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Modelling the Impact of Acid Deposition on Forest Soils in North Bohemian Mountains with Two Dynamic Models: the Very Simple Dynamic Model (VSD) and the Model of Acidification of Groundwater in Catchments (MAGIC)

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Abstract

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Enormous acid deposition that culminated in the 1970s contributed largely to accelerate the process of acidification of soils in northern Bohemia. As a consequence a wide forest decline occurred shortly afterwards. In this paper we present a long-term soil acidification modelling with two dynamic models (Model of Acidification of Groundwater in Catchments and Very Simple Dynamic Model) to describe history, make successive prediction, and assess possibility of recovery of the ecosystem. Focused on eight soil acidification indicators we found a strong rise of the soil acidification status in 1970s, when emission load culminated, and a large decrease after the year 2000 (after flue gas desulfurization). We further revealed slight differences, but general similarity, for both dynamic models. The results indicate that the impact of historic massive pollution will not probably be eliminated in the future by the year 2100.

Keywords: air pollution; Black Triangle; historical deposition; long-term modelling; mass balance; soil solution; soil chemistry

North Bohemia belongs to the most heavily industrialized and polluted regions in Europe. It is part of the so-called “Black Triangle” (area where Poland, Germany, and the Czech Republic meet) shaped by a mountain range (the Krušné hory Mts. stretching from southwest to northeast which rise steeply above the Most Basin on their Czech side and descent gradually on their German side, the Krkonoše Mts. oriented from northwest to southeast which are steeper on the Polish than on the Czech side, and the Lužické and the Jizerské hory Mts. which are located between the Krušné hory and the Krkonoše Mts.) stretching along the borders between the states. This mountain belt forms a wind barrier causing a microclimate situation over the Most Basin with unfavourable air conditions for emissions dispersion. In the 1970s and 1980s coal-fired power plants and district heating plants concentrated in this area due to nearby lignite mines were producing probably the highest quantity of SO_2 and NO_2 emissions in the world (Hruška & Ciencala 2003). Obviously, the rising emissions together with poor air pollution dispersion have strongly affected all parts of the ecosystem, including air, water, soil, and living organisms, as well as human health. These adverse effects have also led to a large-scale dieback of forests in North Bohemian mountain areas (Akselsson *et al.* 2004). Satellite based estimations of coniferous forest cover change in the Krušné hory Mts. published by Ardö *et al.* (1997) indicated that

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50% of coniferous forest disappeared between 1972 and 1989. The enormous acid deposition also largely contributed to accelerated acidification process in the soils. As has been documented on the example of the Jizerské hory Mts., soil pH decreasing, lowering of base saturation, Al mobilization, depletion of base cations, poor quality humus material, decelerating of decomposition process, accumulation of raw organic material, and many other belong to the main symptoms of this degradation process (e.g. Mládková *et al.* 2004; Borůvka *et al.* 2009). Moreover, rainfall redistribution (Nikodem *et al.* 2013) together with prevailing spruce monoculture (Tejnecký *et al.* 2013) have also largely contributed to soil acidification in this area. The consequences of the massive historical pollution have been clearly visible to the present day.

However, over the last two decades, after political changes in Central Europe, and consequently thanks to flue gas desulphurization, reduction of sulphur and nitrogen emissions led to a large decrease in deposition of acidifying compounds. To estimate the response of ecosystem to acid deposition and the possibility of recovery, so-called critical loads for sulphur and nitrogen are used as indicators of the sensitivity of natural ecosystems to acidification and eutrophication. These indicators have been introduced under the Convention of Long-Range Transboundary Air Pollution (LRTAP) within the United Nations Economic Commission for Europe (UNECE). Critical loads represent the maximum deposition on ecosystem that, on an infinite time-scale and according to current knowledge, will not lead to significant harmful effects. Critical loads are usually computed with simple steady state mass balance models (Sverdrup & De Vries 1994; UBA 2004). In regions where the critical load was exceeded in the past and where the present deposition is smaller than the critical load, ecosystems are expected to recover. According to Akselsson *et al.* (2004), in 1992 the critical load of acidity was exceeded on 75% of the forest soils in the northern parts of the Czech Republic (study area of 4000 km^2). Critical loads, however, do not provide information about the time needed for the ecosystem recovery. Therefore, dynamic acidification models such as SMART (De Vries *et al.* 1989), MAGIC (Cosby *et al.* 1985a, 2001), SAFE (Warfvinge *et al.* 1993) or VSD (Posch *et al.* 2003; Posch & Reinds 2009) have been developed to evaluate the possibility of ecosystem to recover under different future deposition scenarios.

