (chapter 4) introduces to the applicability of **modeling** in forest soil chemistry. Special emphasis is paid to speciation models and to water flux models. Each topic is introduced with a brief overview of the state of knowledge, followed by several chapters with the author’s contributions.

2 Soil chemical studies in forest field experiments

2.1 Forest fertilization experiments - field studies

2.1.1 History

Improving the growth rate of forests: Many forest soils in Central Europe are degraded due to former land-use practices (Glatzel, 1999). In order to restore the soil nutrient pool efforts were made within 2 or 3 decades after World War II. Early on fertilization of forests aimed at increasing the growth rate of a stand or to improve site conditions upon the establishment of a new stand (Assmann, 1961; Baule & Fricker, 1967; Fiedler et al., 1973; Rehfuess, 1982). The assumption was that the production rate of the commodity wood will not keep pace with the demand. In the conducted experiments the focus was to assess the growth response of the stands. Additional information such as the effect on soil

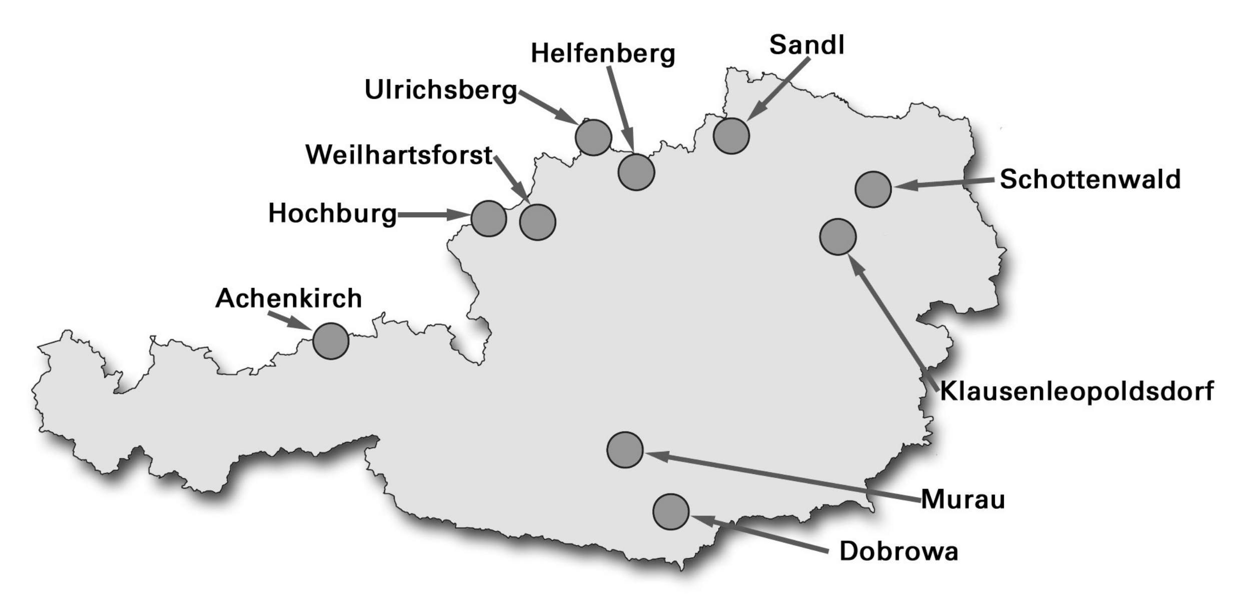


Figure 1: Location of sites where field studies have been conducted.

chemistry was appreciated but was not considered to be crucial. The state of the art was to analyze for soil nutrient pools and *p*H before and several years after the fertilizer application. The interest in forest fertilization experiments vanished after the general ideas about the potential of forest soil amelioration had taken shape.

Mitigating the consequences of ”acid rain”: Upon the upcoming concern of forest dieback in the mid 70s the topic of forest fertilization regained momentum. Widely observed soil acidification and unusual needle losses of Norway spruce and Silver fir suggested liming of forest soils as an appropriate counter measure (ULRICH, 1987). The concept of soil acidification builds on the soil buffer ranges and an understanding of the Al-chemistry (ULRICH, 1966; SCHWERTMANN et al., 1987). Soil acidification shifts the distribution of Al species towards the phytotoxic Al^{3+}. It was concluded that Norway spruce was armed by toxic levels of Al as a direct effect of soil acidification. Elaborate techniques were developed in order to distinguish between the concentrations of phytotoxic and non-toxic Al species (DRISCOLL & SCHECHER, 1988). By now it is solidly established that the connection between growth (as the ultimate indicator of vitality) and Al-toxicity is weak (BINKLEY & HØGBERG, 1997), because Al is tied up in stable organic complexes. The ratio of Ca:Al in the soil solution is used to qualify the soil solution as a nutritional medium (CRONAN & GRIGAL, 1995; SVERDRUP et al., 1992). The debate on Al-toxicity had also stimulated the research on the dissolution of Al-silicates and the formation of Al-complexes (BERGGREN & MULDER, 1995; VAN HEES & LUNDSTRÖM, 2000).

“Acid rain” has been recognized as driving force for the leaching of base cations (K, Ca, Mg). The deposition of high amounts of sulfur increased the salt concentration of the soil solution and increased cation leaching due to the salt effect (REUSS & JOHNSON, 1986; FISHER & BINKLEY, 2000; RICHTER et al., 1983).

A known problem of forest fertilization is that a considerable amount of the applied nutrients leach out of the soil and eventually into the ground- or streamwater. *Leaching of nitrate* has received special attention. The concentration of nitrate has the reputation of being a good indicator of water quality. Forests are regarded as parts of the landscape that purify already polluted water. The provision of high quality water assumes a central position in the “wake theory of forestry” that claims that sustainable managed forests automatically will provide water of high chemical quality. At this point the forester willing to fertilize his stand has to choose: meliorative fertilization adds to the sustained productivity of forests, but simultaneously the water quality may suffer. In practice, most Central European forests are still N limited and the growth rates respond strongly to N addition, although N fertilization is not welcome for environmental reasons (see chapter 2.4). Of special concern are readily soluble NPK fertilizers, where N is released at a rate that can impossibly be met by the nitrogen uptake of trees. It had been shown that fertilizers with a slow release rate of nutrients are equally or even more effective than traditional NPK fertilizers.

Magnesium was identified as deficient nutrient in some forests on non-calcareous bedrock. Several studies showed a likely linkage between elevated rates of S and N deposition and needle yellowing due to insufficient Mg supply. It was suggested that nitrogen was suddenly available in sufficient amounts and that forests will respond with high growth rates. The demand for magnesium rises simultaneously and would exceed the actual supply on Mg poor bedrock. The hypothesis of *induced nutrient imbalance* was very influential (Nihlgard, 1985; Schulze, 1989; Hüttl & Schaaf, 1997, compare chapter 2.4). Often the situation at experimental sites was complex. Stands showed not only Mg deficiency, but also infestations with pests and/or evidence for site degradation. There was little doubt that adding alkalinity in the form of limestone or dolomite or a similar product would improve the soil conditions. Magnesium rich products were often chosen in order to avoid the induction of Mg deficiency.

