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MODELING CRITICAL LOADS OF AIRBORNE ACIDITY AND EUTROPHICATION OF POLISH FOREST ECOSYSTEMS – THE SONOX MODEL

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Abstract: A mass balance model to calculate critical loads of airborne acidity and eutrophication to forest ecosystems has been computerized. The SONOX software developed at the Institute of Environmental Protection replicates the sequence of events on the path from sulfur and nitrogen emission through their deposition and next overlaying it on critical loads values to identify the extent and areas of critical loads exceedance. To support decision making a converse direction is offered to assess the necessary emission reductions to meet assumed environmental goals by eliminating or suitably abating the critical loads exceedance. This software originally developed and applied to support the Polish contribution to the negotiations of the Oslo and Gothenburg Protocols of the Convention on Long-Range Transboundary Air Pollution was thereafter used to assess the capacity of achieving the interim environmental quality targets of the NEC Directive in Poland, to support the development of air protection programs for administrative units exposed to transboundary fluxes and other decision making purposes.

INTRODUCTION

Beginning from the late 60s of the 20^{th} century scientists started to link the observed acidification of rain and surface waters in Scandinavia with emission sources of acidifying gases and in particular with increased coal and oil burning in Europe. These observations became a starting point for scientific research on the effects of sulfur and nitrogen deposition. In Central Europe the adverse impact of acid deposition was addressed to forests and the most dramatic effects are still observable in the so called Black Triangle in the bordering area of Poland, Czech Republic and Germany. According to the generally accepted hypothesis, forest damage results from changes in soil chemistry caused by the air pollution [10]. The responses in soils to acid deposition is explained as a sequence starting with leaching of base cations leading to decreased base saturation and increased soil acidity followed by the release of inorganic aluminium ions into the soil solution [11].

Chronic excess input of nitrogen to forest ecosystems causes nutrient imbalances, i.e. deficiencies of the macro-nutrients (K, P, Mg and Ca) relative to N in needles or leaves, which in turn increase the sensitivity of plants to climatic factors such as frost or drought, and susceptibility to parasite attacks [1].

Two protocols of the Convention on Long-Range Transboundary Air Pollution (LR-TAP Convention) are based on the so called "effect oriented approach" binding emission of air pollutants with their observed adverse effects to aquatic and terrestrial ecosystems. These are the Protocol on Further Reduction of Sulphur Emissions (Oslo, 1994) and the Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg, 1999). Negotiations of the both protocols were supported by critical loads, a quantitative measure of the sensitivity of ecosystems to sulphur and nitrogen deposition. Two main environmental effects of this deposition are recognized, i.e. acidification and eutrophication.

"Critical load of acidity" is defined as the maximum deposition of sulphur and acidifying nitrogen below which significant harmful effects on specified sensitive ecosystem do not occur in a long-term perspective. "Critical load of eutrophication" is the highest deposition of nutrient nitrogen below which harmful eutrophying effects in ecosystem structure and function do not occur according to present knowledge [6].

The difference between actual and/or predicted deposition of sulphur and nitrogen and critical loads is defined as "critical load exceedance" and provides a quantitative measure of potential risk to structure and functioning of ecosystems exposed to this deposition.

The development of critical load databases and maps on the national scale as well as the calculations of the magnitude of exceedances and their geographical extent require a vast computational effort feasible by use of a specific computer tool only.

The critical loads concept links air pollution emission with effects to natural ecosystems by quantifying their sensitivity with critical loads. The LRTAP Convention adopted the critical load concept as a useful approach for considerations of the abatement of nitrogen and sulphur emissions. Following this adoption, a series of national and international activities were initiated which have worked towards applying the concept to future abatement strategies.

The role of critical loads maps for the development and implementation of air pollution control strategies is shown in Figure 1.

METHODOLOGY OF CALCULATING CRITICAL LOADS AND THEIR EXCEEDANCES

The derivation of critical loads methodology was a considerable international effort involving a large number of experts in different fields. Since the early 90s of the 20^{th} century international workshops and other expert meetings were organized to summarize the current state of knowledge and to identify challenges for the future.