Dynamic acidification models have been frequently applied in North-West Europe and North America (see e.g. Lepistö *et al.* 1988; Hinderer & Einsele 1997; Reynolds 1997; Ahonen *et al.* 1998; Evans *et al.* 1998; Forsius *et al.* 1998; Cosby *et al.* 2001; Reinds *et al.* 2009) but rarely in Central and East Europe (Krám & Bishop 2001; Hruška & Krám 2003; Malek *et al.* 2005).

This paper presents a long-term soil acidification modelling in the Jizerské hory Mts., a top affected region in Central Europe. The objectives of the paper are (1) to describe historical changes of soil acidification status and to forecast the possibility of the ecosystem recovery; (2) to compare two dynamic acidification models, the Model of Acidification of Groundwater in Catchments (MAGIC) and the Very Simple Dynamic model (VSD).

MATERIAL AND METHODS

MAGIC model. The Model of Acidification of Groundwater in Catchments (MAGIC), introduced by Cosby *et al.* (1985a), is a process-oriented dynamic model that attempts to describe the long-term impact of atmospheric deposition, net uptake by vegetation, weathering, and cation exchange on the chemical composition of soil and outflow water. Solution chemistry is governed by charge and mass balance principles, using lumped process description. The model is designed for catchment scale. The model has already been described in detail (e.g. Cosby *et al.* 1985a, b, 1986, 1989; Hornberger *et al.* 1986; Jenkins & Cosby 1989; Ferrier *et al.* 1995), therefore just briefly: the model calculates separate Gaines-Thomas equilibrium for the exchange of Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and Na^+ cations. Sulphate adsorption is described by Langmuir isotherm. The model calculates mass budgets and chemical equilibria of all major ions including organic acids. MAGIC enables accommodation of a large number of input parameters concerning soil, surface water, nitrogen dynamics, deposition, climate, etc. One may specify which compartments will be included into calculations. For the soil compartment setting it is possible to choose between one soil layer, two soil horizons or two soil types (only one option is possible). Next, it can be specified if a wetland occurs in the catchment or not. The lake is always placed. The main model functions are: hindcast simulation, forecast simulation, episodic response, and fish status. Also, the single critical load for catchment and multiple

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critical load function are built-in. Model outputs can be displayed as tables of concentrations and fluxes, plots of long-term variation, and plots of seasonal variation. In this paper we used MAGIC software in Version 7.77 (Cosby 2001).

VSD model. The Very Simple Dynamic model (VSD) (Posch *et al.* 2003; Posch & Reinds 2009) is a simple model that simulates soil solution chemistry and soil nitrogen pools for natural or semi-natural ecosystems. The model represents the simplest extension of the simple mass balance (SMB) critical load model. The SMB model (Posch & De Vries 1999; De Vries & Posch 2003) is designed to compute maximum input of S and N into ecosystem (i.e. critical load) that will not lead to harmful effects, using simple mass balance equations. VSD also consists of a set of mass balance equations, describing the soil input–output relationship of ions, and a set of equations describing the rate-limited and equilibrium soil processes. Soil solution chemistry in VSD depends solely on the net element input from atmosphere (deposition minus net uptake minus net immobilization) and geochemical interactions in soil (CO_2 equilibrium, base cation weathering, and cation exchange). Soil interactions are described by simple rate-limited reactions (e.g. nutrient uptake and weathering), first order processes (denitrification), and by equilibrium reactions (e.g. cation exchange). VSD models the exchange of Al, H, and Ca + Mg + K with Gaines-Thomas or Gapon equation. Solute transport is described by assuming complete mixing of the element input within one homogeneous soil compartment with a constant density and a fixed depth. VSD is a single layer soil model that neglects vertical heterogeneity. It predicts the concentration of the soil water leaving this layer (mostly the root zone). Validation of the model should thus be based on measurements from soil solution just below the root zone. Annual water flux percolating from this layer is taken equal to annual precipitation excess. The model resembles SMART model (De Vries *et al.* 1989) but leaves out some of the processes modelled by SMART such as aluminium mass balance and soil solution chemistry in carbonate-rich soils. The time-step for simulations is one year. The model is mainly used for soil solution chemistry simulation. In addition the model also includes functions for Target loads, Critical loads, and Delay time computation. Input parameters are considered to be constant, while the observations might be varying in time. Output data can be exported as text files and graphs in EPS format. The VSD Studio application (a graphical user interface to the VSD model) in Version 3.1.2 was used in this paper.

