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Dynamic Modelling Predictions of Airborne Acidification of Polish Terrestrial Ecosystems

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1. Introduction

Once the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone adopted in Gothenburg in 1999 has entered into force the process of its review started. According to the Protocol statements the adequacy of its obligations and the progress made towards the achievements of its objectives are the basic subjects of this review. Recent scientific findings mainly achieved from the effect-oriented activities of the Working Group on Effects (WGE), a sub-body of the Convention on Long-range Transboundary Air Pollution (CLRTAP), show that a considerable reduction of geographical extent and magnitude of excess acidification would be achieved in 2010 due to the sulphur and nitrogen emission cuts determined by the Protocol obligations (Working Group on Effects, 2004). Nevertheless still some areas also in Poland will remain under the permanent ecological risk resulting from the exceedance of critical loads of acidity. This means that current Protocol commitments are insufficient to prevent these areas from further acidification of ecosystems in a long-term scale and that additional measures are required to protect them. Another important question that the Protocol review answered, addressed to areas where critical loads are not exceeded, was when ecosystems will recover in response to the agreed emission reductions. The both questions may only be answered using a dynamic approach to estimate the response of ecosystems to changes in atmospheric acid deposition thus dynamic models are considered the most appropriate practical tools. A number of dynamic models to simulate acidification of soils and surface waters have been developed, tested and successfully applied to specific integrated monitoring sites in various countries but for a pan-European scale application a new Very Simple Dynamic (VSD) model has been elaborated suitable to support the integrated assessment of emission reduction scenarios (Posch et al., 2003). The VSD model was applied to assess the Polish terrestrial ecosystems soil chemistry reaction and consequently the damage and recovery time delays due to changing acid deposition. Dynamic modelling calculations were done for six distinct terrestrial habitats (Table 1). The spatial resolution applied is determined by 1 km² grid squares which contains 1 ha or more of the habitat.

2. From steady-state to dynamic approaches

Critical load concept supporting the Gothenburg Protocol is based on a steady-state approach where critical loads are constant depositions that an ecosystem can be exposed to

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Ecosystem	EUNIS code	Area km ²	No of grid cells	Percentage of receptor area
Broad-leaved forest	G1	16056	30153	17.8%
Coniferous forest	G3	48398	88151	53.6%
Mixed forest	G4	23107	42992	25.6%
Natural grasslands	E	577	1145	0.6%
Moors and heath land	F	78	128	0.1%
Mire, bog and fen habitats	D	2114	3956	2.3%
Total		90330	166524	100.0%

Table 1. Ecosystems subject to dynamic modelling calculations

with no damage to its functioning and structure in a long-term perspective. Thus, this concept refers to situation where equilibrium between a given deposition and biochemical status of an ecosystem is reached. A mathematical model has been constructed to reflect quantitatively the considered relations (UBA, 2004)

The model is based on the following mass balance equation:

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

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 $\text{eq ha}^{-1}\text{yr}^{-1}$. $BC = \text{Ca} + \text{Mg} + \text{K} + \text{N}$ and $Bc = \text{Ca} + \text{Mg} + \text{K}$

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 (Figure 1).

This function is defined by the three quantities:

CL_{maxS} - maximum critical load of sulphur, which is the maximum tolerable sulphur deposition in case of zero deposition of nitrogen:

$$CL_{\text{maxS}} = BC_{\text{dep}} + BC_{\text{w}} - Bc_{\text{u}} - ANC_{\text{le(crit)}} \quad (2)$$

Where:

$$ANC_{\text{le(crit)}} = -Q \cdot \left(\frac{[Al]_{\text{crit}}}{K_{\text{bibb}}} \right)^{\frac{1}{3}} + [Al]_{\text{crit}} \quad (3)$$

Q - precipitation surplus [$\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$]

K_{gibb} - gibbsite equilibrium constant

$[\text{Al}]_{\text{crit}}$ - critical aluminium concentration in the soil solution

