Prediction of medium- and long-term soil reaction changes in a beech forest based on beech stemflow zone observations

V. Pichler (1), J. Gregor (1), M. Homolák (1), J. Capuliak (2), J. Bebej (1), E. Gömoryová (1) and J. Váľka (3)

(1) Department of Natural Environment, Faculty of Forestry, Technical University Zvolen, T. G. Masaryka 24, 960 53 Zvolen, Slovak Republic (e-mail: pichler@vsld.tuzvo.sk)

(2) Institute of Terrestrial Ecosystems, ETH Zürich, Switzerland

(3) Institute of Forest Ecology, Slovak Academy of Sciences, Štúrova 2, 960 53 Zvolen, Slovak Republic

Abstract The active soil reaction under a mature beech forest subject to alkaline dust deposition reflected parallel influence of both the alkaline and acid deposition. As a result, the active soil reaction decreased at the 5–10 cm depth within the stemflow zone from 7,4 and 6,5 to 5,9 and 4,7, respectively. Outside the stemflow zone, soil pH was reduced from 7,9 to 6,6. This phenomenon occurred due to the long-range acid air pollution transport. Stechiometric calculations showed that the amount of acid deposition was amplified by the stemflow effect of beech trees that in turn partly offset the alkaline deposition. Thus, the active reaction of topsoil subject to stemflow moved from moderately alkaline to moderately acid range during the period 1991–2006 while a similar shift from moderately alkaline range towards neutral values occurred outside the stemflow zone. The pH decrease was correlated with a more than 90 % reduction of alkaline dust emissions from the magnesite works. The active soil reaction within the stemflow zone will remain in the respective intervals until 2030 at the 0–5 cm depth. Outside the stemflow zone, the active soil reaction will persist in the neutral range until 2015 at the 5–10 cm depth. Subsequently, the active soil reaction will move towards the moderately acid range even outside the stemflow zone. Standard forest management will cause the active soil reaction to converge at the original soil pH 5 in the course of approximately 200 years.

Key words: *forest soils, beech forests, stemflow, alkaline deposition, acid deposition, long-term soil pH predictions*

1. Introduction

Acidification or alkalinization of soils occurs through H+ transfer processes involving vegetation, soil solution and soil minerals (Bremen et al., 1983). Important determining factors are: composition and development of vegetation, soil-forming parent material, woody species composition, air pollution and variability of soil properties. On one hand, Slovak Republic has an unfavorable position, being heavy influenced with the long-range air pollution transport. Prevailing western and northwestern winds displace airborne pollutants towards the Central Europe. Therefore, inputs of sulphates, nitrates and other acid components into forest ecosystems remain high, despite a considerable drop in domestic emissions (Pichler and Bublinec, 2006).

Along with the acidification of forest soils however, their alkalinization took place across certain localities, such as the Muráň Valley, as well. It features a high concentration of magnesite industry whose products play an important role in the exports of the Slovak Republic. The production is based on the magnesite deposits in the Carboniferous rocks. Currently, two major plants in Jelšava and Ľubeník function within the area of interest, but their recent impact on the surrounding environment has been limited due to the introduction of efficient separation facilities. In the past, mainly between 1970 and 1990, that situation was different due to the continuous release of polydisperse emissions containing magnesium and calcium oxide solid particles, totaling several thousand tonnes every year. That resulted in a considerable degradation of the adjacent areas, where the Mg content in soils has exceeded 2000 $mg.kg^{-1}$ (Bobro et. al. 2000, Hančuľák and Bobro, 2004). According to these authors, soils in some monitoring plots have already begun to lose the Mg surpluses due to improved immissions conditions, i. e. in places where the Mg input does not exceed the natural Mg losses of 23–34 $kg.ha^{-1}.year^{-1}$ any longer. The alkaline reaction of local soils has been caused by little soluble minerals such as periclase, magnesite, calcite and amorphous MgO.

