BIOINDICATION OF ECOSYSTEMS REGENERATION ABILITY THRESHOLDS

Angela Schlutow and **Philipp Kraft**
OEKO-DATA Strausberg Hegermuehlenstrasse 58, D-15344 Strausberg, Germany

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Summary

In order to better integrate ecological conditions into environmental cause-effect relationships and critical load values, the BERN model (Bio indication of Ecosystem Regeneration potentials towards Natural conditions) was developed on the basis of empirical surveys in Germany.

Since nearly all biological components in a natural or semi-natural ecosystem are adapted to a long term evolutionary developed status of relations between essential nutrients, such as nitrogen (N), phosphorus (P), carbon (C), and base cations, as well as water supply and temperature conditions, changes in vegetation structure may serve as an indicator for endogenic alterations.

Plant communities contain the highest and most exact level of information. Because the structures of plant communities exhibit a high level of information, one can derive more accurate information about side variables, then from individual plant species.

At first, the fundamental niches of plant species (currently 1050) with their fuzzy thresholds of the suitable site variables (base saturation, C/N-ratio, soil moisture, length of vegetation period and climatic water balance) are included in the BERN database. In a second step the real niches of plant communities (285 communities from Germany)

are integrated by combining the fuzzy fundamental niches of the consistent plant species with the minimum operator of the fuzzy logic. The real existing combinations of site variables are classified to basic site types.

This Access-database enables the user of the BERN-model to assess the current regeneration ability, to quantify the critical limits and critical loads of natural plant communities for eutrophying and acidifying depositions, to determine the dynamic change of vegetation structure in the past and future depending on history and future scenarios of utilization, depositions and climate change and to evaluate future options for potential regeneration targets.

1. Background

The anthropogenic sulfur and nitrogen emissions reached its culmination between 1975 and 1985 over most of middle Europe. Endogenic changes are indicated by the productivity of plants and soil organisms and characterized by the changes of the vegetation structure and conversion of humus structure. Before strong industrialization in middle Europe most ecosystems had not or only slightly been influenced by pollutions.

The spontaneous natural vegetation was adjusted to a site specific nutrient storage with a steady-state relationship between carbon, nitrogen, phosphorus, calcium, potassium and magnesium in connection to the site specific supply of water and temperature.

If, through nutrient input or nutrient loss the same relationship is reached at a higher or lower trophic level, a new natural (or potentially natural) plant community, typical for the habitat may immigrate. A certain number of sites in middle Europe are currently characterized by a relationship of essential nutrients caused by soil-chemical processes as a result of anthropogenic eutrophication and acidification during the last decades, which did not exist in middle Europe before 1960.

The main consequence was the reduction of vitality and ecosystem’s functional efficiency, first for some individuals, then later including entire local populations. Persisting this extinction were plant species with very large ecological niche widths. Later, the original, over centuries developed natural plant community is no longer existent - only fragments remain or new derivate communities of few species settle in.

The investigation of the current state of the anthropogenic change has to implement the natural balance between site and vegetation as a starting point. The state variables, which are anthropogenically difficult to influence (“basic state variables with slow dynamics”), have been determined for the basic state site classification. The vegetation, which reflects the basic state variables with slow dynamics, is defined as the “basic form of vegetation”.

The basic forms of vegetation, which are included in the BERN model, are the plant communities with self regenerating and self regulating ability in the sense of TÜXEN (1957) (see glossary) in their steady-state sociologic-dynamic balance and harmony with site conditions. Succession phases as a result of short term transient conditions and gradual variations in space in overlapping boundary ecotones are neglected and not included in the BERN model. Only non- or rarely extensively utilized communities are considered, because the species balance due to competition is staying in homeostasis over a long time, and therefore the indicator value of changes is meanly forced by pollutions.

These basic plant communities have been described and classified comprehensively in the literature about the flora of Europe before 1960, as natural plant communities for woodland, fen and swamp, or as semi-natural communities for extensive dry grassland and heath (in the following summarized to the term “natural basic plant communities”).

A great amount of knowledge is available about the qualitative relation between site properties and the indicated plant communities. In order to transform the not exact expert knowledge into exact mathematical formulas the BERN model uses the approach of a fuzzy correlation (see glossary) of site types to plant species regarding empirical experiences about plant physiology and plant competition. The degree of the fuzzy correlation is determined by a distribution function of possibilities of plant occurrence in dependence on one or more site variables ranging from 0 to 1.

This definition in accordance to the definition of the ecological niche after HUTCHENSON (IN: SHUGART 1984) describes the ecological niche as an n-dimensionally hyper volume in the functional space of all site factors.

WHITTAKER et al. (1973) distinguishes fundamental and real niches. The fundamental niche corresponds to the hyper volume, which is defined by the fuzzy conditions of plant adaptation to the exogenous site factors, excluding the endogen competitive factor between the plant species. This range of occurrence possibilities is determined by the physiological and genetic properties of the plant species and changes only slowly by evolution.