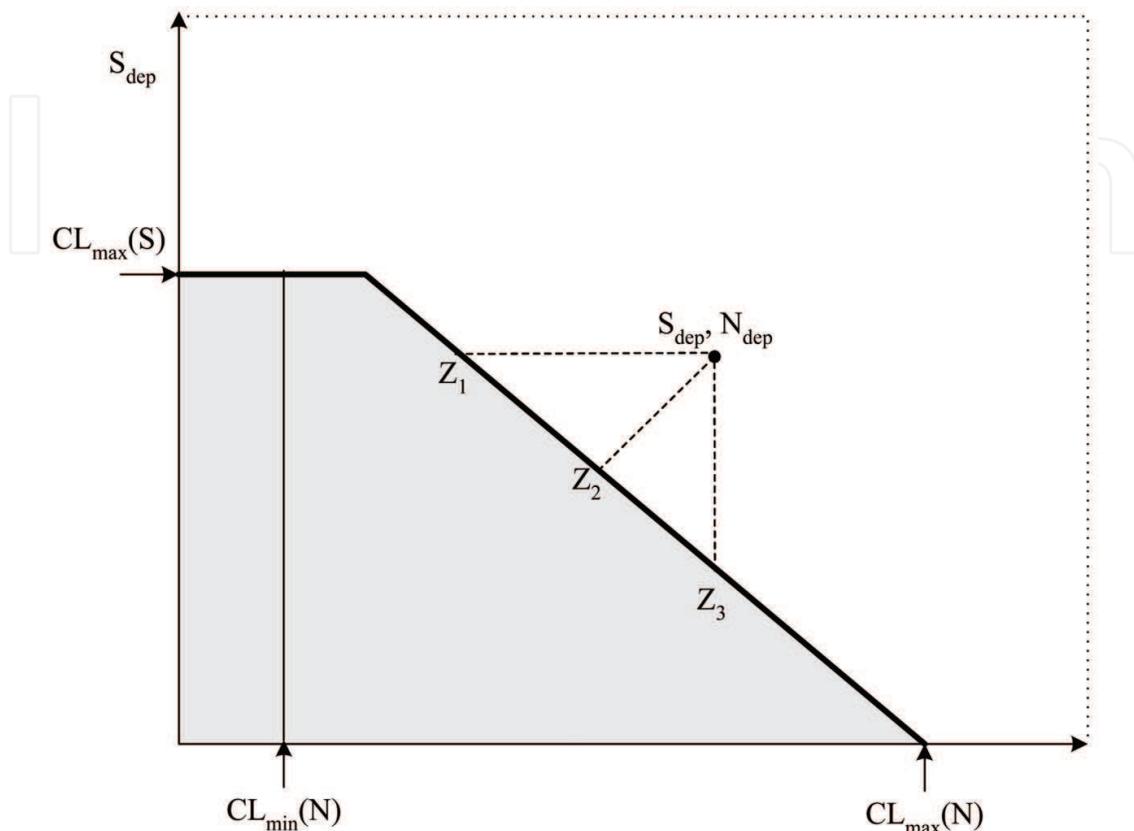


Fig. 1. The critical load function of acidity

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

$$\text{CL}_{\text{min}}\text{N} = \text{N}_i + \text{N}_u + \text{N}_{\text{de}} \quad (4)$$

$\text{CL}_{\text{max}}\text{N}$ - maximum critical load of nitrogen is the harmless maximum deposition of nitrogen in case of zero sulphur deposition:

$$\text{CL}_{\text{max}}\text{N} = \text{CL}_{\text{min}}\text{N} + \frac{\text{CL}_{\text{max}}\text{S}}{1 - f_{\text{de}}} \quad (5)$$

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

However, in reality the equilibrium can practically not be kept due to processes delaying for decades the ecosystems reaction to relatively fast deposition changes. A dynamic model identifies the magnitude of critical loads exceedances and areas where they occur and provides information on time of both the damage and recovery delay as well as determines target loads, e.g. the maximum deposition allowed to reach a certain ecological goal within a fixed time horizon. To perform these functions the model structure bridges the steady-state critical load approach with dynamic interpretation of ecological processes in a way that any dynamic model output has to be coherent with results from critical loads calculations. This

consistency is also required by the integrated assessment model RAINS (Alcamo et al., 1990) to evaluate cost effective and technically feasible emission reduction scenarios.