The magnesium losses thus occur mainly owing to the secondary minerals such as hydromagnesite, nesquehonite, brucite and others that are able to migrate as a part of the soil solute (BOBRO et al., 2000).
The main adverse effect of a strongly increased alkalinity consists in the nutrients immobilisation, because the optimum reaction varies between pH 5,0–6,5. Among the elements whose intake by plants is effected, phosphorus, potassium, nitrogen and trace elements rank comparatively high (BUBLINEC 1971).
In this context it is important to note that conclusions on the impact of natural or anthropogenic depositions are often made based on their isolated effects. In reality however combined effects of various depositions are a rule rather than an exception and they depend on their concentrations and variable exposure times. Thus, the result may by additive, synergic or even antagonistic (ANONYMUS). Neither assessments nor predictions of immissions impact on soils should therefore be made without proper attention paid to their mutual interactions. The interaction processes in respect to their transport mechanisms, deposition, chemical reactions kinetics and spatial heterogeneity of the environmental patterns feature high variability both in space and time. To identify trends means to investigate processes on appropriate time scales and choose validation procedures.
In our study, we leaned on the amplification of immissions input through stemflow. Stemflow is typical of various beech species due to the specific habitat of the genus *Fagus* (GERSPER 1970, GERSPER and HOLOWAYCHUK 1970), as different from other species such as oak (TUŽINSKÝ and SOROKOVÁ 2002). JOCHHEIM and SCHÄFER (1988) established that the stemflow zone received eight times more water enriched by particles and dissolved chemical compounds in comparison with areas only exposed to throughfall. Such processes led to formation of spots in which soil was significantly acidified due to higher amount of acid deposition from coal-fired power plant and remote air pollution sources (ŠÁLY and PICHLER, 1993). Thus the stemflow impacted zone was used by WERNER (1988) to study the processes of heavy metals accumulation in forest soils. In a broader sense, it has been the application of geobiocenotic fields concept as defined by ZINKE (1962) and KARPACHEVSKY (1977). It relies on the fact that trees as the main edificators in forest ecosystems modify the effects of environmental factors in a predominantly circular or radial pattern.
Our approach aimed at the description, interpretation and prediction of soil reaction changes under the influence of past alkaline deposition and continuing acid deposition in the Muráň Valley. The study goals consisted in establishing how the soil pH changes under the European beech trees (*Fagus sylvatica* L.) in the area of interest are likely to be influenced by the stem flow given current immission situation.

2. Material and methods

We based our investigations on several assumptions:

a) The increase of hydrogen protons in the buffer intervals of carbonates (pH 6.2–8.6), silicates (pH 5.0–6.2) and sorbents (pH 4.2–5.0) as defined by ULRICH (1983) can be approximated as a linear process;
b) An n-fold increase in the acid deposition causes an n-fold speeding of a soil acidification (SPARKS, 2003).

2.1 Site description

Soil sampling was carried along a transect in hills of Revúcka Vrchovina, on the northern slope of Tri Peniažky (583 m a. s. l.), 2.5 km SSW of the Jelšava Magnesite Plant, at the elevation of 490 m a. s. l. The area is built by black and grey schists and white crystalline limestones from the carboniferous period. The yearly precipitation amount reaches 800 mm. The 95-year-old beech stand had 0.8 stocking and 90 % canopy closure in 1990 when the first sampling was performed. It belongs to the Fagetum pauper forest association with scarce herb layer of *Hedera helix*. The original soil type was Dystric Cambisol whose reaction was around pH 5.0 but it increased to 7.5–8.0 by 1990 due to magnesite immissions. In spite of the alkaline immissions load the beech forest did not show signs of physiological damage.

2.2 Soil samples

Soil samplings were carried out under five beech trees from the main canopy (tree classes 1 and 2 according to Kraft) in October 1990 and 2006. Samples weighing 250 g were taken from the depth of 5–10 cm. The active soil reaction in samples was measured in the laboratory using a glass ion-sensitive electrode referenced with a standard calomel electrode and a meter (SCHOFIELD and TAYLOR 1955).