Description of the study area and samples collection. The Jizerské hory Mts. are situated in the north of the Czech Republic (Figure 1). Total area is about 368 km^2 and the altitude ranges from 600 to 1124 m a.s.l. The mountain climate here is characterized by annual precipitation of approximately 1700 mm per year and the average annual air temperature of 6°C. The majority of the area is covered by low vegetation (former dead forest zone) with minor occurrence of beech (i.e. native species for this area) and artificial spruce monoculture. According to World Reference Base for Soil Resources (WRB) (FAO 2007), the main soil units were identified as Entic and Haplic Podzols accompanied by Cambisols (Alumic).

To survey the area, totally 98 sampling sites were visited within the sampling campaign in 2002 (Mládková *et al.* 2004) during which only forest soils were sampled. The data collected are used as input for long-term modelling purposes. The soil parameters to be used for model calibration are computed as weighted average for all soil horizons belonging to the same soil profile and consequently these were averaged in order to achieve a single value for particular soil property for the area as a whole (i.e. the averaging was done firstly for all soil horizons from the same site and secondly for all sampling sites). The summary of all available input soil data used for model calibration is offered in Table 1. This comprises soil thickness, bulk density, soil moisture, CO_2 presure in soil solution, cation exchange capacity, average soil temperature, percolation, C:N ratio, amount of carbon in topsoil, pH of soil solution, base saturation, and molar Al:Bc ratio.

Figure 1. Location of the study area

Table 1. Calibration soil data for the reference year 2002

Soil thickness (m)	0.70
Bulk density (g/cm^3)	0.90
Soil moisture (θ, m^3/m^3)	0.30
CO_2 pressure in soil solution (atm)	15
Cation exchange capacity (meq/kg)	75
Average soil temperature (°C)	4.0
Percolation (m/a)	1.30
C:N ratio in topsoil (g/g)	19.64
Amount of C in topsoil (g/m^2)	6000
pH of soil solution (supplied with pH of soil leachate)	3.95
Base saturation (%)	10
Molar [Al]:[Bc] ratio (mol/mol)	2.0

The second group of data used for validation purposes comes exclusively from successive soil survey in 2008 (Tejnecký *et al.* 2010) when study data of just one sampling site under spruce vegetation cover were adopted to evaluate simulations as made by both, VSD and MAGIC, dynamic models. Soil samples were collected from all sufficient soil horizons, i.e. surface fermentation (F), humified organic (H), surface organomineral (Ah), and subsurface (Bhs) horizon. Selected soil solution characteristics for comparison to model simulations were soil pH and content of H^+, Al^{3+}, and SO_4^{2-}.

Reconstruction of historical deposition and future deposition scenario. Historical acid deposition was reconstructed using data in part from the Czech Hydrometeorological Institute (CHMI), in part from the study of Hruška and Ciencala (2003), and in part from the study of Kopáček and Veselý (2005). As illustrated in Figure 2, there had been an important increase of SO_2 deposition in the early 20th century continuing up to the end of the World War II, when the deposition decreased quickly. After the war, growing industry caused a very strong increase of pollutants emission into atmosphere and consequently acid deposition also increased strongly. Emission of acid pollutants culminated in the 1970s and 1980s, when SO_2 deposition was almost 1.4 eq/m^2/year and NO_X plus NH_4 was approximately 0.4 eq/m^2/year. This massive emission period coincides with the wide forest damage in mountainous areas of North Bohemia. The changes of NO_X and NH_4 deposition follow sulphur dioxide deposition. Over last two decades, due to several factors such as flue gas desulfurization (which was completed in 1999), reduction of heavy industry and automobile exhaust pollutants, the decrease of sulphur and nitrogen emission has led to a large fall in the deposition of acidifying compounds. The current deposition load corresponds approximately to that which occurred in preindustrial age. In addition, as a result of a high concentration of heating plants and predominant western air flow, the deposition load in the Jizerské hory Mts. region in the 1970s and 1980s was approximately 10 to 15 times higher than the average for the Czech Republic.