A Very Simple Dynamic (VSD) soil acidification model has been developed (Posch et al., 2003) to provide national scientific communities, acting within the effect-oriented program of the WGE, with a modelling tool of less possible input data requirements.

3. The VSD model concept

The VSD model concept is based on a set of mass balance equations replicating the change over time of the total amount of base cations and nitrogen in soil solution, in response to the temporal changes of atmospheric deposition of acidifying compounds. Consequently, the soil solution chemical status in VSD is interpreted as a product of the net element input from the atmosphere i.e. deposited minus uptaken minus immobilized mass, and the geochemical processes occurring in the soil i.e. CO₂ equilibrium, weathering of carbonates and silicates and cation exchange. The cation exchange mechanism between the liquid phase and the soil exchange complex is described by the Gains-Thomas or Gapon exchange equations. The exchangeable cations considered are: base cations (Ca+Mg+K), aluminium and protons. Soil water transport is simplified by assuming complete mixing of the element flux within one homogenous soil layer of a fixed thickness. Only vertical water transport is considered. The basic output of the VSD model are predicted concentration changes of considered chemical components of the soil water, leaving the soil layer, mostly limited to the root zone. The forecasting time-step is one year.

4. Critical loads database

The recently updated critical load database (Mill & Schlama, 2008) for Polish forest and semi-natural ecosystems was applied. Three parameters of the critical load function for acidity i. e. $CL_{\max}S$, $CL_{\min}N$ and $CL_{\max}N$ have been derived using the Simple Mass Balance model (UBA, 2004) and were addressed to forest and semi-natural ecosystems as the most widespread sensitive receptor of sulphur and nitrogen deposition in Poland. The applied spatial resolution for mapping critical loads and their exceedance was based on a 1x1 km grid cell. Accordingly 166524 single sites were subject to modelling. The long-term average values of input parameters to calculate critical loads were derived from national or single site measurements. Data from 1468 I-level and 148 II-level forest monitoring sites provided the main input to calculations (Wawrzoniak & Małachowska, 2006). From this monitoring soil physical and chemical property, base cation depositions and vegetation parameters were derived. Default values of denitrification fraction, nitrogen immobilization, and gibbsite equilibrium constants have been obtained through an extensive review of existing literature data or adopted from the Manual for Modelling and Mapping (UBA, 2004). For mineral/organo-mineral soils dominating in the considered ecosystems the critical chemical threshold $[Al]_{\text{crit}} = 0.2 \text{ eq} \cdot \text{m}^{-3}$ was used.

Geostatistical smoothing techniques were used to generate interpolated critical load maps of 1x1 km grid resolution from monitoring sites maps.

5. VSD model database

In addition to data already existing in the critical load database parameters characterizing the cation exchange process and nitrogen balance have been derived and inserted into the

VSD model database. These are soil bulk density, cation exchange capacity CEC, base saturation, exchangeable cation fractions and C/N ratio. All of the data are based on the II-level forest monitoring records (Wawrzoniak & Małachowska, 2006) assigned to the following four soil horizons: O - 0.05 m, A/E - 0.10 m, B - 0.30 m and C - 0.40 m. While VSD is a single-layer model the input data were averaged over the entire rooting zone of 0.5 m depth. These parameters (except C/N ratio) multiplied by soil layer thickness produce the pool of exchangeable cations.

Cation exchange constants based both on the Gaines-Thomas and Gapon exchange reactions were adopted from the Manual for Dynamic Modelling of Soil Response to Atmospheric Deposition (Posch et al., 2003). Historic sulphur and nitrogen deposition sequences contained in the VSD model were applied.

6. Results and discussion

The basic calculation runs were preceded with a preliminary step aimed at the exclusion from further calculations all these sites where critical loads are not exceeded in 2010 and the adopted chemical criterion is not violated. There is no need to calculate target loads for such sites. This operation resulted in a decrease of the total number of 166524 sites gathered in the national database to 48721 sites for which further tests were performed. Table 2 summarizes the VSD model results with three possible cases distinguished.

