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Modelling and Mapping of Critical Loads of Acidification and Eutrophication on Forest Ecosystems in Latvia

Iveta Steinberga, *Faculty of Geography and Earth Science University of Latvia*

***Abstract* – The Very Simple Dynamic model (VSD), which has been developed as the simplest extension of steady-state models, has been used for dynamic modelling of critical loads to forest ecosystems. The model consisting of a set of mass balance equations describes the soil input and output data relationships and fluxes, and soil properties. The mapping of critical loads of acidity and eutrophication effects is performed on 25562 deciduous, coniferous and mixed forest soil receptor polygons (area > 0.01 km^2). The results have been mapped in the geographical units of EMEP grid (50 × 50 km^2).**

***Keywords* – Atmospheric pollution, acidification, critical loads, eutrophication**

I. INTRODUCTION

At the beginning of the 1980s the increasing damaging (e.g. defoliation) of forest trees was observed almost in all parts of Europe. Prevailing researches leading to the development of such scientific hypothesis blame air pollution as the main cause. Increasing emissions of nitrogen species into the atmosphere, long-range transport and deposition processes have been a persistent problem not only in Europe for quite a long time [1-6].

Relevant effects of acidification and eutrophication on ecosystems mostly include the following processes: (1) direct toxicity of nitrogen gases and aerosols, (2) accumulation of nitrogen compounds, which result in the increased nitrogen availability and changes in composition of species; (3) soil mediated acidification effects, and (4) increased susceptibility to secondary stress and disturbance factors such as drought, frost, pathogens and herbivores [7].

As the summarised effect, it could be assumed that the increasing nitrogen inputs may lead to biodiversity loss in terrestrial ecosystems [6, 8].

For the protection of the environment in Europe, specific targets – threshold values - have been defined. Critical loads are such threshold values. By definition, they are quantitative estimates of an exposure to a deposition of one or multi pollutants below which significant harmful effects on specific sensitive elements (e.g. forests, bogs, fishes, monuments) of the environment do not occur according to present knowledge. The 1999 Gothenburg protocol sets emission ceilings for 2010 for acidification and eutrophication processes responsible substances – nitrogen and sulphur, as well as for volatile organic compounds. The aforementioned emission ceilings were negotiated on the basis of assessment of critical loads and levels.

Critical load exceedances have been also used for managing emission reduction targets, which is a part of the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP Convention) and the European Union air pollution abatement policy plans.

According to the land use data, forest ecosystems have been set as an indicator for describing acidification and eutrophication effects in Latvia.

Forests cover 3.1 million hectares or 48 percent of the total area of Latvia. During the last 90 years this percentage has had a stable trend of growth, e.g. the increase was from 24.7 percent in the early 1920s to 48 percent in 2010. The territorial distribution of forests in Latvia is not even. Areas with higher forest coverage are in the central part (Riga region), the southeast area (Cesis and Madona regions), as well as in the western parts (Ventspils, Liepaja, Talsi regions). Latvia's forests are regenerated either naturally or artificially. Natural regeneration of pine, spruce and deciduous species take place according to the site conditions on wet mineral and wet peat soils. Artificial rejuvenation involves the use of genetically improved seed and planting stock; forest seed orchards cover a total area of 10811 ha. The main forest tree species are: pine (914.5 thsd ha or 28.9 % of total forest area); spruce (537.4 thsd ha or 17.0 % of total forest area); birch (883.6 thsd ha or 27.0 % of total forest area); asp (244 thsd ha or 7.7 % of total forest area) [18].

Distribution of forest woodlands are shown in Fig. 1, and regional distribution of coniferous, broadleaved and mixed forests are shown in Fig. 2.