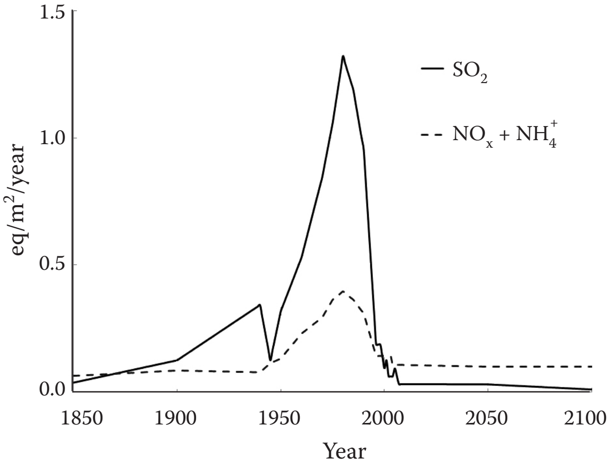

Figure 2. Reconstruction of the SO_2 and NO_X plus HN_4 historical deposition and the future deposition scenario

To investigate if the present emission level will lead to recovery of the ecosystem, we designed a future deposition scenario where the acid deposition load does not much differ from the current state. Also because there is no evidence whether a significant emission reduction or emission rise could be expected during a few next decades. That is why rather a stagnation in nitrogen and a slight decrease in sulphur deposition after the year 2050 was designed. The modelling temporal period is 1850–2100.

RESULTS AND DISCUSSION

History and successive prediction of soil attributes. In long-term modelling of the soil acidification status of the Jizerské hory Mts. forest soils we focused on eight soil characteristics – soil pH, base saturation (BS), C:N ratio, H^+, Al^{3+}, SO_4^{2-}, NO_3^-, and HCO_3^- concentration in soil solution, because all these parameters are important indicators of soil acidification and all of them can be accommodated with both, MAGIC and VSD, dynamic models. Simulations were done on the year basis, i.e. one simulation per one year (MAGIC is designed to handle with monthly simulations, too). Results showed that soil pH decreased rapidly in the 20th century while the biggest fall occurred in the 1970s (Figure 3a). VSD model showed the lowest pH value to be close to 3.9 while MAGIC calculated 4.3. Both models predicted a quite rapid recovery after the deposition load was reduced. For the year 2002 pH value was simulated similarly, 4.3 with VSD and 4.4 with MAGIC. On the long-term run pH simulation indicates that the initial value of 1850 will not probably be reached again by the year 2100, if ever. Hruška and Krám (2003) also described rapid decrease of soil pH from 5.5 (1850) to approximately 3.9 (1980s) in the study conducted on Lysina catchment in the Krušné hory