2.3 Data analysis

Spatial interpolation among the discrete pH values was performed to identify the stemflow zone defined as a circular or elliptical contigeous area with comparatively low pH around the stem. Subsequently, the area-wise ratio between the stem flow zone and the rest of the scheme was calculated. The ratio was used as a percentile dividing the set of measured soil pH values into two classes – affected by either stemflow or throughfall. The pH values were then recast as hydrogen protons concentrations using $pH = -\log[H^+]$ and $C_{(H+)} = 10^{(-pH)}$. Regression and correlation analysis was applied to the hydrogen protons activities. Extrapolated trends in both active and exchange reactions were projected using regression lines. To assess the prediction, the $C_{(H+)}$ increase in soil subject to stemflow from 1990 through 2006 was compared with that in soil exposed to througfall only during the same period of time. We then established whether the result would fell into the same order of magnitude as the stemflow/throughfall ratio, i. e. 6–12, as given by TUŽINSKÝ (2004) and JOHNSON and LEHMANN (2006)

3. Results and discussion

Interpolated contours of the active soil reaction in the 5–10 cm depth under the beech trees based on values measured in 1990 are given in Fig 3. Similar contours based on samples taken from the same depth in 2006 are graphed in Fig. 4. A simple ocular inspection of the graphs shows a considerably increased soil reaction span in 2006 when compared to 1990. Also the spatial variability of soil reaction increased by 2006 due to heterogeneity of throughfall, as indicated by an increased number of circular patterns of pH contours. The comparatively lower spatial variability of soil reaction as recorded in 1991 apparently occurred due to distinctive processes of acid and alkaline deposition. The deposition of the alkaline dust on the soil surface is spatially more even. During the winter season, it settles on the snow cover surface that releases it during the snowmelt. At the same time, acid immissions are much less captured by the snow particles. Their maximum input occurs in the spring, when they are dissolved in the raindrops that must penetrate the foliated tree canopies that cause a considerable spatial variability of throughfall (KREČMER and FOJT 1981). It is the liquid precipitation that has the highest capacity to capture and dissolve the sulfate emissions (PICHLER and BUBLINEC 2006). Finally, only them take part in the stemflow process. The observed increase in the active soil reaction over an entire soil surface developed owing to the highly active MgO and a better soluble CaO, along with the products of its reaction with the air and soil CO_2, or with the air and soil moisture, i. e. $MgCO_3$ and $Mg(OH)_2$ (NOVÁK 1981), as well as $Ca(OH)_2$.

In spite of the full area soil pH increase, the process of the planar differentiation had already begun by 1991 as the initial stage of stemflow zone formation could be detected at that time (Figure 3). Data in Table 1 show the 10^{th} and 90^{th} percentiles for the measured soil pH values. All data bellow the 10^{th} percentiles fall into the zone subject to stemflow that had an average planar area of 0.16 m^2, as seen from Table 2. From these tables, a 10th percentile decrease and a stemflow zone planar increase are evident.

That resulted from an antagonistic effect of the acid deposition containing H_2SO_4 and HNO_3 along with H_2CO_3 on one hand side, and the aforementioned alkaline dust on the other side. If the S and N deposition within the area of interest, amounting to 2.0 $g.m^{-2}.year^{-1}$ S and 1.5 $g.m^{-2}.year^{-1}$ N (ZÁVODSKÝ 2002 a, b), is considered, it corresponds stoichiometrically to approximately 2.8 $g.m^{-2}.year^{-1}$ Mg that enters chemical reactions with both elements. According to the measurements from the margins of the area of interest, the total deposition of Mg in 1998 varied around 2.1 $g.m^{-2}.year^{-1}$ (Hančuľák, Bobro 2004). The literature gives 3.0 $g.m^{-2}.year^{-1}$ of Mg as a natural loss from soils (HRONEC, 1996, INDRIKSON and ZALITIS, 2004). From this point of view, secondary minerals originating in an immissions loaded environment such as hydromagnesite, nesquehonite, brucite and others play an important role, inasmuch they are able to migrate at least partially with the soil solute (BOBRO et al., 2000), similar to easily soluble $Mg(NO_3)_2$ that forms during reactions with $(NO_3)^-$ deposition. In this raw approximation the natural loss of magnesium from soil due to retention in the trees biomass that was assessed 0.16 $g.m^{-2}.year^{-1}$ by BUBLINEC (1994), because it is partly offset by S retention too and we assumed that the nutrients intake occurred from the original mineral part of the soil.