STATUS	Target Year					
	2030		2050		2100	
Ecosystems safe in target year	9208	18.9 %	9403	19.3%	9574	19.7%
Target load function exists	38855	79.8 %	39172	80.2%	39147	80.4%
Target load not feasible	658	1.4 %	146	0.5%	0	0.0%

Table 2. Number and percentage of forest sites assigned by the VSD model to three situations characteristic for dynamic response of forest soil chemistry to changing acid deposition

Ecosystem safe in a target year is a one for which critical load is not exceeded and the chemical criterion is not violated. As can be seen from the above table 18.9% forest sites in 2030 to 19.7% in 2100 are safe in the considered target years when acid deposition remains at the level corresponding to the Gothenburg Protocol obligations.

The next step in the model calculations was to find sites which are safe in a given target year with background deposition determined by EMEP MSC-W i. e. the lowest possible deposition caused by non-anthropogenic emissions only. This group of sites appeared to be the biggest making up to approximately 80% of all processed sites.

The third group of sites selected from the database by the VSD model is composed of sites for which target loads are not feasible i.e. the chemical criterion cannot be reached in the target year even at depositions reduced to background values. There are 1.4 % of such sites for the target year 2030 and 0.5 % for 2050 while for 2100 it is not the case.

Figures 2 to 4 show how the dynamic characteristic is spatially distributed over the Polish terrestrial ecosystems in the considered time horizons.