2.1.2 Case Studies - Magnesium fertilization

In order to investigate the extent of Mg deficiency in Austrian forests, I assessed the regional distribution of sites where trees have a low content of Mg in the needles. Among the commonly used Mg fertilizers kieserite ($MgSO_4$) has the disadvantage to increase the concentration of SO_4^{2-} in the soil solution. Therefore alternatives were sought. In several fertilization experiments, I investigated a group of fertilizers (Biomag) with both a quick release and a slow release component. The experiments showed that a mixture of 30% MgO and 70% $MgCO_3$ at a dosage of 2500 kg ha^{-1} is a reliable recipe to quickly improve the Mg nutrition of Norway spruce. Under the investigated site conditions no sustained enhancement of nitrate concentrations in the soil solution took place (Jandl, 1996c; Jandl et al., 2001; Katzensteiner et al., 1995).

A survey of nutrient contents in needles revealed a regional pattern with a high frequency of Mg deficiency in Upper Austria (Stefan, 1991; Jandl, 1996c). At certain types of forests Mg fertilization was suggested:

- sites on granitic bedrock with naturally low Mg supply
- sites with intense land use for the sake of agriculture over centuries
- sites with high loads of anthropogenic N and S pollution and high rates of cation leaching

Stands in the *Bohemian* forest have shown Mg deficiency in the last decade. Reasons were the Mg-poor bedrock, the exploitation of the pool base cations due to historic forms of land use, and increased demand for Mg due to increasing growth rates. In the experiment 'Sulzberg', Mg deficiency was treated with different types of magnesite based fertilizers, called Biomag. The types of Biomag differed with respect to their solubility. The experimental data comprised the chemistry of both the mineral soil and the soil solution, the nutrient content of needles, and the growth response of the forest. The results of this experiment were evaluated in different aspects (Jandl, 1996b; Jandl et al., 2001; Katzensteiner et al., 1995; Jandl & Katzensteiner, 1992). After five years all types of Biomag had greatly improved the tree nutrition. Our results match with similar experiments (Schaaf, 1992; Mitchell et al., 1999). Magnesium deficiency can be mitigated without changing the chemical characteristics of the ecosystem. The regional water quality, assessed by monitoring the soil solution over several years, changed only little. Elevated concentrations of nitrate and an increased *p*H were transient effects. The supply with magnesium was greatly and sustainable improved. The study reinforces that Mg is a nutrient with a rather small effect on the growth rate of the stand. An investment in Mg fertilization at sites where the sole reason is the yellowing of needles, is not necessarily justified in economic terms, but can be regarded as compensation of soil acidification.

Secondary Norway spruce stands in Upper Austria suffer from insect infestations. *Sirococcus conigenus*, the shoot blight, can strike severly and someplaces it is impossible to preserve the stands for the prescribed rotation period of 100 years. The occasional observation of uninfested stands suggested that previously limed sites and well managed stands are less susceptible to shoot blight. Our experiment showed that fertilization can indeed reduce the disponibility of stands and even control the infestation. Chemical analysis suggested the increase in the Mg saturation of the soil as the most likely reason for the amelioration (jandl et al., 2000a).

Some secondary spruce forests in *Central Upper Austria* are affected with *Sirococcus conigenus*, a fungus causing shoot blight. Affected trees show progressive crown deterioration and often stands need to be harvested long before they reach the prescribed rotation age. We investigated whether an improvement of the stand nutrition offers a remedy. The experimental site "Waldzell" is shown in figure 1. Several plots in a 60 year old spruce forest were treated with combinations of organic fertilizers, magnesium rich carbonate fertilizers and classical NPK fertilizers. We assessed the defoliation of the canopies, the intensity of *Sirococcus* shoot blight, soil chemistry and the nutrient content of needles. Seven years after the fertilization the soil *p*H was only slightly raised. The magnesium pool was enhanced where magnesium fertilizers have been applied. The response of nutrient content in needles was quite variable. The greatest improvements were achieved with magnesium carbonate fertilizers. The intensity of *Sirococcus* shoot blight was reduced. The improvement of the nutritional status seems to have modified several resistance mechanisms of trees and have promoted recovery. Therefore stand fertilization has proved to be a valuable tool to stabilize stands that are affected with *S. conigenus* (Jandl et al., 2000a). - Although this experiment had yielded the desired effect of stand stabilization, we could not demonstrate which process had helped to overcome the pest infection. Our conclusions remained "soft": stands with a good nutrient status are less susceptible to stress.

2.1.3 Case Study - Fertilization experiment Dobrowa

> The amelioration of nutrient depleted forest sites can be achieved by several methods. We compared a fertilization (lime, N, P, K), a silvicultural treatment (sowing of N-fixing lupines, establishment of an alder pre-stand), and a combination of both. All treatments mobilized the recalcitrant forest floor material and greatly increased the growth rate of the established Norway spruce stand. The response times of the treatments were different. Fertilization had the quickest effect. In the control plot the C pool in the soil was largest, suggesting that degraded forest ecosystems are an effective sink for C. We further found that the effect of all treatments greatly depended on the exclusion of roe deer. Without roe deer control, site amelioration may fail easily (Jandl et al., 2000b; Jandl et al., 2002b).

We evaluated the soil chemistry, plant species composition, and forest growth rate of a the amelioration experiment **Dobrowa** in the southern province of Austria, Carinthia (Site "Dobrowa" in figure 1). The regions name contains the slawic word *dob, i.e.* oak, although the entire region is well known for large pine stands. The amelioration project had been started 30 years earlier. The initial goal had been the improvement of a site that had been degraded due to litter raking. We wanted to know which amelioration method had a sustainable effect and how different treatments might be rated by today's standards. Treatments included fertilization, underplanting with N-fixing plants, and a combination of both. The amelioration was combined with a stand con-version by means of natural regeneration and spruce underplanting. All treatments allowed a spruce dominated forest to replace the former secondary pine stand. The mass of the formerly recalcitrant forest floor (143 Mg ha^{-1}) was reduced by 30 to 50% in treated plots, thereby reducing the total soil pool of C, N and exchangeable cations (table 1). The mineral soil was enriched with N, Ca, and Mg at treated plots. An increase in *p*H was restricted to the forest floor. The C pool of treated soils was much smaller than that of the control plots. However, the loss from the soil was at least partly offset by increased growth rates of the aboveground tree biomass. At treated plots the stem volume was more than twice the volume of the control plot (38.3 m^3). Soil chemical data and the composition of the ground vegetation suggest that even the control plots have changed compared to pretreatment conditions. The comparison of different blocks of the experiment suggests that roe deer exclusion by fencing was the most significant treatment required for successful stand conversion. Prior to fencing deer browsing inhibited the establishment of a new stand (Jandl et al., 2000b; Jandl et al., 2002b).

2.2 Watershed Research

2.2.1 History of Watershed Research

Almost every culture in the history of mankind had to deal with the distribution of water, its limited availability and measures for ensuring its accessibility. Water was in demand for human consumption and for agriculture, and rivers and canals are the veins of a landscape and were decisive for the accessibility of land. Irrigation of agricultural land and skillful urban water supply was reported from the Mayan

Table 1: Nutrient pools: Amounts of C, N, and Ca in the aboveground biomass and in the soil at the experimental site Dobrowa

CONT . . . Control, FERT . . . Fertilization, NFIX . . . LUPINE & ALDER, FERT&NFIX . . . combination.