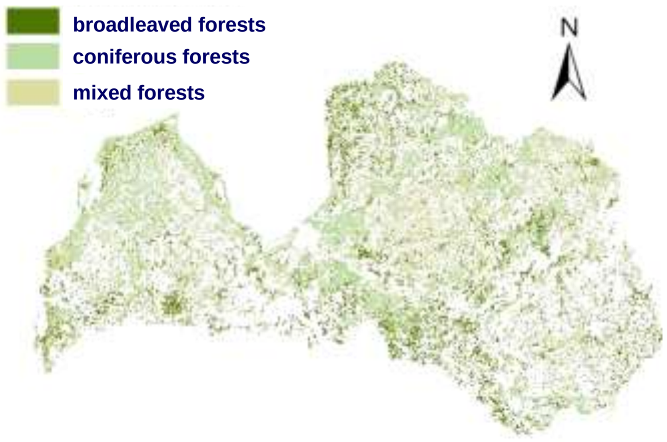

Fig.1. Shematic map of forest woodlands ditribution in Latvia [19].

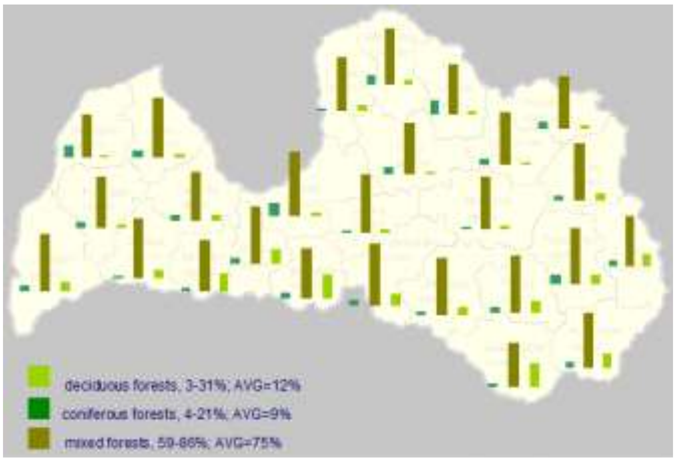

Fig.2. Shematic map of woodland types in Latvia [18].

The main objective of the study is to determine forest areas in Latvia which could be potentially damaged by acidification and eutrophication processes.

II. MATERIALS AND METHODS

The critical load approach has been developed and three different methods could be applied, each of them belonging to different level of sophistication – empirical, mass balance and critical load functional approach. The choice of a methodology depends mostly on the data availability.

The simple mass balance (SMB) method is the most commonly used model in Europe for the calculation of acidity critical loads for woodland ecosystems. This model is based on balancing acidic inputs and outputs in a system, to derive a critical load which ensures that a critical chemical limit (related to effects on the ecosystem) is not exceeded.

For this research, SMB method has been used. A generalization method of the data in EMEP geographical units has been used only for mapping, because of the regional scope, in order to harmonize the data on the European level. Critical loads have been calculated for each forest polygon; only very small polygons (area < 0.01 km^2) were neglected.

A. VSD model description

The VSD model is a very simple dynamic model that simulates soil solution chemistry and soil nitrogen pools for natural or semi-natural ecosystems [9]. The overall VSD model is the simplest extension of the simple mass balance model that computes the maximum inputs of sulphur and nitrogen to an ecosystem that will not lead to harmful effects [10, 11].

The equations have been derived from a charge balance of ions in leaching fluxes from the soil compartment, combined with mass balance equations for the inputs, sinks, sources and outputs of sulphur and nitrogen [9, 17].

The aforementioned processes are described as a simple rate-limited reactions, first order processes and equilibrium reactions – nutrient uptake and weathering, denitrification, cation exchange.

VSD is a single-layer model, i.e., the soil is treated as a single homogeneous compartment. Furthermore, it is assumed that the soil depth is (at least) the depth of the rooting zone, which allows us to neglect the nutrient cycle and deal with net growth uptake only. Additional simplifying assumptions include: (a) all evapotranspiration occurs on the top of the soil profile, (b) percolation is constant through the soil profile and occurs only vertically, (c) physico-chemical constants are assumed uniform throughout the whole soil profile and (d) internal fluxes (such as the weathering rates, nitrogen immobilization etc.) are independent of the soil chemical conditions (such as pH).