There are two major effects of sulphur and nitrogen deposition considered, acidification caused by sulphur and nitrogen dioxides and ammonia and eutrophication caused by excess nutrient nitrogen deposition. From among a number of natural ecosystems adversely affected by the both processes, forest ecosystems are the most widely considered due to their territorial extensiveness and economic significance.

Critical loads of acidity

The model is based on the following mass balance equation [9]:

$$S_{dep} + N_{dep} = BC_{dep} + BC_{w} - Bc_{u} + N_{u} + N_{i} + N_{de} - ANC_{le} \qquad (1)$$

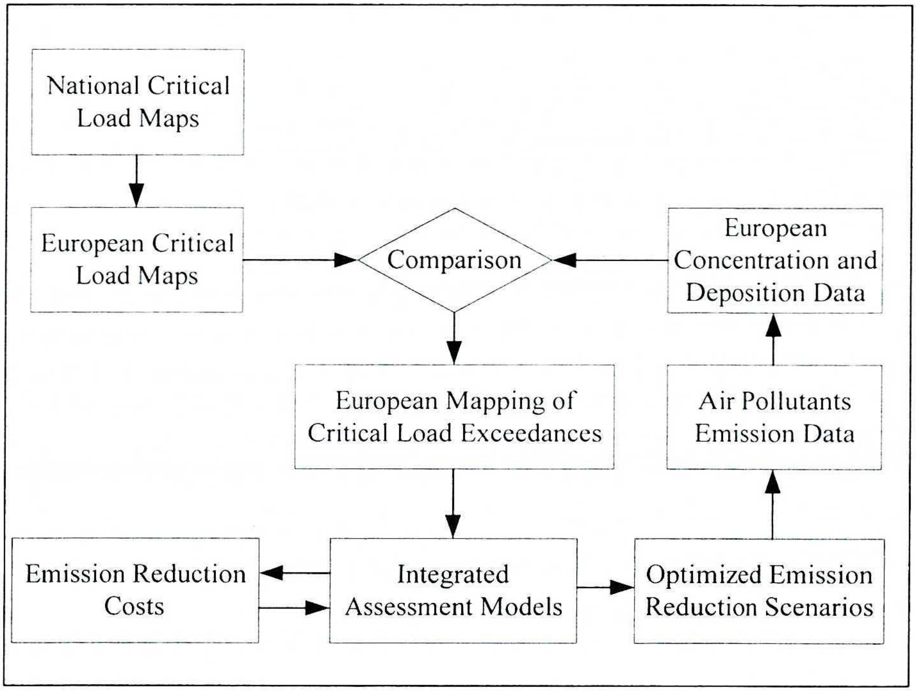

Fig. 1. Critical loads and abatement strategies – a general concept [9]

where:

S_{dep} – total S deposition
N_{dep} – total N deposition
BC_{dep} – base cation deposition
BC_{w} – base cation weathering
Bc_{u} – base cation uptake
N_{i} – long-term net immobilization of N in soil organic matter
N_{u} – net removal of N in harvested vegetation
N_{de} – flux of N to the atmosphere due to denitrification
ANC_{le} – leaching of acid neutralizing capacity
All quantities are given in eq/ha/yr. BC = Ca + Mg + K + N and Bc = Ca + Mg + K

Because sulphur and nitrogen simultaneously contribute to acidification and nitrogen sinks cannot compensate incoming sulphur acidity due to partial consumption by immobilization and denitrification, a function of critical loads of acidity must be considered of the following shape (Fig. 2).