		CONT	FERT	NFIX	FERT&NFIX
Carbon [g.m-2]					
aboveground	needles	391.3	1100.0	830.1	874.3
	wood	1760.9	4949.8	3735.3	3934.1
forest floor		5572.0	2040.0	2300.0	3600.0
mineral soil	0-5cm	2020.0	1720.0	1960.0	2020.0
	5-10cm	1150.0	1109.0	1230.0	1320.0
	10-20cm	1361.0	1311.0	1010.0	1590.0
Soil total		10103.0	6180.0	6500.0	8530.0
Total		12255.2	12229.8	11065.4	13338.4
Total - % of control		100.0	99.8	90.3	108.8
Nitrogen [g.m-2]					
aboveground	needles	6.0	23.6	17.3	16.7
	wood	3.3	9.4	7.1	7.5
forest floor		189.0	77.9	91.8	142.0
mineral soil	0-5cm	52.0	66.0	75.4	82.6
	5-10cm	36.2	35.6	42.9	45.9
	10-20cm	43.5	42.0	34.0	46.6
Soil total		320.7	221.5	244.1	317.1
Total		330.1	254.5	268.5	341.3
Total - % of control		100.0	77.1	81.3	103.4
Calcium [g.m-2]					
aboveground	needles	3.5	19.0	16.9	13.3
	wood	5.2	14.5	10.9	11.5
forest floor		90.0	51.5	34.4	68.0
mineral soil	0-5cm	6.0	17.7	11.1	18.7
	5-10cm	1.6	6.3	3.0	6.2
	10-20cm	1.2	5.8	1.4	4.7
Soil total		98.8	81.3	49.9	97.6
Total		107.5	114.8	77.8	122.4
Total - % of control		100.0	106.8	72.4	113.9

culture; the development of cities in the Mediterranean region depended upon water management. As early as 312 BC the first aqueduct was built to support Rome with water for municipal use and declining skills in watershed management and engineering skills have contributed to the collapse of the Roman empire (NEARY, 2000; PERLIN, 1991). Watershed management for the sake of the protection of settlements was introduced in the 14th century, not surprisingly in Switzerland. Deforestation was recognized as key factor for soil erosion and flooding. Historic records from other countries can be interpreted in the same manner (SCHLAEPFER & ELLIOTT, 2000).

Extensive clear-cutting deprived Central Europe of much of its forest cover during the 18th and 19th century. The industry consumed large amounts of fuel from wood and coal as a replacement was only slowly accepted by the society. Forests were in a poor condition and large flood events and catastrophes occurred. This development and the need of increasing the wood production led to the establishment of the first forestry faculties in Europe (GLATZEL, 1994). The classical watershed experiment is the comparison of water flow rates in the densely forested Sperbelgraben and the Rappengraben (≈ 30% forest) in Switzerland (PENMAN, 1963). - An European flagship project is pursued in the Solling/Germany, where many ecological domains were investigated in great detail (Ellenberg et al., 1986; Matzner, 1988, compare chapter 2.2.2). Based on the solid knowledge of 30 years of monitoring, some treatments were applied to the forest in order to investigate its response to recognized environmental problems, *e.g.* the establishment of a roof-experiment in order to expose the site to controlled deposition scenarios (Lamersdorf et al., 1998). In the first decade of the 20^{th} century watershed studies were started in the USA and in Japan. Within a few decades several studies were established by the USDA Forest Service, that are still used and that serve as the reference systems for research: Coweeta/North Carolina and San Dimas/California (1933), Fernow/Virginia (1934), HJ Andrews/Oregon (1948), Hubbard Brook/New Hampshire (1963) (Neary, 2000). The primary objective of these studies was the understanding of forest management practices on hydrology.

2.2.2 Biogeochemical studies in watersheds

Nutrient cycling in ecosystems received attention in several forest watershed studies. Initially nutrient budgets were set up as difference between the deposition input and the output in stream water. The underlying assumption was that the retention of elements is minimal in undisturbed forests (Vitousek & Reiners, 1975). In consequence, elevated concentrations of ions in the outflowing stream water would be an indication of disturbance. A template of such studies, consisting of the assessment of nutrient pools in the biomass and the soil, the local meteorology, the nutrient input by precipitation, the estimation the microbial activity, the estimation of the nutrient uptake, and the nutrient output by stream water or seepage water, is described in Likens & Bormann (1995). Early on mostly stream water was the object of investigation, whereas the soil and its biology were treated as a black box. The scope of the studies was expanded and besides the chemistry of stream water other biogeochemical processes were monitored.

In the mid-sixties the Solling experiment was started. For geological reasons the nutrient export rate could not be measured at a weir in the outgoing stream. A hydrological simulation model was developed (Ellenberg et al., 1986, chapter 7 by Benecke). The time series of chemical composition of the soil solution was the topic of many dissertations, habilitations, and publications[1] . The soil solution proved to be a valuable indicator for the ecosystem status and helped to gain insights in processes, that are otherwise difficult to study. The Solling project was used as a template for further ecosystem studies in Germany and Austria, e.g. the Arinus project (Feger, 1989) and Schöneben (Führer & Neuhuber, 1994). Each of the experiments embarked on specific local problems, but the general experimental setup was similar.

Many biogeochemical projects deal with the impact of air pollution on forests. Different pollution scenarios were artificially established in Skogaby/South Sweden with the treatments 'artificial drought', 'addition of Nand S', 'amelioration' and similar experiments (Bergholm et al., 1993; Gundersen et al., 1995). Recently the EU-funded projects Nitrex and Exman were finished, where the effects of moderate to high inputs of nitrogen on forests were investigated (Emmett et al., 1998; Farrell et al., 1994). It was found that soils respond very slow and that nitrogen transformations are stronger linked to the pool size of soil nitrogen than to the current N input rate. Water quality, however, responded quickly to changes in N deposition, thereby justifying the call for reductions of N emissions. Ecosystem studies on calcareous bedrock are few because the small scale variability of soil morphology and large differences in chemistry (Rendzina adjacent to loam pockets) makes it difficult to draw conclusions that are valid for the entire site, let alone for the region. The difficulties are increased in such a setting because karst phenomena make it impossible to identify a watershed. A direct measurement of water fluxes is therefore not possible and the investigator must to some extent rely on simulation models that describe the water dynamics (compare chapter 4). A comprehensive study on the hydrology and the biogeochemistry of such a site was recently finished (Katzensteiner, 2000).

Often the *nutrient flow is estimated with simulation models*, e.g. Brook-90 (Federer, 1995), Unsatchem, Hydrus (Šimůnek et al., 1996). The complicated part is to get a reliable estimate for the water flux. Soil physicists are aware of the inaccurate estimates, due to the geometrical heterogeneity of the pore space of any given soil profile. Someeven claim that the currently used assumptions in water flux equations are either wrong or in violation of basic physical principles and therefore they will yield reliable results only by chance (Ott Jury & Flühler, 1992).

[1] Series "Berichte des Forschungszentrums Waldökosysteme / Waldsterben", University of Göttingen (publisher)

2.2.3 Case Study - Experimental site "Achenkirch"

The soil water dynamics of a mountain forest on calcareous bedrock were quantified with the simulation models UNSATCHEM and HYDRUS. The hypotheses was that the local N deposition would not be retained in the shallow soil profile and therefore evidence for N eutrophication of the ecosystem would be detected. Our simulation suggests that the N deposition load exceeds the N output of the soil. The N retention capacity of the forest soil is obviously not yet exceeded. The incorporation of N into the soil organic matter was identified as most likely retention mechanism (JANDL, 2001a; JANDL et al., 2002a).