As the SMB model describes steady state conditions, it requires long-term averages for input fluxes. Short-term variations – e.g., episodic, seasonal, inter-annual, due to harvest and as a result of short-term natural perturbations – are not considered, but are assumed to be included in the calculation of the long-term mean. In this context, the 'long-term' is defined as about 100 years, i.e. at least one rotation period for forests. Ecosystem interactions and processes like competition, pests, herbivore influences etc. are not considered in the SMB model. Although the SMB model is formulated for undisturbed (semi-natural) ecosystems, the effects of extensive management, such as grazing and the burning of moor, could be included.

The charge balance links all ions considered in the VSD model:

$$\begin{aligned} H^{+} + Al^{3+} + BC^{2+} + Na^{+} &= SO_4^{2-} + NO_3^{-} + \\ &+ Cl^{-} + HCO_3^{-} + RCOO \end{aligned} \tag{1}$$

where sum of *Ca*, *Mg* and *K* is treated as a single ion (BC = Ca+Mg+K), *Na* means sodium, SO_4 sulphate, NO_3 nitrate, *Cl* chloride and *RCOO* the sum of organic anions. All concentrations are expressed in equivalents. The leaching of ammonium (NH_4) was neglected because of preferential uptake and complete nitrification within the root zone [4].

Some equilibrium reactions were included in VSD model – dissolution of Al hydroxides, cation exchange and dissociation of bicarbonate and organic acids. Dissolution of Al hydroxides is calculated according to the following equation (known as Gibbsite equilibrium):

$$Al = K_{gibb} \cdot H^3 \tag{2}$$

where K_{gibb} is the gibbsite equilibrium constant. Concentration of bicarbonates is a function of the pH and dissociation of them is calculated via:

$$HCO_3 = \frac{K_1 \cdot K_H \cdot p_{CO2}}{H} \tag{3}$$

where K_1 is the first dissociation constant, K_H is Henry's constant and p_{CO2} is the partial pressure of CO_2 in the soil solution (in atm). Concerning dissociation of organic anions, all anions are assumed as monovalent and that only monovalent organic anions are produced by the dissociation of dissolved organic carbon:

$$RCOO = \frac{m \cdot DOC \cdot K_1}{K_1 + H} \tag{4}$$

where DOC is the concentration of dissolved organic carbon ($molC/m^3$), m is the concentration of functional groups (mol/molC) and K_1 the dissociation constant. Both parameters DOC and m are site-specific [5].

According to the fact that the value of K_1 does not always model the dissociation of organic acids properly, assessment of dissociation constant was done by Oliver equation [6]:

$$pK_1 = a + b \cdot pH - c \cdot (pH)^2 \tag{5}$$

where a=0.96, b=0.90 and c=0.039.

The exchange between the solid phase and soil solution is described for *Al, H* and *BC (Ca, Mg, and K).* For each of these cations and anions (SO_4, NO_3, *and Cl*), mass balance equations in VSD are described as:

$$\frac{dX_{tot}}{dt} = X_{in} - Q \cdot X \tag{6}$$

where X_{tot} is the total amount of ion X in the soil (in eq/m^2), X_{in} describes the sum of all inputs from deposition and uptake-release fluxes (eq/m^2·yr), Q is the runoff (in m/yr).

Concerning SO_4, NO_3, *Na* and *Cl* interactions with the soil VSD assumes that the total amount of them equals the amount in the soil water:

$$Y_{tot} = \theta \cdot z \cdot Y \tag{7}$$

where Y is SO_4, NO_3, *Na*, *Cl*, θ the water content in the soil (in m^3/m^3), and z the thickness of the soil compartment (in m).

Input fluxes in system for sulphate and chloride could be described as depositions alone:

$$SO_{4.in} = SO_{2.dep} \tag{8}$$

$$Cl_{in} = Cl_{dep} \tag{9}$$

where *dep* describes total deposition. The fluxes for base cations are calculated by describing deposition and weathering:

$$\begin{aligned} Y_{in.Ca,Mg,K} = Y_{dep.Ca,Mg,K} + z \cdot Y_{we.Ca,Mg,K} - \\ - Y_{u.Ca,Mg,K} \end{aligned} \tag{10}$$

where $Y_{in.Ca,\ Mg,\ K}$ is input fluxes of base cations in system, $Y_{dep.Ca,\ Mg,\ K}$ deposition of base cations, $Y_{we.Ca,\ Mg,\ K}$ the weathering rates of base cations, $Y_{u.Ca,\ Mg,\ K}$ - net growth uptake (all in eq/(m^3·yr)). The actual weathering rates for non-calcareous soils of depth z (in m) were calculated via:

$$\begin{aligned} BC_{we} = z \cdot 500 \cdot (WR_c - 0{,}5) \cdot \\ \cdot \exp\left(\frac{A}{281} - \frac{A}{273+T}\right) \end{aligned} \tag{11}$$

where *WRc* is the weathering rate class depending on the parent material and texture class, T is the average annual soil temperature and A=3600 K [9].