Further active soil reaction development in the 5–10 cm depth between 1991 and 2006 showed that the magnesium loss from the soil under investigation prevailed over the alkaline dust deposition. During the 15 years, the active reaction dropped from 7.4 to 5.9 within the stemflow zone (Figure 5). In the throughfall zone such drop was much less pronounced, from 7,9 down t o 6,6 (Figure 5). Based on Figure 5 a conclusion can be drawn that the active soil reaction in the stemflow zone decreased from moderately alkaline interval into moderately acid interval. In the throughfall zone, the soil reaction changed from moderately alkaline interval into neutral interval. The reaction will remain in these intervals till 2030 and 2015 respectively.

These predictions are consistent with the generally observed six to twelve times higher rainwater input into the stemflow zone compared to throughfall meaning that such an increase in water percolation linked with a corresponding immission load speeds up proportionally the soil acidification processes in the stemflow zone compared to the throughfall impacted zone. Indeed, according to Figure 5 the soil pH in the throughfall zone will decrease to levels measured in the stemflow zone in 2006 by 2080 so that the process will take six times longer than in the stemflow zone. That is also in compliance with the assumption of increased acidification resulting from higher acid immissions load according to SPARKS (2003).

Table 1: Basic statistical characteristics of the active soil reaction values measured at the Tri Peniažky beech transect

Year	**Valid N**	**Mean**	**Minimum**	**Maximum**	**10th percentile**	**90th percentile**	**Std. dev.**
1996	227	7,80	7,22	7,84	7,50	8,01	0,23
2001	127	6,72	5,25	7,30	6,34	7,06	0,30

Table 2: Planar areas of zones impacted by stemflow and throughfall at the Tri Peniažky beech transect

Zones	**Planar Area [m^2]**	
	1990	**2006**
Stemflow zone	0.16	0.28
Througfall affected zone	3.84	3.72
Total area	4.00	4.00

Figure 1: Tri Peniažky beech transect and Jelšava Magnesite Plant positions in the Muráň Valley

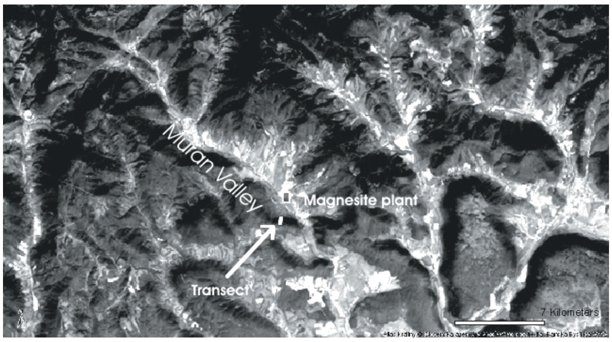


Figure 2: Soil sampling scheme at the Tri Peniažky beech transect

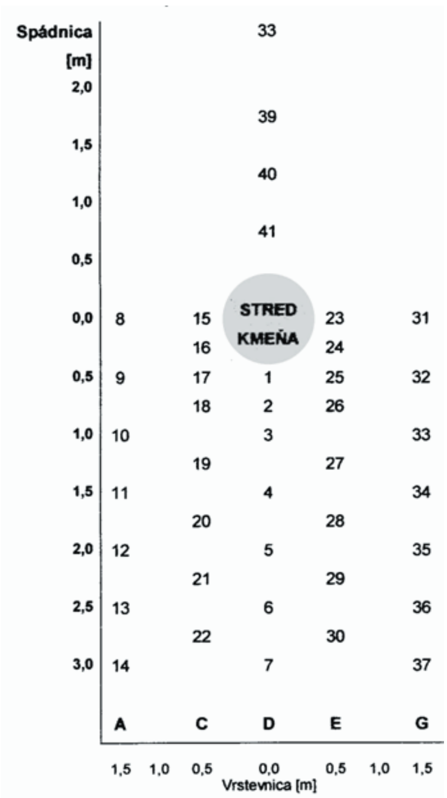


Figure 3: Active soil reaction contours at Tri Peniažky beech transect measured in 1990. Beech stem centres have coordinates [1.5, 1.5].