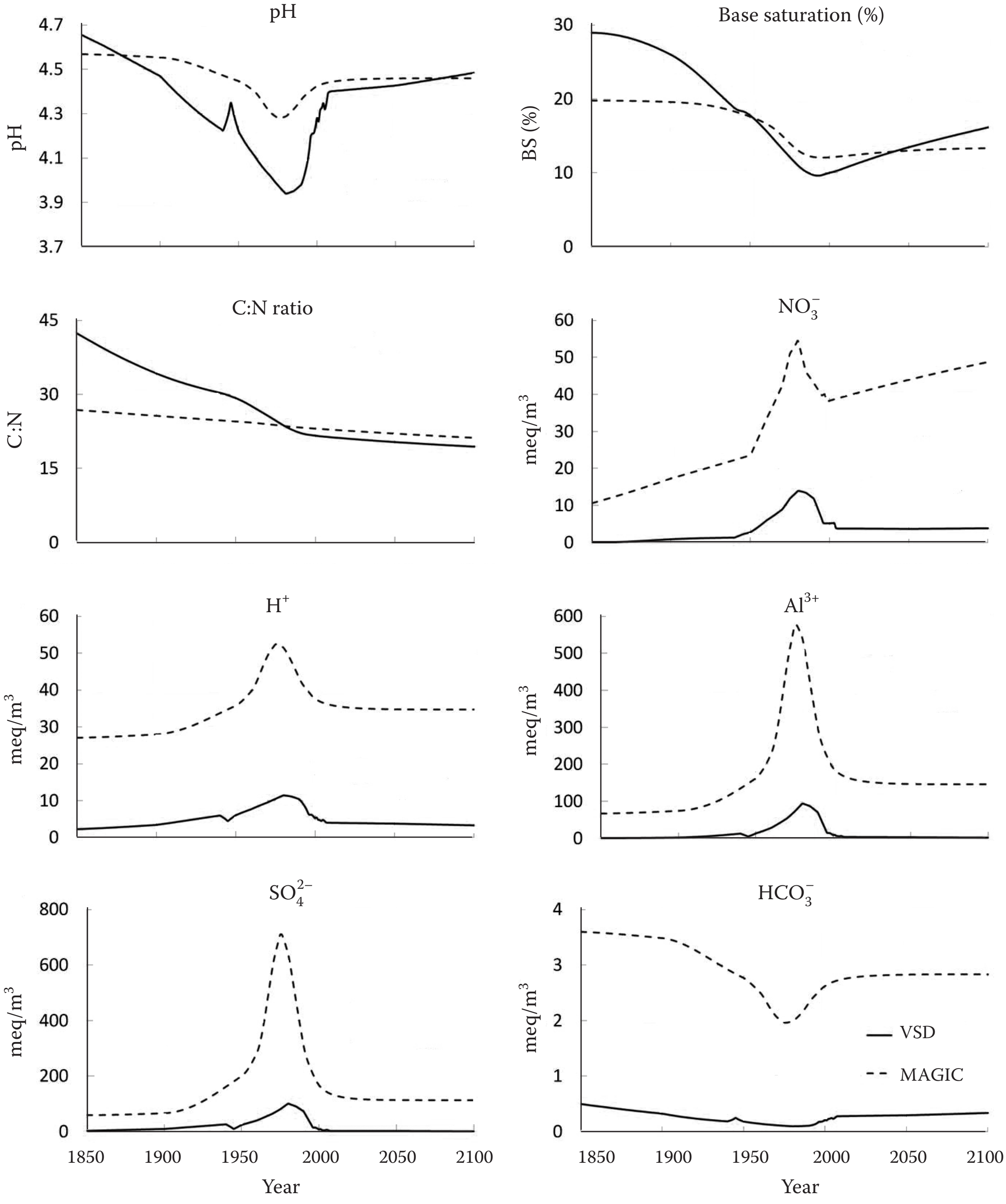

Figure 3. Hind- and forecast of eight soil variables simulated using two dynamic models, Model of Acidification of Groundwater in Catchments (MAGIC) and Very Simple Dynamic model (VSD)

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Mts. (an area with characteristics similar to the Jizerské hory Mts.; i.e. similar altitude range, land cover, bedrock, acid deposition load, etc.). In that work simulation as made by MAGIC further showed (similarly to our results) that the preindustrial estimate of 5.5 will not be reached again by 2030, if the future deposition will remain at the present day level. Malek *et al.* (2005) predicted a large decrease of pH from 6 (year 1800) to approximately 4 (year 2000) on another highly polluted area, Cieszyn Silesia (from the Ostrava region in northeastern Moravia to southern Poland), but with SAFE model.

In the case of BS, the simulation showed a large decrease in the 20th century. Both models drew a lowering of up to 10% approximately, while a slight recovery could be probably expected according to VSD (Figure 3b) in the future. The two simulations, VSD and MAGIC, differ mainly in the initial value – while VSD starts with 30%, MAGIC with only 20%. Since the measured value of BS in 2002 was 10%, both simulations seem to be close to reality. The MAGIC simulation largely coincides with findings as presented by Hruška and Krám (2003) where BS decreased from 25% in 1850 to 6% in 1992 with temporal behaviour highly similar to our results. Malek *et al.* (2005) predicted a large decrease of BS from 90% (year 1800) to approximately 10% (year 2000) with SAFE model.