We established a nitrogen budget for the site Mühleggerköpfl, Northern Tyrol. The experimental site is located in 930 m elevation, on calcareous lime stone. The annual rainfall is high. The forest stand scavenges fog as "occult deposition" that may contribute considerably to the total N deposition (IGAWA et al., 1998; BINKLEY et al., 2000). No stream drains the ecosystem. Surface flow is low due to the high porosity of the soil. The water flux cannot be measured directly in the field and a mechanistic soil physical simulation model is a feasible way to establish a nutrient budget. The initial parameterization with a comprehensive set of field data of the model is already published (JANDL, 2001a). We found that the annual loss of N by percolation is smaller than the annual input. The forest soil obviously accumulates N. This result was unexpected because the amount of fine soil material is low. Under the present deposition conditions N saturation and eutrophication can be expected, although no evidence is apparent from field observations (JANDL et al., 2002a).

2.3 Soil Monitoring as environmental indicator

2.3.1 Soil monitoring networks

Diverging opinions about the causes of "forest decline" have been convincing incentives for long-term monitoring programs. Mankind is indeed conducting a giant experiment without control and without replicates. Largely, it will be the ecosystems of the future that determine the quality of life for most people. Changes in climate, atmosphere and land use impact ecosystems in complex ways that we need to understand and predict. When anthropogenic processes are driving the condition of the biosphere out of the bandwidth of natural variability, the distinction between signal and noise is a major problem. The experiment Biosphere II near Tucson/Arizona has taught that controlled experiments that are to mimic the biosphere, are almost impossible to conduct (SEVERINGHAUS et al., 1994).

National forest soil inventories were combined to a pan-European network in the wake of forest decline. The applied methods are harmonized within the ICP Forest (International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests; http://www.icp-forests.org; leader UN/ECE)[2] . A similar approach toward the Research on Acid Rain in USA was the National Acid Precipitation Program (NAPAP). The forest ecosystem research is supported by many institutions (USDA Forest Service, National Science Foundation, US Geological Survey, Environmental Protection Agency ...), but no commitment to long-term research has been made. However, the Long-Term Ecological Research Program (LTER; http: //lternet.edu) fulfills the goal of soil monitoring. Extensive information on some sites has been published (JOHNSON & LINDBERG, 1992).

[2] The program was launched in 1985 under the Convention on Long-Range Transboundary Air Pollution due to the growing public awareness of possible adverse effects of air pollution on forests. ICP Forest monitors the forest condition in Europe, with two monitoring intensity levels in cooperation with the European Union. The Level I-grid was established in 1986. Since then it has annually been monitoring the crown condition on a systematic transnational grid of 16 x 16 km, complemented by assessments on national grids of varying densities. Between 1992 and 1996 also soil condition and the foliar nutrient status were assessed. The second monitoring intensity level (Level II) has been started in 1994 in selected forest ecosystems. On some of these plots, soil and soil solution chem-istry, foliar nutrient status, increment, meteorological condition, ground vegetation and deposition of air pollutants are measured in addition to the annual crown condition assessments. Currently 38 countries participate in the ICP Forests.

2.3.2 Detecting temporal trends of soil chemical properties

Soils are often highly buffered and therefore changes are especially slow. They may get into a transitional dynamic status and may not change for a long time, until the buffering capacity of the system is exhausted or the soil changes for some other reason, that can not be viewed as deleterious side effect of anthropogenic interventions. From the evaluators point of view a statistically significant treatment effect can only be produced if a treatment is strong enough in relation to a control. In the case of "global change" the treatment is weak and the only control level available is our understanding of the system.

It is realized that experiments at the ecosystem level impose different statistical constraints and considerations as classical experiments, where true replications, factor separation, and discrete treatment levels are possible. A statistically significant effect can be produced if the treatment is strong enough. In this case the data could be straightforwardly evaluated with the analysis of variance. The goal of monitoring projects is rarely the proof if treatments are statistically different or not, but rather the identification of factors that are driving the response of an ecosystem, and the extent of the response (SCHULZE et al., 1999). An example is the evaluation of global warming on soil respiration and consequently on carbon sequestration. Temperature certainly affects a wide array of biotic and abiotic processes, which are again linked by several feedback processes. The apparently easy question yielded contradictory results (LISKI et al., 1999; DAVIDSON et al., 2000). Only the comparison of time-series of multiple sites in different climatic regions allowed to derive a general answer (RUSTAD et al., 2001).

Difficulties arising from the spatial heterogeneity of forest soils is long recognized. As a mere consequence of the size of trees an experimental plot needs to be large in order to represent a site properly. When the number of replications of a treatment needs to be sufficient for a statistical evaluation, the required size of the experimental site quickly exceeds the size of the chosen stand. The evaluation of many old fertilization experiments suffers from an insufficient number of replicates. The remedy was the reduction of the plot size to the immediate surroundings of single dominant trees (STERBA, 1970). This experimental scheme was optimized for the evaluation of the growth response to stand treatments, and was applied for soil monitoring in our Mg-fertilization studies (JANDL et al., 2001; KATZENSTEINER et al., 1995).

The small scale variability of soil properties is a serious obstacle of monitoring projects, that confounds the interpretation of the temporal change and trends in soil chemistry are difficult to detect. Major problems arise from (i) the huge pool size of nutrients and metals, with only a small part biogeochemically cycled within a couple of years, (ii) the spatial variation of soil properties, and (iii) idiosyncratic sampling protocols (LISKI, 1995; YANAI et al., 1999). Soil sampling is destructive. Upon resampling a sample must be taken from elsewhere[3] . The inherent uncertainties impose a major problem on soil monitoring, because changes in the monitored property should be apparent soon, so that counter measures can be taken immediately, and not decades later. It has been shown that the European forest soils change at a rate, that a 15-years interval between sample collections is useful (DE VRIES et al., 2000). The geostatistical method "kriging" allows to derive information for an area from individual sampling points. Each observed value is considered to be the outcome of a random variable postulated for a given position. Unfortunately, geostatistical methods proved to be less accurate than the classical grid-based monitoring, because a large part of the information is used for estimating the shape of the variogram. Overall, a stratified random sampling is the most efficient and accurate design in monitoring (PAPRITZ & WEBSTER, 1995a; PAPRITZ & WEBSTER, 1995b).

2.3.3 Case Study - Austrian Forest Soil Monitoring

> Data of a pre-cursor project of the Level-I project showed that Austrian forest soils have lost base cations during the last 2 decades. However, changes in the soil chemical properties of individual grid-points can not be statistically evaluated due to the chosen experimental design. The assessment of soil changes in larger spatial units (*e.g.* regions) is possible, however either the number of replicate samples or the change in soil properties needs to be large in oder to override the inherent variability of the dataset (JANDL & RIEDLER, 1998; JANDL et al., 1999a; JANDL et al., 1999b).

[3] In the assessments of the Level I program of the EU this particular problem was skillfully circumvented. Soil samples were taken from different spots at a site and were then pooled in the field. Therefore the individual sample represents an area rather than a spot.