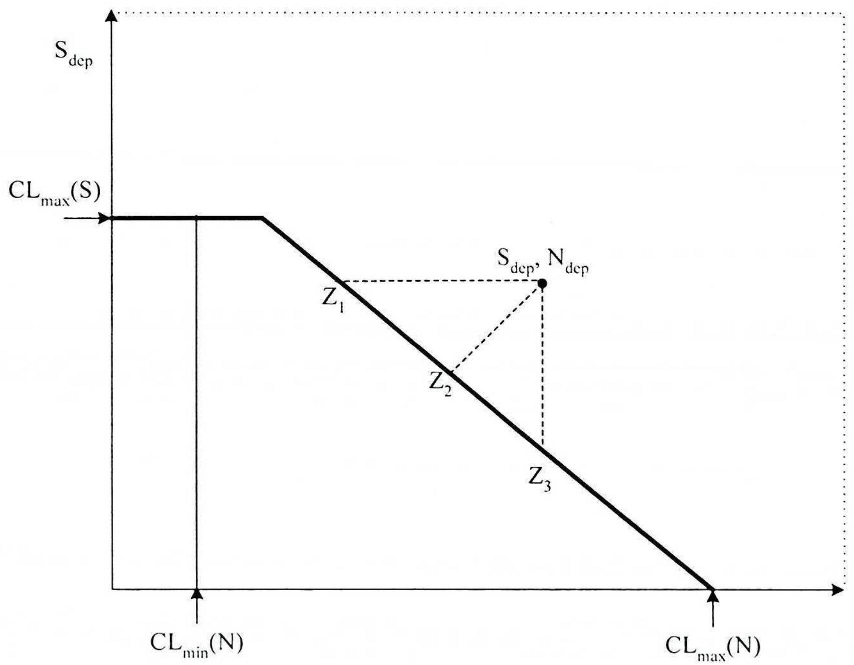

Fig. 2. The critical loads function of acidity [9]

This function is defined by the three quantities:

$CL_{max}S$ – maximum critical load of sulphur, which is the maximum tolerable sulphur deposition in case of zero deposition of nitrogen:

$$CL_{max}S = BC_{dep} + BC_w - Bc_u - ANC_{le} \quad (2)$$

$CL_{min}N$ – minimum critical load of nitrogen, which equals to long-term net removal, immobilization and denitrification of nitrogen in soil:

$$CL_{min}N = N_i + N_u + N_{de} \quad (3)$$

$CL_{max}N$ – maximum critical load of nitrogen is the harmless maximum deposition of nitrogen in case of zero sulphur deposition:

$$CL_{max}N = CL_{min}N + CL_{max}S/(1 - f_{de}) \quad (4)$$

where:

f_{de} is the denitrification fraction, a site-specific quantity.

There are several chemical criteria in use of which the critical base cation to aluminium molar ratio $BC/Al_{(crit)}$ has been accepted as the most widely used.

Critical loads of eutrophication

The point of departure to derive critical loads of eutrophication is the following mass balance equation:

$$N_{dep} = N_i + N_u + N_{de} + N_{le} \quad (5)$$

From this equation a critical load is obtained by defining an acceptable limit to the leaching of nitrogen $N_{le(crit)}$. Inserting this critical leaching to the above equation, the deposition of nitrogen becomes the critical load of nutrient nitrogen also called eutrophication:

$$CL_{nut}(N) = N_i + N_u + N_{de} + N_{le(acc)} \quad (6)$$

Introducing to the above formula a linear relationship between denitrification and the net input of N the final equation for critical load of nutrient nitrogen is as follows:

$$CL_{nut}(N) = N_i + N_u + N_{le(crit)}/(1 - f_{de}) \quad (7)$$

Critical loads exceedance

The accumulated exceedance of acidity for a given pair of sulphur and nitrogen depositions is defined as the sum of the ExN and ExS deposition reductions required to reach the critical load function by the 'shortest' path depicted in Figure 3 by the section E2 – Z2.