The statement for critical loads of nutrient N calculation states to take account of all inputs and outputs of nitrogen, taking account of such processes as denitrification and leaching:

$$N_{dep} = N_i + N_u + N_{de} + N_{le} \tag{12}$$

where N_{dep} is total N deposition, N_i the long-term net immobilization of N in the soil organic matter, N_u the net removal of N in harvested vegetation and animals, N_{de} the flux of N to the atmosphere due to denitrification, N_{le} the leaching of N below the root zone.

In case by defining an acceptable limit to the leaching of N, $N_{le(acc)}$, equation (11) could be used for critical load of nutrient nitrogen $CL_{nut}(N)$ calculation:

$$CL_{nut}(N) = N_i + N_u + N_{de} + N_{le,acc} \tag{13}$$

In the simplest case, denitrification is linearly related to the net input of N [8, 12-15]:

$$N_{de} = f_{de} \cdot (N_{dep} \cdot N_i - N_u) \tag{14}$$

if the $N_{dep} > N_i + N_u$, else $N_{de} = 0$, where f_{de} $(0<f_{de}<1)$ is the denitrification fraction.

Nitrogen immobilization refers to the long-term net immobilization and accumulation in the root zone, and this process should not lead to significant changes in the prevailing C/N ratio.

Nitrogen uptake flux N_u equals the long-term average removal of N from the ecosystem, and it depends on the harvesting practice. Basically, nitrogen uptake is calculated as a function of removed nitrogen (N$_{rem}$) and intervals between harvests (T):

$$N_u = \frac{N_{rem}}{T} \tag{15}$$

The amount of nitrogen in the harvested biomass (stems and branches) is calculated as follows:

$$N_{rem} = k_{gr} \cdot \rho_{st} \cdot (ctN_{st} + f_{br,st} \cdot ctN_{br})) \tag{16}$$

where k_{gr} is the average annual growth rate, ρ_{st} is the density of stem wood, ctN is the nitrogen content in stems and branches and $f_{br,st}$ is the branch-to-stem ratio.

The maximum critical load for acidity (sulphur) has been determined as follows:

$$CL_{\max}(S) = BC_{dep} - Cl_{dep} + BC_w - BC_u - ANC_{le,crit} \tag{17}$$

where $ANC_{le,crit}$ is the leaching of acid neutralizing capacity. If bicarbonates and organic anions do not contribute significantly at low pH, ANC is determined as follows:

$$ANC_{le} = -Q \cdot (H + Al) \tag{18}$$

where *Q* is the precipitation surplus. The relationship between *[H]* and *[Al]* is described by gibbsite equilibrium [16].

$ANC_{le,crit}$ was determined by using critical base cation to proton ratio:

$$ANC_{le,crit} = 0{,}5 \cdot \frac{BC_{dep} + BC_w - BC_u}{(BC/H)_{crit}} \tag{19}$$

where *(Bc/H)crit* is critical molar base cation to proton ratio. Values used for *(Bc/H)crit* are expressed as multiples of *(Bc/Al)crit*, and these multiples ranging from 0.3 for deciduous forests and ground vegetation to 1 for spruce and pine [7]. The most commonly used value is *(Bc/Al)crit=1* (for the coniferous forests), for other types the critical *Al* leaching is calculated from the leaching of *Bc:*

$$Al_{le,crit} = 1{,}5 \cdot \frac{Bc_{le}}{(Bc/Al)_{crit}} \tag{20}$$

Finally, the maximum critical load of nitrogen is calculated as:

$$CL_{\max}(N) = CL_{\min}(N) + \frac{CL_{\max}(S)}{1 - f_{de}} \tag{21}$$

B. Model input data

Input to VSD model consists of a set of 24 parameters, listed in Table 1.