The real niche is a result of the social properties determined by the competitive power of a particular species and its ability to reproduce, in comparison to all other existing species at the site. While the fundamental niche is normally bell-shaped, the curve for the real niche can be very different and may exhibit for example two peaks.

Due to the difficulties in describing competition between different plant species to each other at one site, the BERN model describes in the first stage only the fundamental niches of the plant species. In a second stage the real niche of the whole plant community is modeled.

Other common approaches like ordination or bioindication based on species (e. g. by ELLENBERG 1996) are not suitable for the BERN model. It is not possible to predict the occurrence of plant species on the basis of site variables, due to not predictable competition influences. In order to model the real possibility of a species the points of dynamic competition equivalents between all species at a site had to be considered.

But there is not enough knowledge about these equivalent points of the species among each other. However, it is possible to predict the possibility degree for a natural plant community occurrence, since it represents the present final solution of long term competition balance between the species.

There is enough published expert knowledge about natural plant communities with respect to their preferred site type. To use this knowledge for determining the fundamental niche of the whole community, in the next stage of the BERN model combines the fundamental niches of those plant species, which mainly constitute the community.

For this reason we regard only the native species, which occur consistently in this community (see Section 2.2). The assemblage of consistent plant species of a plant community do not vary significantly within a climatic region or at a short time scale, if the site state variables do not vary significantly in space or change in time.

The niches of a natural basic plant community then show the basic state variable ranges of a site type.

2. Model Concept

2.1. Aims of the BERN Model

The concept of the model contains 6 steps:

- The determination of the basic state variables a) with slow dynamics b) with fast dynamics and their classification to basic state site types
- Assignment of basic natural plant communities to the basic state variable ranges of the basic state site types
- The determination of the variables with fast dynamics at a currently observed site and the comparison with the basic state variables of the basic state site type.
- The determination of the regeneration target and their regeneration potentials.
- Derivation of the critical loads for eutrophying and acidifying depositions and the critical limits (indicated as C/N ratio and base saturation) in the root zone for (1) structural changes of natural basic plant community and (2) the irreversible loss of the ability of regeneration of every natural plant community
- Determination of suitable potential natural communities taking into consideration, predicted sulfur and nitrogen depositions as well as the predicted climate change in the dynamic BERN – model

2.2. Mathematical Concept

The distribution function of possibility ("DFP") of a plant species occurrence depending on a site variable has to be heuristically derived since a theoretical derivation is not available (ROBERTS 1986). At first the fuzzy thresholds of the basic state variables for the plant species occurrence, which are consistent in a natural basic plant community, are determined and put into the data base of the BERN model.

Site factors are usually not independent from each other. In order to consider several factors of a real existing site type, the fuzzy conditions of the single factors are combined within the BERN model. This step is necessary to declare the range of the functional n-dimensionally space in which the plant species exists.

The DFP for the whole plant community should be assessed such that all plant species, which mainly constitute the plant community (all consistently occurring plant species in the community) determine the DFP of the plant community. The combination of the n-dimensional DFP has to be evaluated in a way that the possibility space of the plant community reaches the highest values at the point where the most consistent species have their highest possibility values.

Since the DFP of a community is defined by the DFP of its consistent plant species, application of the function to the n-dimensional vector of all relevant site variables of one site type is trivial.

The implementation into other models, e.g. critical load assessment models (UN/ECE 2004), using exact defined quantities like critical limits (UN/ECE 2004) needs to change the fuzzy quantity of site variables for a plant community into a classical sharp quantity by assessing a so called α-level-quantity. Therefore a threshold of possibility has to be given. All elements with contribution values which lie above this threshold are elements of the α-level-quantity.

According to the definition of the critical loads (see glossary), the maximum stress loads of one or more pollutants are met (but not exceeded) as long as changes in the structure or/and functionality specified sensitive elements of the environment do not occur. Therefore biologically determined critical load results from a threshold value of the possibility function of the natural basic plant community.

A reasonable threshold value is the possibility degree of 0.5. At this value of the site variable (critical limit), the natural basic plant community has only half the possibility of its occurrence. At this point, either the steady-state structure of the natural basic plant community could be reproduced or the basic structure could change even further up to the extinction of the natural basic community.

2.3. Databases

At first for calibrating and testing the BERN model, our investigation areas were the Northern lowlands of Germany and the low mountains of Saxony. After the successful verification of the results and practical applications of the BERN model we integrated all published natural basic plant communities indicating the typical basic site types of Germany. Currently, the database consist 143 natural basic plant communities of woodland and 140 basic plant communities of grassland, heaths, fens and swamps.

For the area of Germany we evaluated 28 907 vegetation plots (=”releveés”) with additional information about site state variables which have been published before 1960. We also integrated our own vegetation releveés and measurements of soil variables on 1689 plots into the evaluation. Dynamic changes of forest vegetation structure we verified on the basis of 72 German Level-II-Plots of the Forest Investigation Program.

In the BERN model database the natural basic plant communities are assigned to basic site types taking into consideration the basic state variables with slow dynamics in geological time-frames, e. g. type of climatic region, altitude zone, relief type, exposition type, soil type/parent material group.