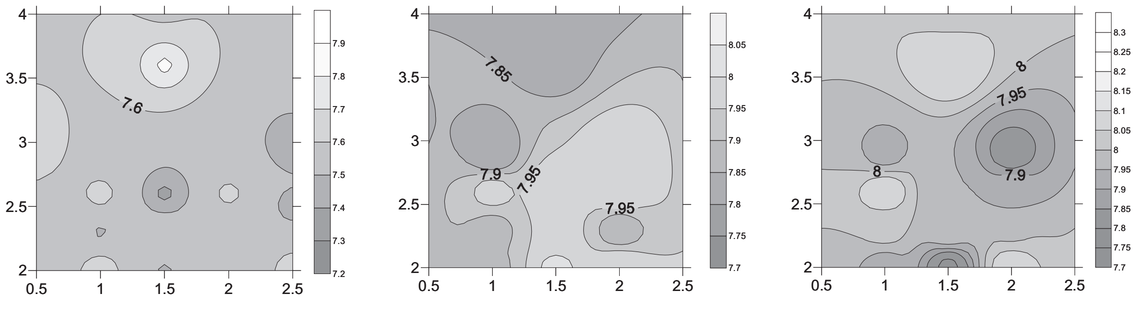


Figure 4: Active soil reaction contours at Tri Peniažky beech transect measured in 2006. Beech stem centres have coordinates [1.5, 1.5].

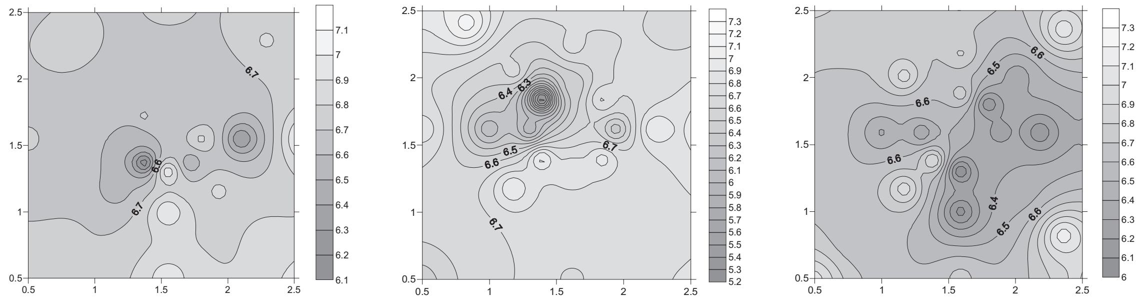
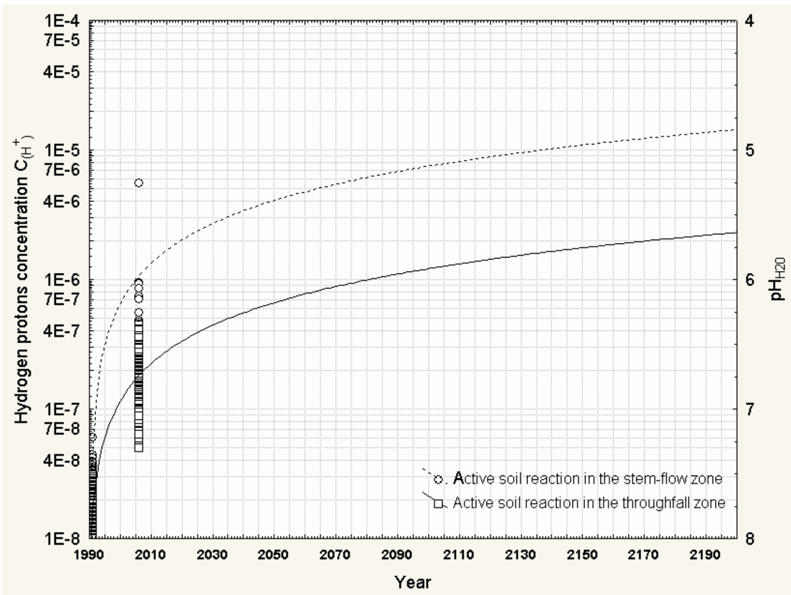


Figure 5: Regression lines of the actiue soil reaction in the stemflow and throughfall zones at the Tri Peniažky beech transect.