Calibration was done only for model process parameters, such as equilibrium constants, denitrification and immobilization fractions. The above mentioned parameters are uncertain, because estimates are very often based on limited (very small) data sets, and the most important parameters (pH, Al, Bc, base saturation) are very sensitive to these processes parameters. Moreover, these parameters cannot be measured directly.

The thickness of the root zone was set to 50 cm, a part of the soil data were obtained from measurements, and another part was theoretically calculated by using transfer functions. Hydrological and meteorological data, such as temperature, precipitation, evapotranspiration, were prepared by the Latvian Environment, Geology and Meteorology Center.

Deposition data were obtained from integrated monitoring sites. Integrated monitoring in Latvia has been started in 1985 at Rucava station. Description of integrated monitoring sites is given in Table 2.

Forest map of Latvia from Corine Land Cover was used to obtain information about forest types and density.

Data on harvesting practices were obtained from the State Forest Service annual reports.

The modelling and mapping of critical loads for acidification and eutrophication is based on 25562 deciduous, coniferous and mixed forest soil receptor polygons (area > 0.01 km^2). The results have been aggregated for the geographical units of the EMEP (50 · 50 km^2) grid.

TABLE I

VSD MODEL INPUT PARAMETERS

Parameter	**Description**	**Calibration**	**Data source**	**Parameter**	**Description**	**Calibration**	**Data source**
thick	Thickness of the root zone	-	Soil data	f_de	Denitrification fraction	+	Assumption
bulkdens	Bulk density	-	Soil data	percol	Precipitation surplus	-	Calculations
theta	Soil water content	-	Calculations	BCwe	Base cations weathering	+	Calculations
pCO2fac	Partial pressure of CO_2 in soil	-	Assumption	ctNst	N content in stems for N uptake	-	Calculations
CEC	Cation exchange capacity	-	Calculations	ctCast	Ca content in stems for Ca uptake	-	Calculations
lgKAlox	Equilibrium constant H-Al	+	Assumption	Ca_dep	Ca deposition	-	Measurements
lgAlBc	Exchange constant Al-BC	+	Assumption	SO_2_dep	SO_2 deposition	-	Measurements
lgKHBc	Exchange constant H-BC	+	Assumption	NOx_dep	NOx deposition	-	Measurements
Nim_acc	N immobilization	+	Calculations	Mg_dep	Mg deposition	-	Measurements
Cpool_0	Initial C poll	-	Calculations	K_dep	K deposition	-	Measurements
CNrat_0	Initial CN ratio	-	Calculations	Na_dep	Na deposition	-	Measurements
cRCOO	Organic anion concentration	-	Assumption	Cl_dep	Cl deposition	-	Measurements

TABLE 2

INTEGRATED MONITORING SITES DESCRIPTION

Station	**Rucava**	**Zoseni**
Established	1985	1994
Coordinates	56º09`41`` 21º10`23``	57º08`06`` 25º54`20``
Elevation, m	18	183
Annual average precipitation, mm	772	727
Annual average temperature, ºC	+6.3	+4.5
Predominant wind direction	SW, SE	SW
Annual average velocity of wind, m/s	4.2	2.8
Duration of stable snow cover, days	72	126
Sunshine period, h/yr	1874	1622
Duration of vegetation period, days	198	186

III. RESULTS

Critical loads have been calculated using data derived from GIS maps. Critical loads of nitrogen and sulphur have been compared to the actual atmospheric deposition and exceedances evaluated. A deterministic critical load assessment is based on the principle that the deposition of sulphur, oxidized and reduced nitrogen deposition should not exceed the critical load. But it should be recognized that there is uncertainty in the deposition (and the critical load).

The calculated values for critical loads of sulphur and nitrogen give a good initial indication of the spatial variability of the ecosystem sensitivity to acidification in Latvia.