To these plant communities, the consistently occurring plant species have been assigned. In the BERN database the consistent plant species of all relevant natural plant communities are described by their possibility ranges of the basic state variables with fast dynamics in geological time-frames (type of hydromorphy (degree of water saturation), humus form, using type, C/N-ratio, base saturation (or pH respectively) as well as by variables with fast dynamics observed recently due to climate change processes (length of the vegetation period and climatic water balance).

The influence of phosphorus has still to be neglected in the BERN model, since the interaction with the plant species occurrence could not be verified satisfactorily by experimental evidence. Presently, we have an input of 1050 plant species with their variables ranges.

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Bibliography

Clements, F. E.: (1916), *Plant succession*. Carnegie Institute Washington Publication 242:3-45 [This is the first description of plant's development under conditions of competition in space and time]

Ellenberg, H.: (1996), *Vegetation Mitteleuropas mit den Alpen in ökologischer, dynamischer und historischer Sicht*, Ulmer, Stuttgart, 1095 pp. [Description of the middle European vegetation including Alps. This work contains the “Ellenberg-values” of all middle European plant species regarding their preferred optimum of 8 abiotic environmental factors, i. e. relativ numbers between 0-10]

HUTCHENSON, G.L.: (1981), *Ecological niche*. In: SHUGART H. H.: 1984, *A Theory of Forest Dynamics*, Springer, New York, p. 185 [describes the ecological niche as a n-dimensionally hyper volume in the functional space of all site factors]

IPCC: (2000), *Climate change 2000*. Cambridge University Press, Cambridge, 146 pp. [The International Panel on Climate Change predicted the world wide changes of climatic parameters on the basis of several scenarios of the economical development in the world]

Roberts, D. W.: (1986), *Ordination on the basis of fuzzy set theory*, Vegetatio 66: 123-131 [Method for assignation plant species´ occurrence to environmental factor gradients]

Sverdrup, H., Warfvinge, P.: (1993), *The effect of soil acidification on the growth of trees, grass and herbs as expressed by the (Ca+Mg+K)/Al ratio*. Reports in Ecology and Environmental Engineering 2, Lund University, Lund, Sweden, 177 pp. [List of recently published critical base cation to aluminum-ratios of several trees and forest ground species]

Tüxen, R., (1957). *Entwurf einer Definition der Pflanzengesellschaft (Lebensgemeinschaft)*. Mitteilungen der Floristisch-Soziologischen Arbeitsgemeinschaft (6/7):151. [This fundamental basis for all botanists includes the definitions for plant sociology and the generalities of vegetation classification]

UN/ECE: (1999), *Protocol to the 1979 Convention on Long-range Transboundary Air pollution to abate Acidification, Eutrophication and Ground-level Ozon. Göteborg*. www.unece.org/env/lrtap/multi-hl.htm [This protocol is ratified by 20 nations up to 2006. They commit to reduce the long-range transboundary air pollution up to a fixed amount.]

UN/ECE: (2004), *Manual on methodologies and criteria for mapping critical levels/loads and geographical areas where they are exceeded*, www.icpmapping.net [Comprises the accepted methods to derive ecological thresholds for sensitive elements of ecosystems. This manual serves as a harmonized basis for all countries they ratified the Göteburg protocol – see UN/ECE 1999]

WHITTAKER, R.H., LEVIN, S.A., ROOT, R. B., (1973): *Niche, habitat, and ecotop*. The American Naturalist. Chicago 107 (955):321-338 [definitions of fundamental and real niche and further generalities of plant sociology]

ZADEH, L. A.: (1978), *Fuzzy Sets as a basis for a theory of possibility*, Fuzzy sets and fuzzy systems I: 3-28 [Generalities of fuzzy theory including the definitions, mathematical approaches and applications]

Biographical Sketches

Angela Schlutow is working for the German National Focal Centre of the International Cooperative Programme for mapping and modeling critical loads and levels under the 1979 Convention on Long-range Transboundary Air Pollution of the UN/ECE. Furthermore she is guest-professor of landscape planning at the University of Greifswald, Germany. Her researches are focusing on the relationships between the occurrence of plant species and communities and the abiotic environmental factors which they prefer spontaneously. Numerous own field studies conducted in middle European areas have led to the development of a model for predicting the self-regeneration ability of anthropogenic changed ecosystems. She continues working on problems of vegetation changes caused by climate change.

Philipp Kraft as the co-author developed the mathematical approach of the BERN-model. He is a geo-ecological scientist with focus on implementing and developing ecologic models. His major task in is the calculation of Critical Loads of acidity, eutriphying nitrogen and heavy metal intoxication and their exceedances. He creates the consistent spatial data source as the base of a national object oriented environmental database and model system. Upon this system he calculated the official national dataset of Critical Loads (both sulphur/nitrogen and heavy metals) for Germany and Cyprus. The next future work is mainly focused on the feedback loops of the nutrient cycle at a spatial level above the topic dimension,