Long-term trends in chemistry of a nitrogen-deposition loaded beech forest ecosystem

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Introduction

On a notable number of Level II-sites in Germany, monitoring and the determination of atmospheric deposition are combined with investigations of soil solution chemistry for a better understanding of the externalities of forest ecosystems, their structures and functions. One of these sites is located in Schleswig-Holstein the most northern federal state. The analyses of an acidified beech forest ecosystem have a long tradition in comparative ecosystem research, which goes back to the project *Ecosystem Research in the Bornhöved Lakes Region* (Müller 1991) starting in 1989 and lasting until 1999 (Fränzle et al. in Fränzle et al. 2008). Following, great store has been set to keeping and continue the outstanding highly frequented long-term data sets. Conforming aims and chief intent regarding the principles of an ecological orientated observation of the environment as well as monitoring and research intentions have been recognized and consequently induced to join the Level II-Program in 1995/96 (Link in German). Principle objectives of research of Ecology Centre are to bundle and provide data evaluation and interpretations on the bases of philosophy of science and theoretical approaches. In this sense, e.g. thermodynamic and related references allow for reproducible criteria being suitable for describing the states of ecosystems. Finally, theoretically based state variables, orientators and indicators should be applied as they are the absolute essentials that grant for representativity in comparative ecosystem research and for assessing observed trends with respect to ecosystem functions. The maxim and one of the topics of research of Ecology Centre is: How to come from monitoring to ecosystem research?

Methodology

In a large degree of congruity with the ICP-manuals (UNECE continued), atmospheric deposition fluxes of throughfall, stem flow and bulk deposition are recorded during periods of one week. Soil solution sampling is performed during periods of two weeks by zero-tension lysimeters in the humus layer and controlled vacuum supplied ceramic-cup samplers in the mineral-soil horizons. The installation in 5 depths downwards to 400cm has been in particular conformed to the spheres of organic matter transfers, the rooting zone and thus uptake and recycling of nutrients, the zone of unsaturated water flux and the soil parent-material. The frequented data sampling is complemented by the mandatories of the Level II Program (UNECE continued) regarding other matter quantities such as element pools and soil water budgets.

Results

Atmospheric desposition trends

By 10 kg ha^{-1} yr^{-1} decreasing SO_4-fluxes with bulk and throughfall deposition (stemflow incl.) during the 1989-2006 period with 8 kg SO_4-S in 2005 reflect the larger scale trends in Germany owing to successful air pollution control. However, these fluxes also include approx. 20% of marine origin. Like trends observed on the national scale, the nitrogen-flux rates by throughfall do not decrease accordingly. Recent fluxes of approx. 20 kg N ha^{-1} yr^{-1} in the beech forest remain comparatively high, whereas total deposition rates must be assumed particularly higher owing to dry deposition in particular of the reduced nitrogen species NH_3 and NH_4 (see comparison or throughfall with bulk-deposition trends). The total deposition rates may be assumedly up to 40 kg N ha^{-1} yr^{-1} as predicated by modelling internal transfers of

the ecosystem. Approximately one third of nitrogen fluxes consist of NH_4. In comparison with the nitrogen deposition on the national scale the rates are one of the highest. Critical load exceedances by acidifying effects and eutrophication both calculated by PROFILE (Wellbrock 2002) model are remarkable.

Ecosystem and soil solution chemistry

Owing to exergy capture and related dissipation of structures, element concentrations in ecosystems are highly varying but the limited number of organic matter categories (proteins, carbohydrates and lipids) ensures a certain stochiometry in the transfers destinated to biological production of the three major biomass constituents. For the environments of the ceramic-cup samplers, concentrations in the soil solution may even differ more than 100% in time as exemplified by pH, EC (electric conductivity) and the concentrations of Na, Cl, NO_3N and Al as those of the other elements in the depths of 5 and 12cm. However, the variation between the years (K, Na, NH_4N, NO_3N) is in similar order. Rating concentrations of elements performing conservative (sodium and chloride) with those of non-conservative behaviour indicates for nitrate and potassium same processes and strong biotic influence to the fluxes (see below), whereas the variation of values is due to pronounced heterogeneity of soil properties and ecosystem influence on the sampling scale.

Although the spatial and annual variance, diagrams like in the above figures and on the basis of element fluxes in the different subhorizons of the forest soil allocate extensive information about ecosystem functions in element cycling. The dominant nitrogen compound of soil solution is nitrate. Owing to temperature and soil moisture controlled mineralization and nitrification, nitrate concentrations regularly attain maximum concentrations in summer due to temperature-controlled nitrification processes of the organic matter and of the coincident, seasonally elevated, ammonium inputs. In the deeper soil horizons, both the concentrations and seasonal differences decrease rapidly owing to plant uptake, attaining the minimum below 150 cm with only very small intermonthly oscillations. Considering the seasonal variations of the generally low ammonium concentrations (with the exception of the L,O horizons), the rapid decrease with depth is in either case indicative of intense uptake and oxidation processes.