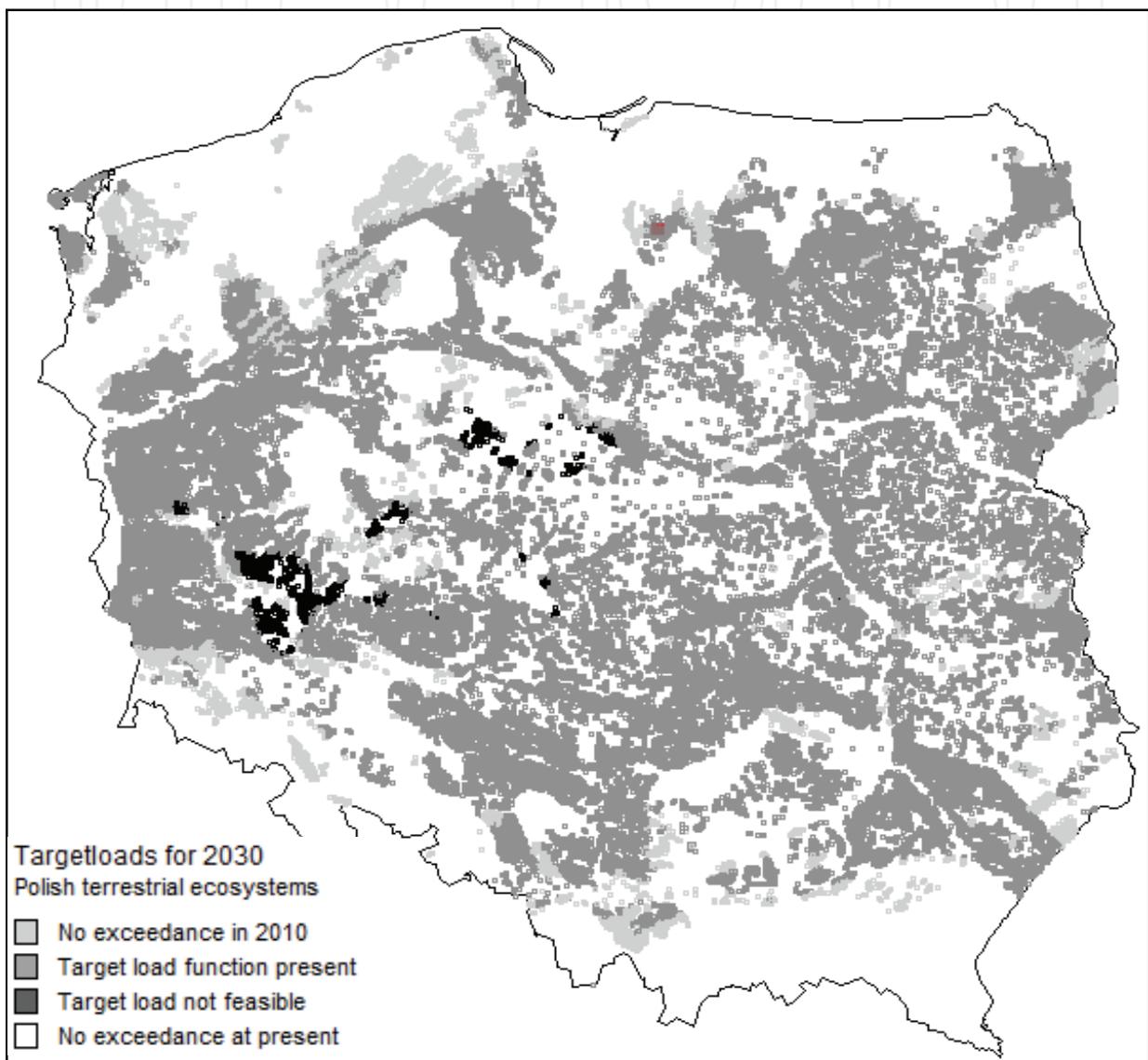


Fig. 2. Spatial distribution of results of target load calculations for 2030

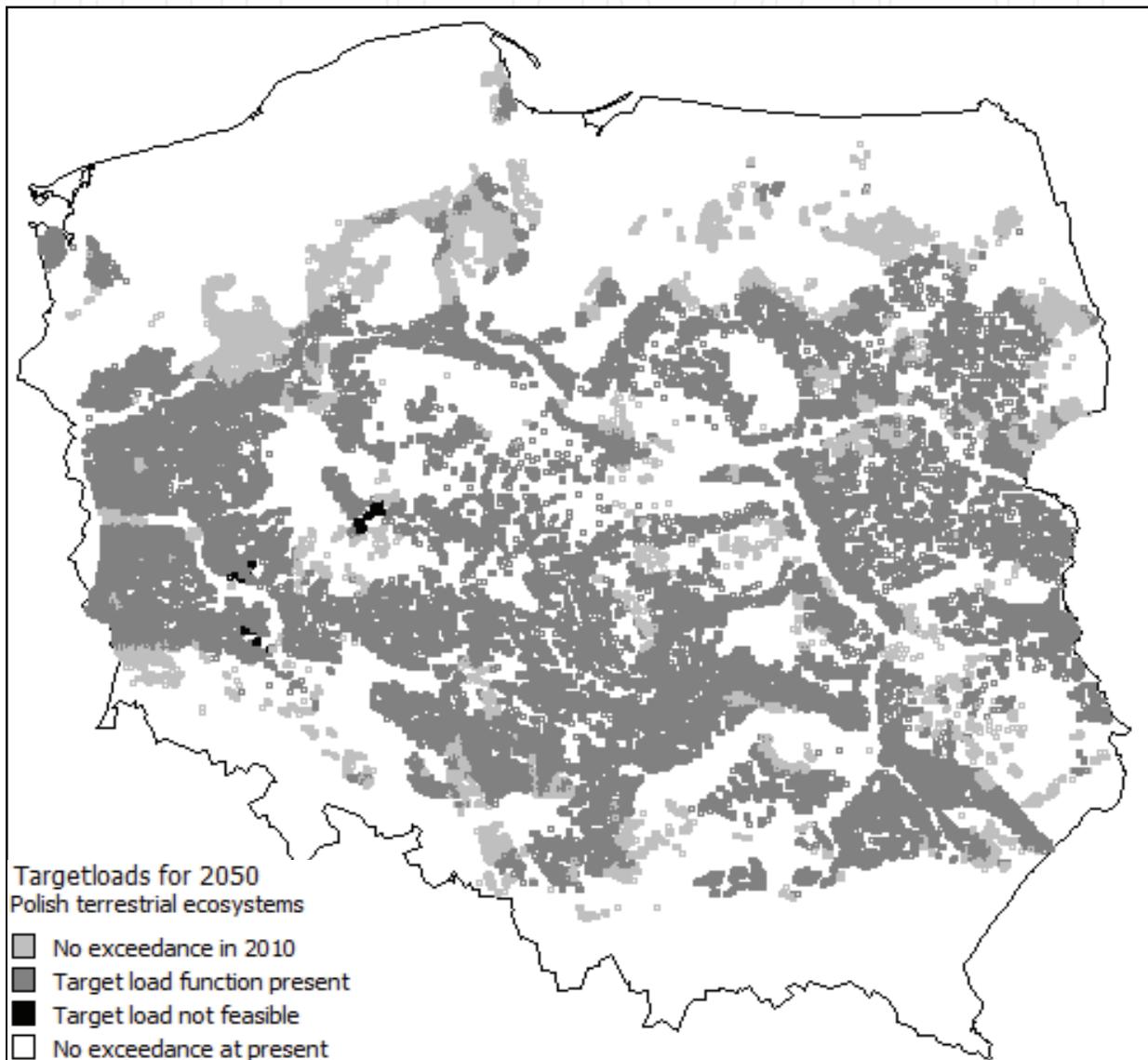


Fig. 3. Spatial distribution of results of target load calculations for 2050

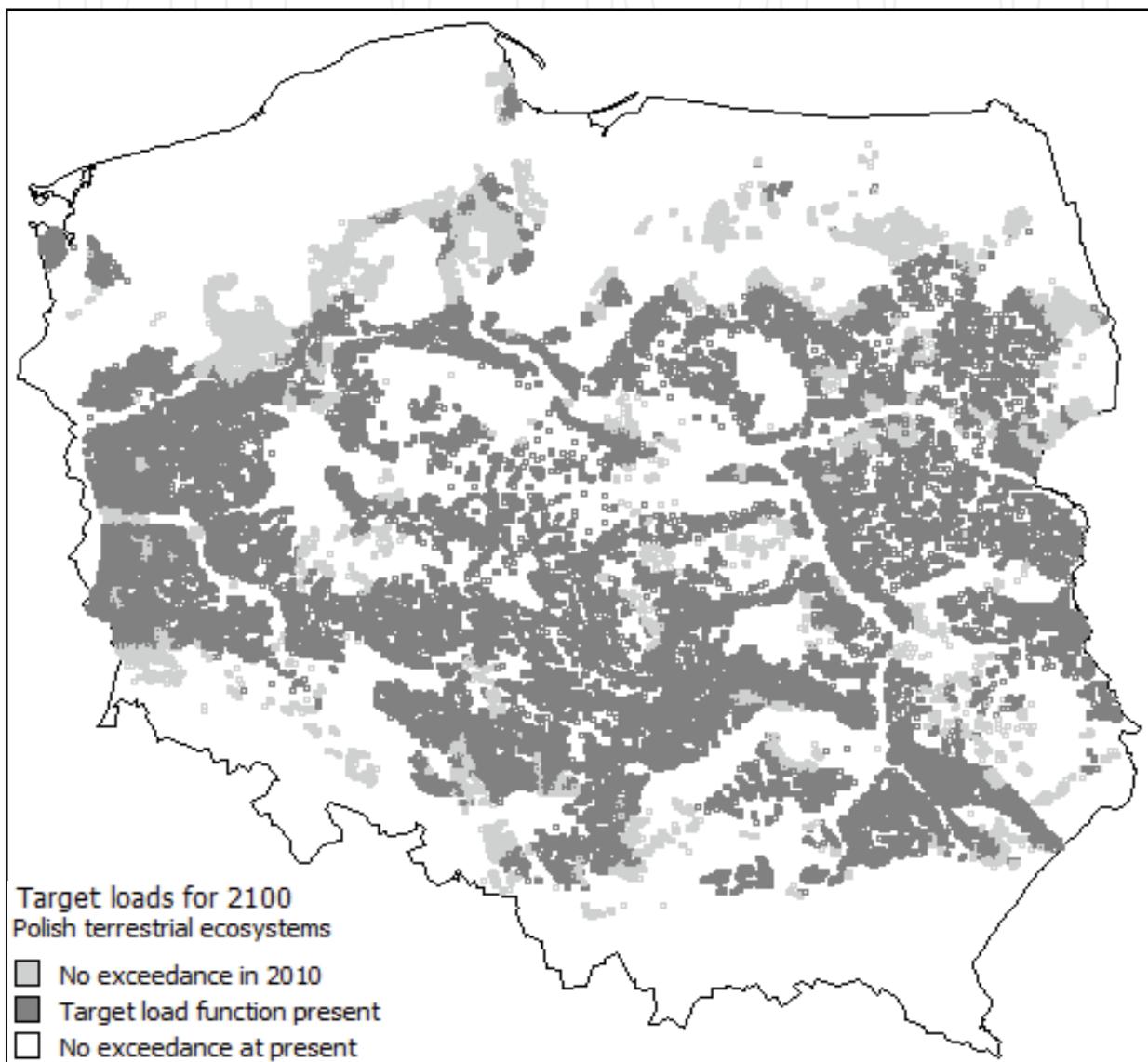


Fig. 4. Spatial distribution of results of target load calculations for 2100

Sites for which no exceedance in the three target years has been identified with the deposition of 2010 mainly occupy the northern and southern parts of the country being the less sensitive to acid deposition. The biggest central part is taken by sites for which target load functions exist for the all considered target years. Sites for which target loads does not exist because the chemical criterion cannot be met are located in the most sensitive areas partly in central but mainly in the west-southern part of Poland.

Calculations of recovery and damage delay times in the period 2010 – 2100 were based on the sulphur and nitrogen deposition scenarios for 2010 resulting from the Gothenburg Protocol. Table 3 presents the number and contribution of sites for which relevant delay times were identified as well as contribution of sites in which recovery or damage took place before 2010 and after 2100.

	2010-2100			2010<		>2100	
RDT	712	1.46%	Recovered	8821	18.11%	14	0.03%