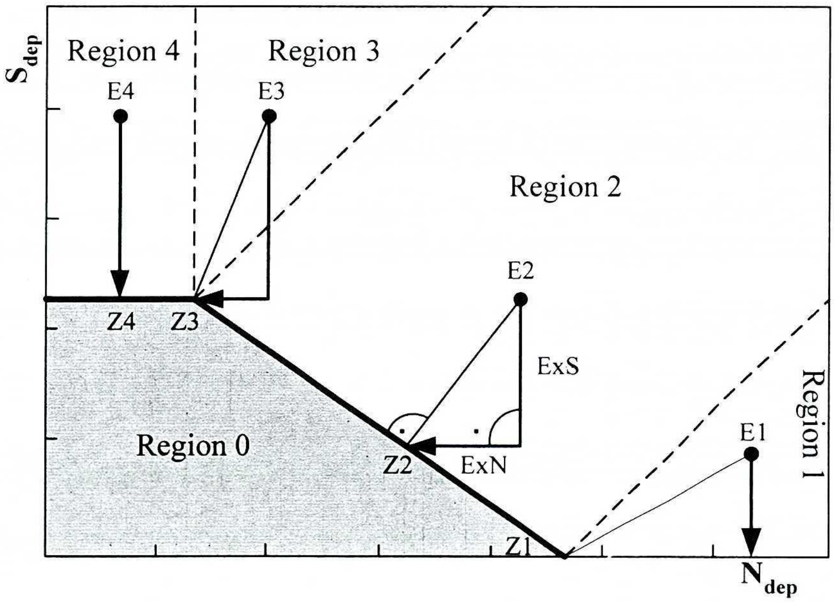

Fig. 3. Illustration of the different cases for calculating the exceedance for a given critical load function [9]

There are five possible cases represented as regions that can occur when calculating critical load exceedances, summarized in equation 8:

$$Ex(N_{dep}, S_{dep}) = \begin{cases} 0 & \text{if } (N_{dep}, S_{dep}) \in \text{Region 0} \\ N_{dep} - CL_{max}(N) + S_{dep} & \text{if } (N_{dep}, S_{dep}) \in \text{Region 1} \\ N_{dep} - N_0 + S_{dep} - S_0 & \text{if } (N_{dep}, S_{dep}) \in \text{Region 2} \\ N_{dep} - CL_{min}(N) + S_{dep} - CL_{max}(S) & \text{if } (N_{dep}, S_{dep}) \in \text{Region 3} \\ S_{dep} - CL_{max}(S) & \text{if } (N_{dep}, S_{dep}) \in \text{Region 4} \end{cases} \quad (8)$$

The exceedance of nutrient nitrogen, causing eutrophication is calculated simply by subtracting the value of critical load of nutrient nitrogen from actual deposition of nitrogen:

$$Ex_{nut}(N_{dep}) = N_{dep} - CL_{nut}(N) \quad (9)$$

THE SONOX MODEL

General characteristics

The above presented mass balance models were used to calculate parameters of critical load functions of acidity and eutrophication for Polish forest ecosystems with a distinction into coniferous and deciduous trees as sub-ecosystems. Based on the input data availability on one hand, and the expected maximum obtainable accuracy on the other hand, the spatial resolution defined by a 1 x 1 km grid cell size was chosen. Such a cell size provides that in a cell a unique sub-ecosystem type is represented and no statistical interpretation within a grid cell is required. This detailed spatial resolution resulted in 88 383 records in the derived input and output database and in a huge computing effort taking into account the complex numerical procedures to perform for every record. To automate and speedup the computations a special computer software SONOX was developed. The same software is also capable to generate maps of the calculated quantities, i.e. critical loads and their exceedances.

The spatial processing is based on a special case of the so-called polar stereographic projection where each point on the Earth's sphere is projected from the South Pole onto a plane perpendicular to the Earth's axis and intersecting the Earth at a fixed latitude Φ0. This spatial system was adopted from Co-operative Program for Monitoring and Evaluation of the long-range transmission of air pollutants in Europe (EMEP) a sub-body of the LRTAP Convention, providing deposition estimates necessary to calculate critical load exceedances (http://www.emep.int/grid.html). The resulting maps are also offered in geographic coordinates.

The SONOX model replicates the sequence from emission of sulphur and nitrogen through their atmospheric transport and deposition and finally to the examination of the exceedance of deposition tolerable by forest ecosystems – Figure 4.