’Forest vitality’ is an undefined term and is has not yet been established how foliage density relates to air pollution. It is well known that climate factors and water relations affect foliage density, but that it will potentially recover in consecutive years. After more than 10 years of monitoring the defoliation in European forests, results remain fuzzy. Given the amount of scientist’s creativity that has been eluded on the relationship between deposition rate and ’forest health’ without finding strong evidence for useful indicators of ’forest vitality’ it requires a fair amount of optimism to expect such results in the near future. A European forest ecosystem monitoring is necessary, but the scope shifts away from forest vitality issues.

The experimental design of the Forest Soil Survey within the Austrian Level I (512 plots) was to collect soil samples from fixed depths from different soil pits near a grid point and to pool the samples to “one representative sample per site and horizon” (Englisch et al., 1992). It is a safe assumption that no denser soils information will be available in the future. Initially the network was not intended to serve monitoring purposes. Therefore it was acceptable to ignore the assessment of the local variance of soil properties. However, within a few years after the first assessment some interest for the temporal trend of soil chemical properties was expressed. The idea is gaining momentum if a world-wide carbon accounting system (Kyoto Protocol to the IPCCC) is to be implemented.

In feasability study for the detection of statistically significant changes in soil chemistry we used the results of the monitoring project “diagnosis profile”, that had served as pilot study to the Level I soil assessment. At the onset of this project in the early 80s the assumption was that forest soils are greatly affected by air pollution. The sites that were considered most susceptible for soil acidification and nutrient loss were selected as starting points of transects into areas with a presumably lesser pollution load. In that sense the chosen sites could be the worst case of soil de-cline. The soils that had already been rather acidic at the beginning of the experiment, had remained stable within their *p*H range. However, a loss of base cations had taken place (Jandl et al., 1999a; Jandl et al., 1999b). We used the measured soil changes found in this experiment in order to estimate how big a change in soil chemical properties would are collected in order to be detected with statistical significance. A sampling scheme was suggested where at least 6 replicates of samples are collected per plot and horizon in order to identify a true soil change of 20% (Jandl & Riedler, 1998). This number of replicates is still prohibitingly large for the Level I network. However, it is reasonable for the companion project Level II, that includes only 20 sites.

2.3.4 Case Study - Austria Level II program - Soil solution

The EU-forest-monitoring program was extended and at selected sites more intensive studies are taken. The Level-II-program includes the measurement of deposition rates, soil solution chemistry, forest growth rate, and the measurement of climate data. The design of a typical monitoring site has been greatly influenced by the concept of ’critical loads and critical levels’ (see chapter 2.4). The chemical composition of the soil solution has the reputation to be the most sensitive part of a soil (“. . . the parrot in the mine ...”) that can be monitored with a reasonable work load. Austria is contributing two sites with soil solution studies to the European Level II net-work (Jandl, 2001b); compare chapter 2.3.1 and figure 1. The applied methods and the sites with soil solution studies in Austria are given in Jandl et al. (1997b). The site “Klausenleopoldsdorf” is located in a beech forest in the southern part of the Vienna woods on decalcified sandstone, the site “Murau” is a pure mature spruce forest in the montane area on nutrient poor bedrock. In a first evaluation step we compared the sites with respect to their soil nutrient dynamics. Our evaluation is based on a simulation with the Brook-90 model (Federer, 1995). We derived a simplified water and nutrient budget by means of the dataset that is recommended for a Level II plot (EC DG VI, 1998). We demonstrated how differences in the bedrock material and in climatic conditions are reflected in the chemical composition in the soil solution. Moreover, we showed that the concern of nutrient leaching can impossibly be approached by a critical interpretation of the soil solution chemistry only, but also needs to account for soil physical conditions (Jandl & Zotrin, 2000).

2.4 Nitrogen - friend or foe of European forests

2.4.1 Nitrogen as a pollutant

Global change has many facets. It is a reality at presence and will continue in the future. A thorough scientific understanding of its consequences is the key to deal with it successfully. One of the most pronounced alterations in the biosphere is the eutrophication with nitrogen. Human activities have already vastly changed the global N cycle and anthropogenic processes mobilize more N than natural processes combined (VITOUSEK et al., 1997; FALKOWSKI et al., 2000).

A full accounting for the pathway of N through a forest ecosystem is apparently impossible. Difficulties arise from N being present in solid compounds, dissolved in water, in gases, and both in living biomass and in old organic matter. The measured N budgets in biogeochemical experiments are rarely closed. Leached nitrogen can only rarely account for the deficit in the budget. This uncertainty is a fascinating observation, given that as early as 1955 two scientists summarized

> "...The study of the general course of mineralization of organic nitrogen in soil was practically completed before 1935. It is surprising that many of the modern publications still consider it worthwhile to consider parenthetically observations dealing with these entirely solved problems. ..."
>
> cited in Paul & Clark (1989, p. 3)

Several thousand mineralization studies and a large number of skillful field experiments later our knowledge is still incomplete and reliable predictions of the consequences of high N deposition are uncertain.

The then new 'Nitrogen-hypothesis' for forest decline by NIHLGÅRD (1985) proposed how nitrogen input to forests can induce nutrient imbalances (compare chapter 2.1). An increase in the N availability had been reported from Sweden, but also from sites in Central Europe (FALKENGREN-GRERUP & ERIKSSON, 1990). In order to quantify how much N deposition was acceptable, the concept of critical loads/levels was outlined in Skokloster/Denmark and later explored in the NITREX project and its companions (ABER et al., 1998; EMMETT et al., 1998; FENN et al., 1998; GUNDERSEN & RASMUSSEN, 1988; GUNDERSEN et al., 1998).

Several definitions of N saturation of forests define, at which point a system does not benefit from incoming N. The Ndeposition rate at this point is the 'critical load'. The equation

$$\text{Critical load} = N_l + N_i + N_d + N_b \qquad (1)$$

where N_l ... acceptable N leaching, N_i ... net N immobilization, N_d ... denitrification, N_bb ... biological fixation of N, describes one possible definition. Presently many forest soils are accumulating N, schematically outlined in figure 2 and demonstrated in the survey of many, quite different forests in Europe and North America (DE VRIES et al., 2000; JOHNSON & LINDBERG, 1992). In a Norwegian chronosequence of spruce stands most of the N was accumulated in the forest floor, whereas the amount of N in the mineral soil remained unchanged over time (SOGN et al., 1999). Ultimately, high rates of N deposition will lead to N leaching out of forests, and comprehensive conceptual frameworks of ecosystem changes have been elaborated (ABER et al., 1998). There have obviously been several studies that aimed at defining critical threshold values for N deposition. The topic is discussed controversially. For many ecologists it is difficult to accept that nitrogen quickly turned from the growth limiting element into a matter of concern. It was shown that present rates of N addition are not a disadvantage for Swedish forests. Most of them are N limited with respect to growth and no evidence for risks due to N deposition has been demonstrated (BINKLEY & HOGBERG, 1997).

Increasing evidence for actually increased growth rates at specific sites in Europe was unexpected and artifacts due to changes in the forest inventory methods and changes in landuse practices were assumed. Soon it was proposed that site productivity is actually increasing in Central Europe, and N was hypothesized as the major factor (SPIECKER et al., 1996). The project RECOGNITION as a joint effort of several European forest research organizations was prepared (REHFUESS et al. (1999); compare chapter 2.4.2).