4. Conclusions

The measurement and evaluation of both active and exchangeable soil reaction under a mature beech forest growing within an area featuring alkaline dust deposition from the Magnesite Works, Inc., Jelšava, showed an antagonistic influence of the alkaline pollution and acid deposition from local and remote sources. The resulting pattern was co-determined by the stemflow water percolation through the topsoil.

Thus in 1991, the soil pH values measured in H_2O unexpectedly indicated no increase compared to values measured in samples taken outside the stemflow zone. Instead, there was an overall increase in the actual reaction to 7.5–8.0 over the whole area irrespective of the sampling point position.

Stoichiometric calculations showed that the amount of acid deposition amplified by the stemflow effect of beech trees could has offset the alkaline deposition. By 2006, such trends in the respective forest stand prevailed entirely. The active soil reaction decreased at the 5–10 cm depth within the stemflow zone from 7.4 and 6.5 to 5.9 and 4.7, respectively. Outside the stemflow zone, the pH reduction was less dramatic, from 7.9 to 6.6. So the active reaction of topsoil subject to stemflow moved from moderately alkaline to moderately acid range during the period 1991–2006 while

a similar shift from moderately alkaline range towards neutral values occurred outside the stemflow zone. The pH decrease was correlated with a more than 90 % reduction of alkaline dust emissions from the magnesite plant.
The active soil reaction within the stemflow zone will remain in the respective intervals until 2030 at the 0–5 cm depth. Outside the stemflow zone, the active soil reaction will persist in the neutral range until 2015 at the 5–10 cm depth. Subsequently, the active soil reaction will move towards the moderately acid range even outside the stemflow zone. Under the standard forest management, the active soil reaction to converge at the original approximate soil pH 5 in the course of approximately 200 years.

5. Acknowledgements

This investigation was supported by scientific grants awarded by the Research and Development Agency APVV-0468-06 and the Scientific Grants Agency of the Ministry of Education and the Slovak Academy of Sciences Nos. 1/2383/05, 1/2357/05 and 1/3548/06.

6. Literature

ANONYMUS: Reduction of SO_2 and Particulate Emissions – Synthesis report. The regional environmental center for Central and Eastern Europe. Szentendre (Hungary), 52 p.

BUBLINEC, E. 1994: Koncentrácia, akumulácia a kolobeh prvkov v bukovom a smrekovom ekosystéme [Concentration, accumulation and cycling of elements in beech and spruce ecosystems]. Acta Dendrobiologica. ÚEL SAV Zvolen, Veda, Bratislava, 132 p.

BUBLINEC, E. 1971: Intoxikácia pôdy v okolí závodov na spracovanie magnezitu, jej meliorácia a vplyv na výživu rastlín [Soil Intoxication in the surroundings of magnesite plants, its amelioration and influence on plants nutriution]. Biologické práce, 5, 17, 88 p.

BOBRO, M., HANČUĽÁK, J., DORČÁKOVÁ, H., BÁLINTOVÁ, M. 2000: Monitorovanie imisnej záťaže pôd v Muránskej doline. Acta Montanistica Slovaca, 5, 1: 33–35.

GERSPER, P. L., 1970: Effect of American Beech Trees on the radioactivity of soils. Soil Sci. Soc. Amer. Proc., 34: 318–323.

GERSPER, P. L., HOLOWAYCHUK, N. 1970: Effect of stemflow water on a Miami soil under a Beech Tree. Morphological and physical properties. Soil Sci. Soc. Am. Proc., 34: 779–786.

JOHNSON, M. S., LEHMANN, J. 2006: Double funneling of trees: Stemflow and root-induced preferntial flow. Ecoscience, 13, 3: 324–333.