The low values of base cations deposition, due to precipitation together with other parameters, lead to high values of the critical loads for the acidifying pollutants. The calculated values for $CL_{max}(S)$ vary between 734 and 8782 eq/(ha·yr) for deciduous, coniferous and mixed forests. Critical load values for eutrophication ($CL_{max}(N)$) are much higher, ranging from 2419 to 25497 eq/(ha·yr), and, for nutrient nitrogen ($CL_{nut}(N)$), between 107 and 680 eq/(ha·yr).

The dominating $CL_{max}(S)$ values of 63 % are in the range from 4301 to 4800 (eq/(ha·yr)), but only 0.4 % of them are very high (ranges between 5301 to 5700 (eq/(ha·yr))), see Fig. 3.

More than 50 % of $CL_{max}(N)$ values vary between 12901 and 13900 eq/(ha·yr), see Fig. 4, which means that more than 50 % of forest ecosystems have a high buffer capacity against eutrophication effects.

About 44 % of $CL_{nut}(N)$ values vary between 201 and 300 eq/(ha·yr), see Fig. 5.

The highest $CL_{max}(S)$ and $CL_{max}(N)$ values detected in the central part of Latvia (EMEP grid cell 66/71 close to the capital city - Riga) and in the western part of Latvia (EMEP grid cell 64/68 – Ventspils region). Such values could be explained by high base cation deposition values and high depositions of sulphur and nitrogen as well.

Significant differences in critical loads have been detected in different types of woodlands. The highest $CL_{max}(S)$ values have been found in broadleaved forests (800 - 8782 (eq/(ha·yr)) in the central and western parts of Latvia (EMEP cell grids 66/71; 64/68).

Overall critical loads for acidification in Latvia have not been exceeded. A much higher potential for the ecosystem degradation and acidification exists in the eastern part of Latvia.

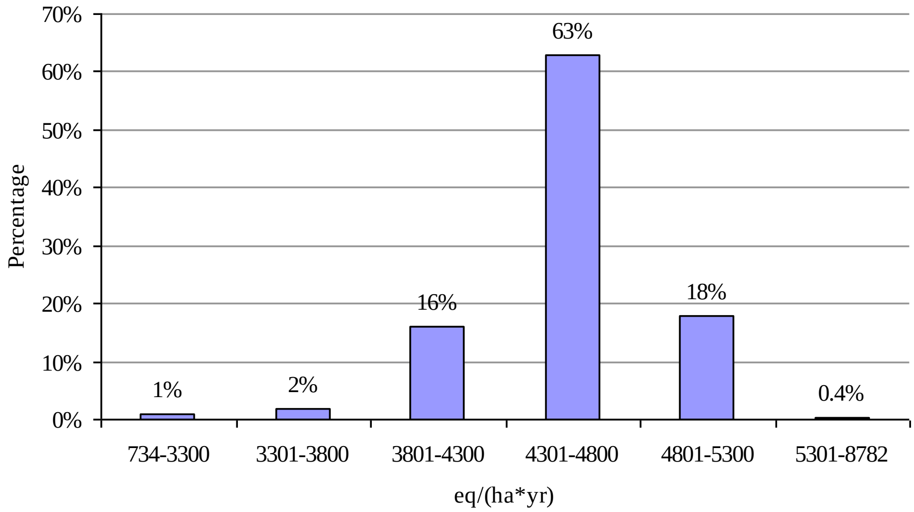

Fig.3. Distribution of $CL_{max}(S)$ critical loads in forest polygons in Latvia.