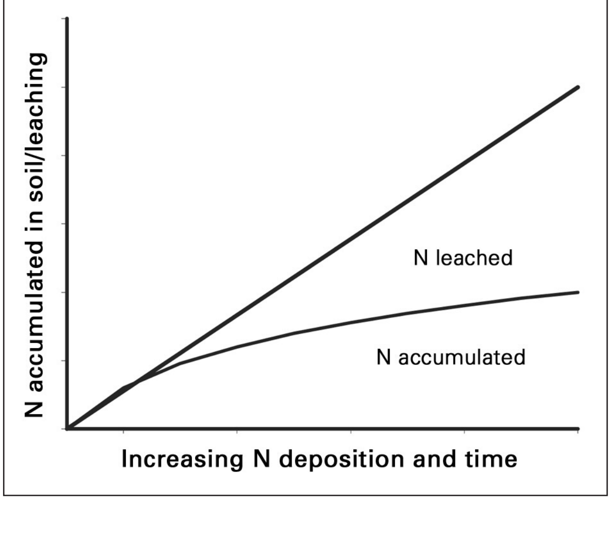
An important question is how trees do respond to changes in nutrient availability. Results of the CANIF project have shown that the root longevity, an indicator for sustainability, is rising and that N deposition so far has mainly positive effects on forests (STOBER et al., 2000). However, these conclusions are valid for the time being and may be revised after several decades of high N deposition, when existing limitations of nitrogen have been overcome.

2.4.2 Case Study Recognition project

We investigated 30-years time series of soil chemistry, nutrient contents in needles, and growth rates of forests. At all sites clear evidence for ecosystem aggradation from the humus form and the herbaceous vegetation was found. The nitrogen contents of needles have remained at low levels and exhibit slight N deficiency. Soil data show a trend towards smaller C and larger N pools and consequently lower C:N ratios, but the variability of the data and inconsistencies in the temporal trend cause that differences are not statistically significant. The growth trend of the stands did not deviate from the temporal pattern, that was suggested by the locally valid yield tables. We conclude that mature forests benefit only little from increasing N deposition, and that a large part of the incoming N is retained in the soil (JANDL & NEUMANN, 00).

Three Austrian forest sites are contributed to RECOGNITION (EU project FAIR CT 98-4124). "Karlstift" and "Helfenberg" are located in the Bohemian massif, the third site, Dobrowa, is located in Carinthia (figure 1). The site descriptions have been published (JOHANN, 2000; JANDL et al., 2000b). We evaluated time series of air temperature, precipitation (monthly values), annual data for nutrient contents in needles and for the growth rate (height and diameter growth, assessed from stem analysis), and soil chemical data, which have been collected in an irregular temporal pattern. The data show no evidence for a response to increasing nitrogen deposition. A thorough evaluation is forthcoming (JANDL & NEUMANN).

Figure 2:
Hypothesized relation between N deposition, N accumulation in the soil, and N leaching.



2.4.3 Case Study - Range of natural variation of soil solution chemistry - The 'vernal dam' study

Forests with *Allium ursinum* in the herbaceous vegetation are an excellent study object for naturally N enriched ecosystems. Soils need to be moist and nutrient rich in order to enable Allium to develop. Where these conditions are met, the geophyte has a strong influence on the biogeochemistry of N. The decay of the aboveground biomass of the herb in early summer liberates N in excess of the actual demand of the trees. An increase in the microbial activity is seen from high N mineralization rates, high rates of N_2O emissions, high microbial biomass, and prolonged periods of high nitrate concentrations (> 300 mg NO_3^- mg L^{-1}) in the soil water. The N temporarily also affects the abundance of the mesofauna. Our study demonstrates that forests are by no means nitrogen-tight ecosystems. There are obviously some 'hot-spots' where nitrogen is released at high rates, either into the groundwater or into the atmosphere (JANDL et al., 1997a; ZECHMEISTER-BOLTENSTERN et al., 2002).

The term 'vernal dam', coined by Robert MULLER and Herbert BORMANN (1976), describes the temporal nutrient retention in the herbaceous vegetation during spring. Under temperate climate conditions soil nutrients are leached between snow smelt and the onset of water transpiration by trees. When rains are heavy in spring the water flux out of the soil can potentially export nutrients at high rates. The microbial biomass and spring geophytes can serve as a temporal nutrient pool, that reduces the nutrient loss.

At the study site 'Schottenwald' in the Vienna Woods we studied the impact of a dense layer of the spring geophyte *Allium ursinum* on the local nutrient dynamics in an 140-year old beech forest. The method of choice was to monitor the chemical composition of the soil solution. Emissions of N_2O and CO_2 in conjunction with measurements of microbial biomass-N were made in several consecutive years. We found that *Allium* retains a similar amount of nitrogen in its leaves, as the mature beech stand stores in the canopy later in the year. The transfer of nitrogen from the herb to the tree is by no means seamless. Although beech takes up large quantities of nitrogen in early summer, the N supply from decaying leaves of *Allium ursinum* exceeds the demand. Highest N_2O emission rates (<150 μg N m^{-2} h^{-1}) were recorded in mid-summer, simultaneously with nitrate concentrations in the soil solution (>300 mg L^{-1}), and high rates of leaching. The mineralization of organic matter led to a drop in the *p*H in the soil solution. In similar studies it has even been argued that nitrification can acidify the mineral soil. Considering the discrepancy between the small amount of protons generated during mineralization and the huge amount permanently present in the soil solution, this process is unlikely. The change of *p*H in the soil solution is at least partly a salt effect: when the concentration of anions (nitrate) is enhanced charge needs to be balanced by cations from the exchange complex. The set of cations released into the soil solution is determined by the percentage of various exchangeably bound cations, refered to as base saturation, and by their tendency to dissolve in the solution, expressed as selectivity coefficient. The salt effect demands that after the nitrate concentration drops to previous levels, the previously released cations will be readsorbed by the exchange complex and the *p*H will return to the original value.

We identified recurring cycles of microbial growth triggered by soil wetting and by pulses of N release due to the decline in microbial biomass. Microbial biomass carbon related inversely to concentrations of extractable sugar carbon substrates. Our study suggests that within nitrogen-enriched forests, nitrate leaching and N_2O emissions may be linked during the growing season. Nitrogen losses appeared to be strongly affected by biomass turnover and microbial mineralisation. - The coincidence of the high availability of nutrients, the already warm soil temperatures and the rather high moisture content of soils provide ideal conditions for microbial activity. Our data suggest that the soil meso-, and microfauna benefit from these conditions, and nitrogen wanders through a cascade of users. The high activity is evident from high nitrate concentrations in the soil solution, high population densities of the meso- and macrofauna and from high emission rates of nitrous oxides (Jandl et al., 1997a; Zechmeister-Boltenstern et al., 2002).

2.4.4 Case Study - Range of natural variation of soil solution chemistry - Organomass transfer along a ridgetop

Lateral transport of leaves and light organic debris across a ridge-top creates huge differences in soil fertility between immediately adjacent sites. We used this natural setting of a site manipulation in order to investigate the differences in the soil solution chemistry and the mesofauna coenosis. In the leeward position we found higher nutrient concentrations in the soil water, and differences in the abundance and dominance structure of collembolans, that was attributed to differences in the N availability (Kopeszki & Jandl, 1994).