C:N ratio simulation indicated a slight downtrend for the whole temporal period in both cases, although the initial C:N value as simulated by VSD was indeed by 15 higher than that predicted by MAGIC. VSD starts at 43, whereas MAGIC at 28. According to VSD, there is a large decrease of C:N around 1970 followed by a slight continuous lowering. MAGIC showed a continuous lowering for the whole temporal period (Figure 3c). Both C:N simulations for the year 2002 (i.e. 21.55 VSD and 23 MAGIC) are close to the measured value of that year (19.64), which may indicate a proper calibration of the model.

Focused on the concentration of NO_3^-, there is a massive temporal variation again. Both simulations indicated large increase after the year 1950 followed by a steep fall in the last decade of the 20th century. MAGIC predicted a fluent increase in the future, whereas VSD drew rather stagnation (Figure 3d). The maximum of NO_3^- in the 1970s as simulated by MAGIC (53.8 meq/m^3) is about five times higher than shown by VSD (13.1 meq/m^3).

For H^+, Al^{3+}, and SO_4^{2-} the simulations are largely similar but different in absolute terms. There is a significant peak in the 1970s followed by rather stagnation after the year 2000 (Figure 3e–g). The maximum in the 1970s is approximately five times higher for MAGIC. In the future, the contents of all three constituents will be probably slightly higher than in the initial preindustrial period. In the case of H^+ there are some discrepancies relative to soil pH. If the simulated H^+ concentrations are converted onto the pH scale, we get equality in MAGIC simulations, but different values for VSD. For example, in MAGIC simulation the maximum soil pH in the 1970s equals to 4.3 and the corresponding maximum of H^+ is 52 meq/m^3 which, after conversion, gives the same pH value of 4.3. But the previous does not apply for VSD. In this case the pH simulation in the 1970s equals to 3.9 and the corresponding H^+ is 12 meq/m^3, which after conversion gives pH 4.9.

Obviously, an opposite trend compared to examples described above is found for HCO_3^-, when there is a large fall in the 1970s followed by stagnation (MAGIC) or a slight increase (VSD) in the future (Figure 3h). The minimum of HCO_3^- in the 1970s is two times lower for VSD. Results indicate that the initial value will not be reached by the year 2100 again.

Summarily, the disparity between simulations and real state may be caused for example by omitting other environmental factors, which also contribute to acidification boost, e.g. spruce monoculture cover which replaced the native vegetation and which is spread over the majority of the area nowadays (Černý & Pačes 1995; Hruška & Ciencala 2003).

Comparison of VSD and MAGIC simulations with recent soil solution measurements. Having several data from soil solution analysis of the year 2008 available, an independent validation of the model forecast was made. The data are, unfortunately, largely "one-sided" when only one sampling site under spruce monoculture was surveyed. Four soil variables (pH, H^+, Al^{3+}, and SO_4^{2-}) were determined for sufficient soil horizons F, H, Ah, and Bvs. Focused on Bvs soil horizon, the most bulky one and therefore with the highest influence on MAGIC and VSD forecast, we found a concordance between model simulation and laboratory measurement in the case of SO_4^{2-} (Figure 4d), but large discrepancies for pH (Figure 4a). Low pH values indicate that the ecosystem may need more time to recover. In the case of Al^{3+} (Figure 4c) there is only one measurement which belongs to Ah horizon (the second most bulky) which is positioned somewhere between the two forecasts. As is evident from Figure 4b, the measured H^+ content is much