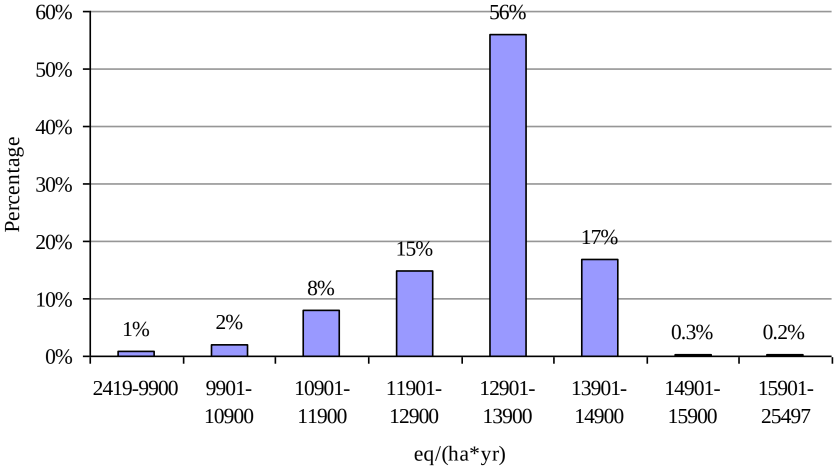

Fig.4. Distribution of $CL_{max}(N)$ critical loads in forest polygons in Latvia.

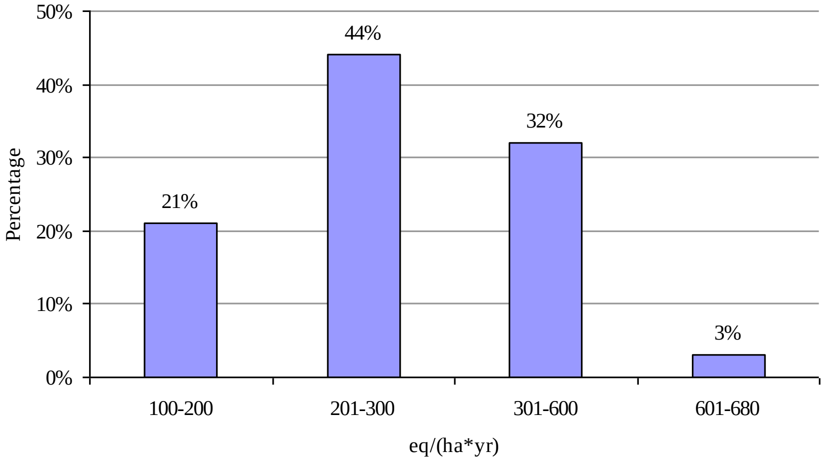

Fig.5. Distribution of $CL_{nut}(N)$ critical loads in forest polygons in Latvia.

IV. CONCLUSIONS

Since the negative influence of nitrogen in all ecosystems becomes worse (loss of biodiversity), it is valuable to calculate critical loads also for the nitrogen sensitive non-forest ecosystem, such as raised bogs in Latvia, also to protect and monitor this very sensitive ecosystem in the future.

Calculation of critical loads of heavy metals (mercury, cadmium, lead) also has high priority, especially with regard to mercury. The accumulation of mercury, especially in the ecosystems of Nordic countries, is becoming a serious problem. It can be expected that the critical loads of mercury in Latvia are exceeding, due to the hydro biological and geological circumstances (wet lands, high organic carbon content in sediments).

According to the data, calculations and simulations, critical loads for acidification in Latvia are high. The Critical Loads for acidification are not exceeded in any Latvian area. Therefore, acidification does not seem to be a problem in the future.

The situation for eutrophication is similar, and there is no evidence for exceedances as yet.

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Iveta Šteinberga, Dr. Geogr., Assistant Professor, University of Latvia, Faculty of Geography and Earth Sciences. Assistant Professor Iveta Šteinberga has been part of academic staff of Faculty since 2005 and Head of Modelling laboratory of Environmental processes. The main research areas are modelling of environmental pollution (ordinary pollutants, noise) processes in atmosphere and ecosystems, assessment of particulate matter pollution. She has Chemical Engeneer Diploma (1999) and Doctoral degree diploma in Environmental Science (2007). PhD thesis “Modelling of quasistatical air pollution levels” was defended in University of Latvia in Faculty of Geography and Earth Sciences.
Address: Alberta street 10, LV1010, Riga, Latvia
Phone: +37126467809
E-mail: iveta.steinberga@lu.lv

Iveta Šteinberga. Kritisko slodžu aprēķini un kartēšana uz mežu apgabaliem Latvijā

Kritiskā slodze (CL) ir viena vai vairāku piesārņojošo vielu ietekmes novērtējums, kas var radīt kaitējumu noteiktiem vides jutīgajiem elementiem, ņemot vērā esošās zināšanas. To aprēķināšanā tiek ņemti vērā ne tikai mērķekosistēmu raksturojoši parametri, bet arī tās eksistenci un labsajūtu nodrošinošo parametru ilgtermiņa izmaiņas.