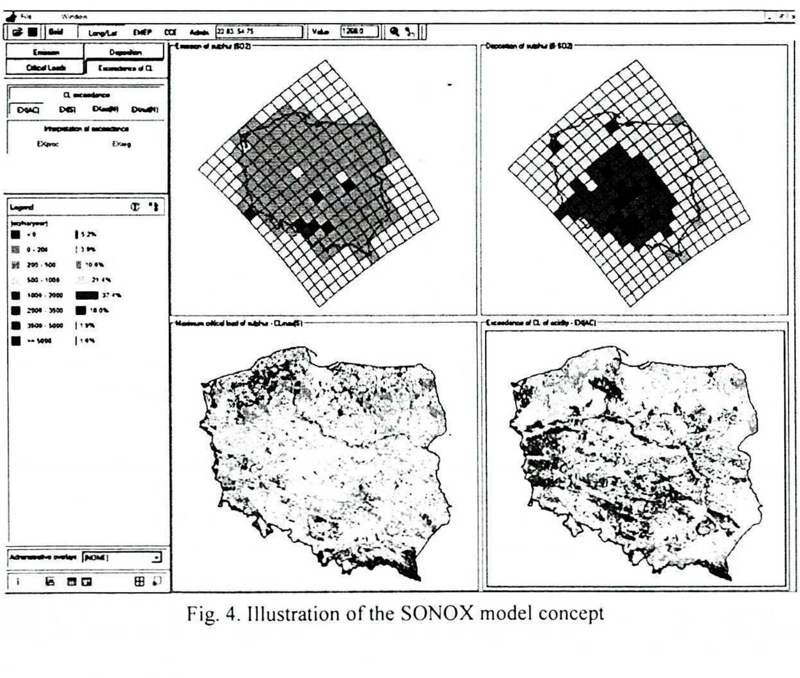

Fig. 4. Illustration of the SONOX model concept

Model structure

Model SONOX is of a modular structure combining sub-models representing the four basic processes, i.e. emission scenarios construction, development of atmospheric deposition patterns, calculating and mapping critical loads and identifying magnitude and geographical extent of critical loads exceedances. Integration of these modules by the main model consists in organization of input and output data flow among the modules and in providing mapping procedures for the calculated quantities. The elements of the model structure and the system of inter modular linkages is presented in Figure 5.

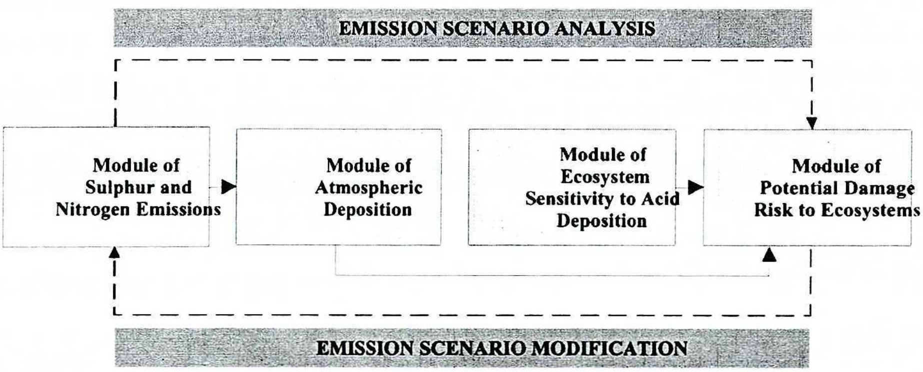

Fig. 5. Flow diagram of the SONOX model structure

The emission module

The purpose of this module is to facilitate the emission scenarios creation in form of specially formatted databases. There are two groups of scenarios provided: official scenarios and user scenarios.

The official scenarios of annual sulphur and nitrogen oxides and ammonia emissions for the period 1980–2005 are adopted from EMEP. The future scenarios for the years 2010 and 2020 are based on the Gothenburg Protocol and NEC Directive obligations. The other group of scenarios may be constructed by the model user following the required database formats. The spatial distribution of the Polish emission data is based on the 50 x 50 km grid while the European data are the country average data.

The emission module offers an option to manage the databases contents.

The deposition module

This module has been developed in co-operation with experts from EMEP [7]. Atmospheric transport and deposition was computed by applying the EMEP Eulerian acid deposition model [8]. The model was extensively validated against measurements at 89 EMEP stations all over Europe. For most cases, the annual concentrations and depositions computed by the model agree with observations within factor of two.