HANČUĽÁK, J., BOBRO, M. 2004: Vplyv magnezitového priemyslu na imisnú záťaž oblasti Jelšavy tuhými imisami [Impact of magnesite industry on the solid immissions load in the Jelšava area]. Acta Montanistica Slovaca, 9, 4: 401–405.

HRONEC, O. 1996: Exhaláty, pôda, vegetácia [Air pollution, soil, vegetation]. TOP, s. r. o., Prešov, Slovenská poľnohospodárska a potravinárska komora Bratislava, 325 p.

INDRIKSONS, A., ZALITIS, P. 2004: Cycle of Water and Biogenous Elements in the Forest Ecosystems in Latvia. In: Folke Andersson, Yves Birot and Risto Päivinen (eds.): Towards the Sustainable Use of Europe's Forests – Forest Ecosystem and Landscape Research: Scientific Challenges and Opportunities. EFI Proceedings No. 49, p. 171–180.

JOCHHEIM, H., SCHÄFER, H. 1988: „Die Baumfuss–Methode" dargestellt anhand einer Untersuchung der Immissionsbelastung von Nordwest–Jugoslawischen Buchenwälder. Zeitschrift für Pflanzenernähr. Bodenk., 151: 81–85.

KARPAČEVSKIJ, L. O. 1977: Pestrota počvennogo pokrova v lesnom biogeocenoze. Izd. Mosk. univ., Moskva, 312 s.

KAZDA, M, GLATZEL, G. 1984: Schwermetallanreichungem und Schwermetallverfügbarkeit im Einsickerungsbereich von Stammablaufwasser in Buchenwäldern (Fagus sylvatica L.) des Wienerwaldes. Zeitschrift fuer Pflanzenernähr. Bodenk., 147: 743–752.

KREČMER, V, FOJT, V. 1981: Kritické poznámky k metodologii měření kapalných podkorunových srážek [Critical remarks on throughfall measurement methodology] . Vodohosp. Čas., 29, 2: 148–164.

SCHOFIELD, R. K., TAYLOR A. W. 1955: The measurement of soil pH. Soil Sci Soc Am Proc 17: 164–167.

SPARKS, D. L., 2003: Environmental Soil Chemistry. Academic Press, London, 352 p.

ŠÁLY, R., PICHLER, V. 1993: Súčasné zmeny pôdnej reakcie v bučinách [Current soil reaction changes in beech forests]. Acta facultatis forestalis, 35, p. 51–69.

TUŽINSKÝ, L. 2004: Vodný režim lesných pôd [Forest soils water regime]. TU Zvolen, 102 p.

TUŽINSKÝ, L., SOROKOVÁ, M. 2001: Hydropedologické cykly v luvizemi pod dubovým porastom [Hydropedological cycles in a luvisol under oak forest]. Acta facultatis forestalis 43, Zvolen-Slovakia, TU Zvolen, p. 355–368.

ULRICH, B. 1983: Soil acidity and its relations to acid deposition. In B. ULRICH AND J. PANKRATH (eds.): Effects of accumulation of air pollutants in forest ecosystems. Dordrecht, Reidel, p. 127–143.

VAN BREEMEN, N., MULDER, J., DRISCOLL, C. T. 1983: Acidification and alkalinization of soils. Plan and Soil, 75, 3: 283–308.

WERNER, W, 1988: Stickstoff- u. Phosphor –Mineralisation im Versickerungsbereich des Stammablaufwassers von Buchen. Flora, 181: 339–352.

ZÁVODSKÝ, D, 2002, a): Depozícia síry emitovanej z domácich a zahraničných zdrojov. Atlas krajiny Slovenskej Republiky [Sulphur deposition form domestic and foreign sources]. Bratislava MŽP, Banská Bystrica, SAŽP, 334 p.

ZÁVODSKÝ, D. 2002, b): Depozícia dusíka emitovaného z domácich zdrojov a zahraničných zdrojov Republiky [Nitrogen deposition form domestic and foreign sources]. Atlas krajiny Slovenskej Republiky. Bratislava MŽP, Banská Bystrica, SAŽP, 334 p.

ZINKE , P. J. 1962: The pattern of Influence of Individual Trees on Soil Properties. Ecology 43, 1: 130–133.