The distinctive change in nitrogen speciation is associated with soil acidification and adequate loss of acid neutralization capacity. Fluxes of the definitive elements and changes progressing with depth depict the performance of a strongly acidified forest ecosystem, where losses of ANC are in particular due to increased atmospheric deposition and subsequently imbalanced nitrogen transfers. In comparison of the fluxes potassium was identified to be the actually limiting element. The juxtaposition of nutrient supply by atmospheric deposition, potentially available element pools of the soil (Nt. 8000, K: 280, Mg 80 and Ca 2700 kg ha^{-1}) in the main rooting zone of 70 cm and comparison with the long-term storage in the standing wood mass (N: 531, K: 163, Mg 56, and Ca: 280 kg ha^{-1}) indicate a superplus of nitrogen over the other nutrients. These wide proportions and stochiometric discrepancies of element ratios give clear evidence for differentiated trends in element transfers of the ecosystem mostly proofed by nitrogen leaching and of Ca and Mg both mobilized by acid neutralization capacities of the ecosystem.

Trends in concentrations allowing for statements about resilience of the ecosystem and possible changes of states were identifiable in the 150cm depth consisting of in particular sandy soil and thus entailing lowest buffering. Significant trends of pH as well as nitrate and Al activities (-log values) illustrate again the importance of nitrogen transfers in soil acidification. During two different episodes of the 1989-2005 period in summer 1996 and the other starting with the drought in 2003, aridity and low soil water contents enhance mineralization and nitrogen oxidation which correlates with increased nitrate activity, free acidity and activity of aluminium species. Owing to cumulative effects of NO_3 mobilisation

from the upper horizons and lasting pressure on the low capacity of the soil buffer system, its resilience is debatable. The recent progress of soil acidification as indicated by the change in cation charge from basic cations (Ca and Mg) in favour of yet potentially toxic Al concentrations and free acidity has already reached the 150 depth.

As a first step towards achievement of the project objectives and thermodynamic substantiation, frequency distributions of pH were tested to identify active buffer soil systems. Significant peaks mark buffer activities in ranges reported for organic matter, soil-aluminium compounds and the CO_3-HCO_3-CO_2-system that is surely active in 400cm depth in presence of solid carbonates. The location of the peaks relative to the pH-scale, prove for certain stability of the identified systems during the 1989-2005 period. The peaks belonging to the upper horizon are in some accordance as well with pKs-values of compounds as they are supposed for organic substances. The wide integrals of the curves depicted for the 150 cm depth indicate kinetic effects due to insufficient reactivities and cover several buffer ranges passing from pH 6.5 to 4.3 in the 1989-2005 period whereas the move of peak positions coincide with the observed trend in pH.

By calculation saturation indices assuming total Al as Al^{3+}, alunite was identified as the most probable aluminium compound of the solid soil-phase before precipitation of other possible secondary aluminium minerals. For the 150cm depth there is also a correlation between the formation of alunite and Al activities of the soil solution and even dissolved sulphate as proved by the element sodium or chloride ratios.

Conclusion and perspectives

The praxis of long-term ecosystem orientated observation and research on the beech forest ecosystem by the Ecology Centre elucidates outstanding potentials of data ascertained in monitoring programs if they are higher-ordered and effect orientated like in the level II-network of ICP-forests. The advantages of the program and the related monitoring were early substantiated with the intention to contribute data and investigations to a better understanding of cause-effect relationships in forest ecosystem functioning. Therewith the level II investigations are beyond conventional environmental control programs.

Highly frequented data sets of atmospheric deposition and soil-solution chemistry represent mobile phases of chemical compounds and depict all matter transfers on higher scales of the ecosystem and its externalities. However, it takes rather frequented time series of over twenty years to identify trends and repeated episodes of ecosystem behaviour significantly against heterogeneities of soil and annual variance. Relevant experience shows that measured data may only reveal trends and cycles over periods approximated in respect to the life-time of ecosystems.

In the near future, the researchers of Ecology Centre will contribute to an upgrade of knowledge for a deeper explanation of ecosystem development. Relating e.g. activities of mobile matter compounds and pools is appropriate to fit for criteria of scientific theories which have been shown in first steps when comparing frequency distribution of pH with standard references of defined buffer systems (pKs-values). It seems also possible to develop theoretical approaches into the scale of ecosystems by relating pools and mobile fractions of matter which leads to reproducible characterisations of ecosystem states on the standards of bio-concentration factors or other indicators. These will be the over-all aim, that indicators of ecosystem health or integrity, the so to say actual mainstream terms, will be achieved.

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