For each emitting region (e.g. country or particular industrial region in Poland) a separate deposition calculation was carried out. As a result, the so called "source-receptor" matrices were computed where the source denotes emitting region and the receptors are the EMEP grid cells covering Poland's territory.

This kind of matrices have been developed for seven major emission regions referring to four largest power plants and three large industrial and/or urban centers of Poland. The eighth emission region was the "background", i.e. all Polish emissions sources except the above seven regions. To simulate transboundary fluxes, transfer matrixes for sulphur and nitrogen have been developed to evaluate the deposition from European countries onto Poland. Conditions average for the period 1991–1996 provides the meteorological background for the "source-receptor" matrices computations.

These matrices were introduced into this module structure. Owing to these matrices a quick simulation of atmospheric transport and deposition of emitted pollutants in spatial resolution of 50 x 50 km was possible.

The critical load module

This module is responsible for calculating and mapping the three parameters of critical loads function of acidity and critical loads of eutrophication. Based on methodologies presented in the above sections a special numerical procedure has been developed and computerized to run the calculations. The resulting databases are then spatially processed to produce maps of the calculated quantities in a resolution determined by a 1 x 1 km grid cell size.

The exceedance module

Using the output data from the deposition and critical loads modules, the exceedance module calculates the excess deposition by subtracting the both estimated for every single grid cell. Finally, according to the described procedure, the module produces maps of Poland with 1 x 1 km resolution, presenting values of critical loads exceedances, percentage of ecosystems protected against acidification and eutrophication and reduction requirements for sulphur and nitrogen deposition.

MODEL APPLICATIONS

The SONOX program was originally developed and applied to support the Polish contribution to the production of first pan-European critical load maps providing a scientific basis for the negotiations of the Oslo and Gothenburg Protocols of the Convention on Long-Range Transboundary Air Pollution – Figure 6 [3, 5]. Besides the international, relevance the program concept and structure enables a wide range of national and local environmental policy applications, examples of which are briefly reported in the following.

A study has been performed to assess the capacity of achieving the interim environmental quality targets of the NEC Directive in Poland [4]. Based on an analysis of future sulphur and nitrogen emission scenarios, supported with the SONOX program, it was concluded that in the target year 2010 and at the emission ceilings set by the Directive, the ecological interim target will be achieved on the whole territory of Poland except the area of Higher Silesia. The progress of meeting the ecological target is strongly influenced by the transboundary sulphur and nitrogen fluxes in western and southern boundary regions. The implementation of the NEC Directive will effect in 80% reduction in areas of exceeded critical loads of acidity to compare with 1990.

Another application of the SONOX model was to identify actual and projected transboundary fluxes of SO_2, NO_x, NH_3 and particulate matter as well as their spatial distribu-

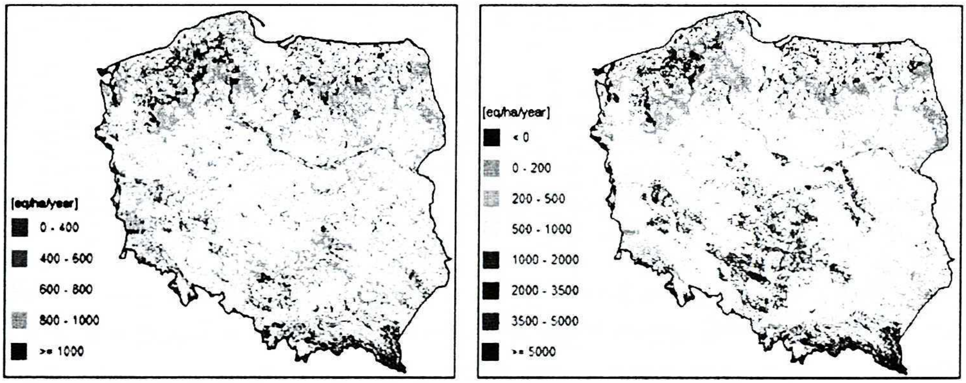

Fig. 6. Maps of maximum critical loads of sulphur (left) and accumulated exceedance of acidity (right) for Polish forest ecosystems

tion on Poland with regard to the administrative division [2]. Based on acquired information, a permanent database has been developed offering numerical and graphical forms of concentration, and deposition balances of the considered pollutants to support the development of air protection programs for administrative units exposed to transboundary fluxes. The developed databases are managed by a special version of SONOX program, especially produced within this project, called SONOX-POP. This program offers a spatial visualization of potential transboundary fluxes and arranges budgets and periodical reports to assist the local air pollution control programs.