The prevailing winds in the Vienna Woods are westerly. At sites, where ridgetops are perpendicular to the wind directions, site characteristics are variable on a small scale: the upper parts of the slopes at the windward side are often much poorer than the upslope sites in leeward positions. Within less than 200 m in horizontal distance and within a negligible altitudinal range the variety of sites is large. A thorough assessment of site differences along this natural gradient was presented by Halmschlager (1987). It had been found that the lateral transport of matter by wind continuously removes light, but nutrient rich leaves and organic debris, which are the most fertile parts of the rapidly recycled nutrient pool. We drew heavily on this established concept and checked, if the composition of the mesofauna and the soil solution chemistry reflect the same pattern, as had been deduced from the communities of herbal plants and from soil chemical investigations. We confirmed that the soil mesofauna is capable of subtly depicting these differences. Moreover, we showed that the chemical composition of the soil solution mirrors the higher nitrification rate in leeward positions (higher NO_3^- concentrations), whereas in windward positions NH_4^+ concentrations were greater (Kopeszki &Jandl, 1994).

3 Laboratory studies and pot experiments in forest ecology

3.1 Dissolved organic carbon as substrate for microorganisms

Large amounts of carbon are processed in forest soils at an annual basis. The pool of total carbon is rather stable over time, but the fluxes are considerable. At steady state an equivalent of the annual litterfall and the root litter undergoes mineralization. The end products of this process are CO_2 due to microbial respiration, carbon dissolved in the soil solution (DOC), and solid organic residues. Sources of DOC are the leachate of the forest floor, and exudates of roots and microbes. The concentration usually shows a steep gradient downward, because most of the DOC is adsorbed to the surface of the mineral soil. Many experiments have treated the amount of DOC in the soil solution, several studies have dealt with its structure (LEENHEER, 1981; HATCHER et al., 1989; GUGGENBERGER et al., 1994), but little is known about its significance for the microbial turnover of C. It is not clear yet if DOC is to be considered an endproduct of the mineralization process. There is no doubt that it still contains unoxidized carbon. It is not clear, however, to what extent DOC serves as substrate. At this point the general idea of the soil solution as central reactor vessel of the soil is scrutinized. Given the dense cover of microbes attached to the soil surface it can well be that they graze in biofilms at the surface on solid soil organic matter, but release only their final metabolites into the soil solution. These metabolites would then be adsorbed at the soil surface without further attention by the microbes. The adsorption capacity has been described earlier (JARDINE et al., 1989; GUGGENBERGER & ZECH, 1992; MAYER, 1994).

3.2 Case Study - Biodegradation of dissolved organic matter

We incubated samples of isolated and purified fractions of dissolved and water-extractable carbon from 2 forest sites. The release of CO_2 was measured during several months. Our results suggest that especially the low-molecular weight, neutral organic moieties are microbially degradable. If these compounds can be quickly regenerated from the litter layer and the organic parts of the mineral soil, they can supply a large portion of the substrate for heterotrophic soil respiration. However, under field conditions organic molecules are not available in the purified form, but are interacting with metals. Hence, the same organic groups that are biodegradable in laboratory experiments are chemically protected from microbes when they form ligands in complexes with Al and Ca. - Our incubation experiments dealt with operationally defined groups of organic molecules. In a later experiment we investigated, which low molecular organic acids comprise the dissolved organic carbon. Citric acid was present in high concentrations in all samples and can therefore serve as model-substance in considerations about the interaction of the dissolved organic carbon in chemical equilibrium calculations (JANDL & SOLLINS, 1997; JANDL & SLETTEN, 1999; HASLINGER et al., 2003).

We measured the amount of DOC over one growing season in the HJ Andrews watershed in the Cascade Mountains of Oregon. A conventional lysimeter study was not suitable, because large quantities of C needed to be extracted and processed in the lab. Moreover we wanted to extend our study over the growing season, which is usually dry in that region. Therefore we chose to use water extractable C as proxy for DOC. The collected soil extracts were purified with exchange resins and fractionated by means of XAD resins, in a modification of Leenheer's method (LEENHEER, 1981). In addition we processed soil solution samples from the Findlay Lake Watershed in Washington. The pure organic compounds of each fraction were subject to a long-term incubation study. We found that the microbial activity was severely limited by nitrogen deficiency, probably as consequence of the sample preparation. Even when nitrogen was supplied only a small fraction of the DOC served as substrate. This fraction needs to be turned over many times in order to account for the measured soil respiration rate. The major part of the dissolved organic carbon is unlikely to serve as substrate and will therefore remain sequestered as "stabilized carbon" in the soil (JANDL & SOLLINS, 1997; JANDL & SLETTEN, 1999). - A shortcoming of the described lab method of the isolation of organic moieties is that the fractions are only operationally defined. In a second experiment we investigated which low molecular weight organic acids are dominant in the soil solution. We found that citric acid is consistently present (HASLINGER et al., 2003). The stability constants of complexes of many metals with citric acid as ligand are tabulated in Handbooks of Chemistry and can serve as substitute for the chemically most active part of the DOC.

3.3 Pot experiments - Fertilizers for forests

The fertilization of mature forests is often done with slowrelease fertilizers. It takes several years before the effect of products can be safely evaluated. Greenhouse experiments with tree seedlings offer the chance to quickly get insights in the effects (and side effects) of fertilizers. Within 2 years we could establish, that calcined magnesite is a useful product for the amelioration of Mg deficiency in forests. The pot experiment was treated as a pilot-study for a later conducted field experiment, were the results were corroborated (JANDL, 1996a).

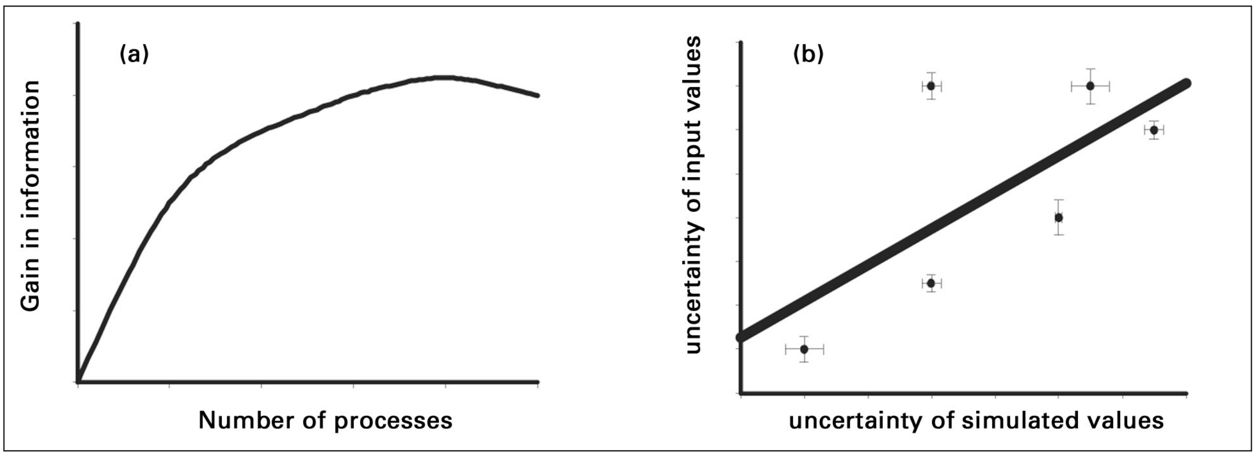
Pot experiments have advantages: the experiment is controlled, complexities of field studies are eliminated, and results are quickly available. We have used pot experiments as pilot studies of fertilization experiments. It seemed appropriate to obtain some information on the effect of a novel fertilizer with a quickly soluble component before it was applied in a mature stand (JANDL, 1996a). The development in the early phase of the pot experiment was promising, so that a large scale field experiment was started (compare chapter 2.1.2). - A second application of a pot experiment was also related to fertilization. In a field trial a previously approved fertilizer was believed to either contain or mobilize chloride. We could proof that the product was free of chloride and that eventually found Cl must have come from other sources. The results are published in an internal report of the Institute of Forest Ecology, BOKU, Vienna.