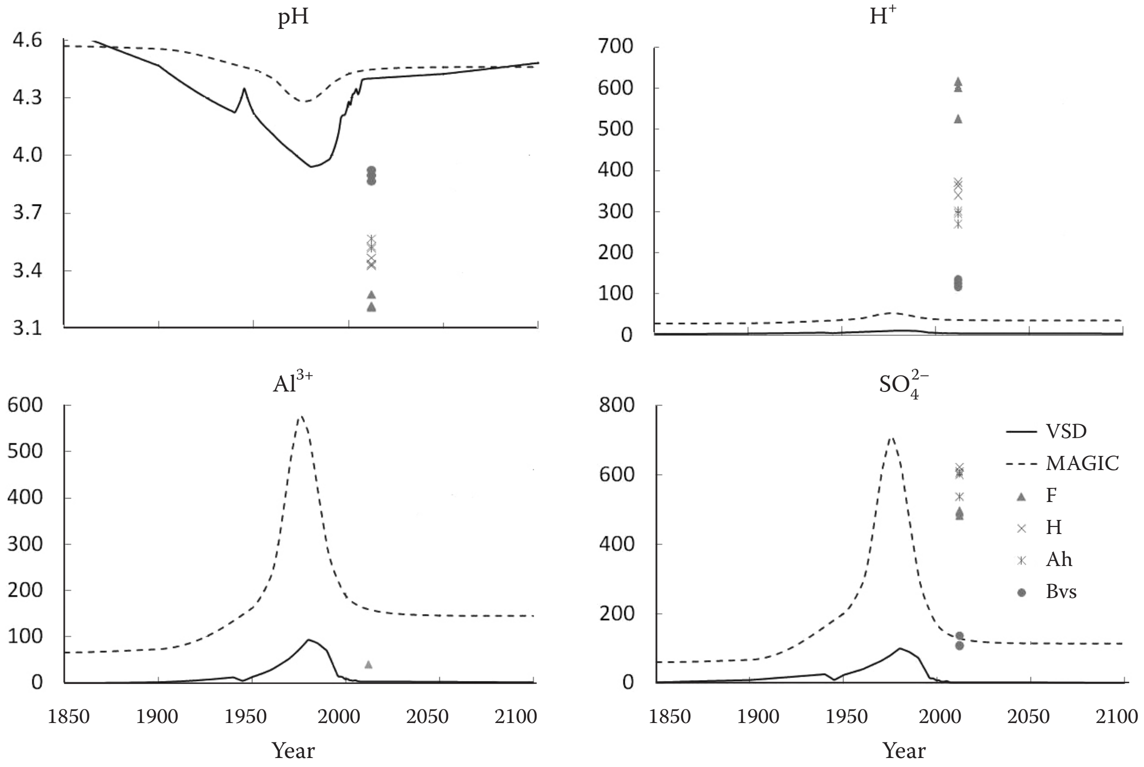

Figure 4. Comparison between temporal simulations by Very Simple Dynamic model (VSD) Model of Acidification of Groundwater in Catchments (MAGIC), and laboratory measurements for four soil variables (pH, H$^+$, Al^{3+}, and SO$_4^{2-}$); F – fermentation layer; H – humose layer ; Ah – humic topsoil horizon enriched with organic matter; Bvs – cambic subsoil horizon enriched with iron oxides

higher than that indicated by both simulations. However, due to the limited data for validation purposes, no accurate comparison of the predictive capability of the two dynamic models could be precisely done.

CONCLUSION

Long-term modelling of the impact of acid deposition on forest soils in the Jizerské hory Mts. region (North Bohemia) showed that the acidification status of soils was changing strongly in the past as a result of fluctuating emission level of acidifying compounds entering the atmosphere. The results indicated that the effect of wide pollution on ecosystem will not be eliminated by the year 2100 on condition that future deposition load will remain at the present day level. However, a distinct recovery of soil is apparent after the flue gas desulfurization at the end of the 20th century. Comparison of hind- and forecast of eight soil attributes (pH, BS, C:N ratio, H$^+$, Al^{3+}, SO$_4^{2-}$, NO$_3^-$, and HCO$_3^-$ concentration in soil solution) showed several important differences between VSD and MAGIC dynamic models. While the temporal behaviour of all eight soil variables was simulated quite similarly, the total concentration of ions in soil solution within the massive deposition load period in the 1970s is approximately five times higher for MAGIC model. Soil pH also differs slightly, when the maximum as simulated by MAGIC is by 0.4 higher than pH simulated by VSD. The highest similarity between MAGIC and VSD was found for BS and C:N ratio. Comparison to other long-term acidification modelling conducted on different but similarly affected areas in the Czech Republic and Poland showed a similarity to our results, particularly in the case of BS.

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