By use of an advanced version of the SONOX program projections of ecological effects of fulfilment of the Gothenburg obligation for Poland have been derived, based on the multivariant emission scenarios of sulphur and nitrogen, with respect to transboundary fluxes. By use of this program an analysis of the air pollution emission abatement strategies under the Geneva Convention have performed as well as a review of the efficiency of national sulphur and nitrogen emission reduction programs in the context of the Gothenburg Protocol commitments. Within the study an update of critical load map of acidity to Polish forest ecosystems has been done as well as an assessment of the contribution of transboundary fluxes of airborne sulphur and nitrogen in the overall acid deposition on Polish woodlands. In conclusion a projection of the future acidification trends for Polish forest ecosystems has been carried out using the SONOX model.

The future of the SONOX model is to extend it with a dynamic modeling module to simulate ecosystems response to changing atmospheric deposition patterns of sulphur and acidifying nitrogen. First attempts in this direction are already done but still a huge effort is needed because of the extreme complexity of modeled processes and their temporal changeability.

CONCLUSIONS

The SONOX model has been tested in several projects:

1. Originally the SONOX model was developed to address the international calls for national inputs to the negotiation process of the first effect-oriented Oslo Protocol

to further reduce sulphur emissions in Europe. Within this task the first critical load maps of acidity for Poland have been produced.

2. The other international challenge for the model to take up was to support the Polish negotiators of the Gothenburg Protocol on the abatement of acidity and eutrophication.
3. The SONOX model flexibility made it applicable for the assessment of the capacity of achieving the interim environmental quality targets of the EU NEC Directive in Poland.
4. To support the local air pollution control programs a permanent database of actual and projected transboundary fluxes of sulphur and nitrogen compounds onto Poland was developed, operated by the SONOX model.

The wide range of successful applications at national and international levels of the SONOX model confirms its value as an efficient tool for developing emission reduction strategies, based on recent scientific achievements.

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MODELOWANIE ŁADUNKÓW KRYTYCZNYCH ATMOSFERYCZNEGO ZAKWASZENIA I EUTROFIZACJI EKOSYSTEMÓW LEŚNYCH POLSKI – MODEL SONOX

Skomputeryzowano model bilansu masy do wyznaczania ładunków krytycznych zakwaszenia i eutrofizacji ekosystemów leśnych. Program SONOX opracowany w Instytucie Ochrony Środowiska odzwierciedla ciąg zdarzeń na drodze od emisji siarki i azotu, następnie depozycji tych zanieczyszczeń do identyfikacji wielkości i przestrzennego zasięgu przekroczeń ładunków krytycznych, poprzez superpozycję rzeczywistych depozycji i ładunków krytycznych. Dla celów decyzyjnych możliwa jest droga odwrotna, umożliwiająca określenie niezbędnych redukcji emisji siarki i azotu dla osiągnięcia zakładanych celów ekologicznych poprzez eliminację

lub obniżenie przekroczeń ładunków krytycznych. Program SONOX, pierwotnie opracowany i wdrożony dla potrzeb negocjacji Protokołu z Göteborga Konwencji w Sprawie Transgranicznego Zanieczyszczania Powietrza na Dalekie Odległości, był także wykorzystany do oceny możliwości osiągnięcia przez Polskę przejściowych celów ekologicznych Dyrektywy Pułapowej Komisji Europejskiej, do wsparcia budowy programów ochrony powietrza przez jednostki administracyjne i innych krajowych przedsięwzięć z zakresu ochrony środowiska.