DDT	4928	10.11%	Damaged	15861	32.55%	18385	37.74%

Table 3. Number and percentage of forest sites for which recovery (RDT) and damage (DDT) delay times were identified and contribution of sites in which recovery or damage took place before 2010 or after 2100

Only for 11.6% of the analyzed sites recovery or damage may occur within the considered time span being constantly exposed after 2010 to acid deposition resulting from the Gothenburg Protocol. Recovery from violated soil chemical criterion is possible for 1.46% of sites while damage may happen to about 10% of sites until 2100.

Sites for which damage may take place before 2010 or after 2100 contribute by about 70% to the total number of sites under consideration. Compared to this only ca. 18% of sites may recover before 2010 while after 2100 practically none of them.

7. Conclusions

The dynamic model predictions indicate that although the implementation of the Gothenburg Protocol will substantially reduce the Polish forest ecosystems area under excess acid deposition, still considerable parts of forests remain at potential risk resulting from the violation of the adopted chemical criterion for soils. This indicates that further sulphur and nitrogen emission reduction beyond the Protocol's obligations have to be considered within its intended review.

8. Acknowledgement

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When talking about modelling it is natural to talk about simulation. Simulation is the imitation of the operation of a real-world process or systems over time. The objective is to generate a history of the model and the observation of that history helps us understand how the real-world system works, not necessarily involving the real-world into this process. A system (or process) model takes the form of a set of assumptions concerning its operation. In a model mathematical and logical assumptions are considered, and entities and their relationship are delimited. The objective of a model – and its respective simulation – is to answer a vast number of “what-if” questions. Some questions answered in this book are: What if the power distribution system does not work as expected? What if the produced ships were not able to transport all the demanded containers through the Yangtze River in China? And, what if an installed wind farm does not produce the expected amount of energy? Answering these questions without a dynamic simulation model could be extremely expensive or even impossible in some cases and this book aims to present possible solutions to these problems.

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