4 Modelling of forest soil chemical processes

4.1 Simulating the biogeochemistry of forests

Models are increasingly used, given that the computing power is always improving and that convenient modeling tools are available. They are useful where either the target variable is not accessible or when a future status of an ecosystem needs to be assessed, e.g. climate change. Some processes are extremely difficult to handle in models (JANDL, 1998). Landuse history had a strong impact on nutrient fluxes, however, it is not clear how to parameterize e.g. the discontinuation of litter raking. The question arises how much insight is gained if model portrayals are inaccurate or incomplete. As JOHNSON et al. (2000) put it, 'can we learn from the behavior of a system, that does not exist in nature?' - On the other hand, the use of models in forest ecology is encouraged, in the way as statistical data analysis is used (ABER, 1997).

Figure 3:
The number of parameters that are included into model needs to be limited. Inclusion of too many parameters reduces the predictive power; (b) the input data of a model are biased. Further uncertainty is introduced by the parameters, that are quantified by data, and the structure of the model.



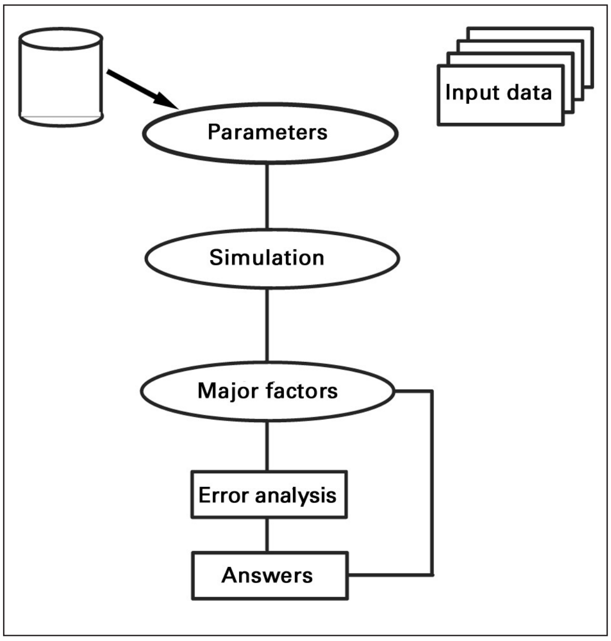


Figure 4:
A model consists of parameters, that are quantified by data, a structure, and of an input dataset

Models can broadly be divided into *statistical models*, which can be used to handle predictions within the range of the database, they are derived of, and mechanistic models that present a view of the system with some simplification. Many factors are driving a system, but not all of them are important. Every additional process included into a model adds an error. Therefore the predictive power of a model has a tendency to level off and even to decrease when too many factors are present (figure 3 a). Mechanistic modeling is the art of simplifying natural processes.

The major steps of modeling are shown in figure 4. Uncertainties in modeling are numerous and can be broken apart systematically. There is the variability that is included in field measurements. To some extent the input data are already biased (y axis in figure 3 b).

Models can serve several purposes. They can be used to evaluate if the current understanding of the system is correct. In that sense models guide inquiry. As Marcel van Oijen put it:

> “ ...if we don’t fail I’m worried. I want to see how we fail ...”

Models allow to provide a processbased context in which to synthesize and analyze experimental data, and they yield predictions that can be used in the interface of science and policy.

4.2 Predictive value of soil chemistry for tree nutrition

4.2.1 Framework of the relation

A logical linkage exists between the nutrient pool in the soil and tree nutrition. Ultimately, the nutrients in the soil, set free by rock weathering, are the upper limit of the amount of nutrients that are available for trees. The ’Eherne Gesetz des Standörtlichen’ (... phrase coined by the German forester Pfeil, 1783-1859) demands that knowledge of the site conditions and soils enables the prediction of the growth rate. There are several factors that often exert a stronger influence than soil chemistry, such as water supply, temperature. Nevertheless, the relation between soil chemistry and tree nutrition is often used, especially for local forecasting. In the Black Forest/Germany, a region of extreme Mg-deficiency, a relation between the amount of exchangeable soil Mg and foliar levels of Mg was established (Liu & Trüby, 1989). A more general relation exists between the amount of N in the soil and site productivity (Andersson et al., 1998; Schulze, 2000). This relation is so close, that it allowed to derive the concept of ’nitrogen productivity’ (Ågren & Bosatta, 1987).

The proximity between soil nutrients and forest growth and tree nutrition is less clear in many other cases. The environment in the intimate vicinity of roots apparently differs greatly from the soil conditions that are reflected by standard soil chemical analysis. We need to bear in mind that soil analysis assesses total or acid/salt extractable nutrients from sieved soil samples. The problems identified with this approach are that the soil skeleton is not taken into account with respect to his nutrient content, that the importance of nutrient release from rocks is ignored, and that the rhizosphere has a different chemistry as the bulk soil.

4.2.2 Case Study - Relation between forest soil chemistry and foliar nutrient content in Austria

We investigated the relation between Yield Class, nutrient content in needles, and soil chemical parameters. The prediction of the Yield Class and tree nutrition by soil chemistry was not possible. Trees are obviously very effective in extracting the required nutrients over a wide range of site conditions (Jandl &Herzberger, 2001).

We investigated if the foliar nutrient level of spruce, a proxy for nutrition, is closely related to the nutrient content of forest soils. In addition we investigated if the Yield Class, a proxy for the general growing conditions of a stand, is related to two common soil chemical indicators, the C:N ratio and the base saturation. We used a subset of the data from the Austrian Forest Monitoring System (WBS). Our analysis was restricted to sites on non-calcareous parent rock, where stands are dominated by Norway spruce. Overall, the relation between tree nutrition, Yield Class, and soil chemical data was weak. Obviously spruce is able to extract the required sufficient amounts of nutrients at a wide range of soil chemical conditions. Spruce efficiently scavenges nutrients over a wide range of soil chemical conditions. Even on poor sites high foliar nutrient levels can be maintained, because nutrients taken up are kept in a tight biogeochemical cycle. We conclude that soil chemical conditions are weak predictors of the Yield Class. Other factors, such as climate and water relations, seem to exert a larger influence on the nutrition and growth rate of spruce forests (JANDL & HERZBERGER, 2001).

An evaluation of this topic with respect to Ca is forthcoming (JANDL & ALEWELL & PRIETZEL & LUNDSTRØM). We will demonstrate that a loss of base saturation has been a common phenomenon in Central European forest soils during the last decades. However, neither the Ca levels in the needles have dropped nor are growth rates declining. We conclude that nutrients are made available from sources, that are not reflected in standard soil chemical data.

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