CL modelēšana veikta mežu apgabaliem Latvijā izmantojot VSD (*Very Simple Dynamic model*) masas bilances modeli. Mežu apgabali izvēlēti kā Latvijas teritoriju raksturojošs indikators paskābināšanās un eitrofikācijas procesu novērtējumam.

Kritisko slodžu aprēķināšanai nepieciešamie dati nosacīti iedalāmi 5 pamatblokos: (1) augsnes kvalitāti raksturojoši dati; (2) mežu stāvokli un apsaimniekošanas praksi raksturojoši dati; (3) meteoroloģiskie rādītāji; (4) nokrišņu ķīmisko sastāvu raksturojoši rādītāji un (5) EMEP režģa modelēšanas slānis. Modelēšanas ceļā tika iegūti rezultāti 25562 mežu poligoniem: (1) maksimālā slāpekļa kritiskā slodze svārstījās robežās no 2419-25497 eq/(ha×a); (2) maksimālā sēra kritiskā slodze svārstījās robežās no 734-8782 eq/(ha×a). Modeļa kalibrēšana veikta izmantojot augsnes ķīmiskā sastāva rādītājus, papildus tika veikta starprobežu rezultātu salīdzināšana.

Galvenie secinājumi: (1) ņemot vērā slāpekļa savienojumu nelabvēlīgo ietekmi uz dažādām ekosistēmām, būtu nepieciešams veikt līdzīga tipa modelēšanu cita veida jutīgām ekosistēmām, piemēram, purviem, (2) smago metālu kritisko slodžu modelēšana uzskatāma par nākotnes prioritāti, jo īpaši dzīvsudraba; ņemot vērā Ziemeļvalstu pieredzi un vietējos apstākļus, potenciāli sagaidāmi dzīvsudraba kritisko slodžu pārsniegumi, (3) saskaņā ar veiktajiem aprēķiniem, paskābināšanās risks un eitrofikācijas risks pašlaik mežu apgabalos Latvijā ir salīdzinoši zems.

Ивета Штейнберга. Расчеты критичных нагрузок и их картирование на лесных массивах в Латвии

Критичная нагрузка (CL) – оценка воздействия одной или несколько загрязняющих веществ, которые могут вредить определенным чувствительным элементам окружающей среды, используя имеющиеся знания. При их расчетах учитываются не только параметры, характеризующие целевую экосистему, но и долгосрочные изменения параметров, обеспечивающих ее экзистенцию и благополучие.

Моделирование CL лесных массивов Латвии проводилось с использованием VSD (Very Simple Dynamic model) модель. Лесные массивы выбраны как индикатор, характеризующий территорию Латвии при оценке процессов подкисления и эвтрофикации.

Необходимые данные для расчета критичных нагрузок условно можно разделить на 5 основных блоков: (1) данные, характеризующие качество почвы; (2) данные, характеризующие состояние лесов и лесное хозяйство; (3) метеорологические показатели; (4) показатели, характеризующие химический состав осадков и (5) слой моделирования клетки EMEP. При моделировании получены результаты для 25562 лесных полигонов: (1) максимальная критичная нагрузка азота колебалась от 2419 до 25497 экв/(га×год); (2) максимальная критичная нагрузка серы колебалась от 734 до 8782 экв/(га×год). Калибровка модели произведена используя показатели химического состава почвы, дополнительно производилась сравнение трансграничных результатов.

Главные выводы: (1) учитывая неблагоприятное влияние соединении азота на разные экосистемы, желательно произвести подобного рода моделирование и для других чувствительных экосистем, например, болот; (2) моделирование критичных нагрузок тяжелых металлов можно считать приоритетом будущего, особенно ртути; учитывая опыт Скандинавии и местные обстоятельства, потенциально ожидается превышение критичных нагрузок ртути; (3) согласно произведенным расчетам, риски подкисления и эвтрофикации в настоящее время для лесных массивов Латвии относительно низкие.