

Sources and Sinks of Nitrogen in Acidified Glacial Lakes of the Bohemian Forest, Czech Republic

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Abstract

Many central European forested watersheds including those in the Bohemian Forest of the Czech Republic have shown signs of damage due to long-term exposure to high levels of nitrogen and sulfur in atmospheric deposition. Symptoms of nitrogen saturation include acidification, leaching of critical nutrients such as calcium along with potentially toxic metals such as aluminum from the soils to lakes and streams. As lakes in the Bohemian Forests became increasingly acidified and as aluminum concentrations increased, higher trophic levels of organisms such as macrozooplankton and fish disappeared. We have conducted a study in four watersheds in the Bohemian Forest, all vegetated primarily with Norway spruce ranging in age from 80 to 150 years. Since 1989 there has been a 35% decline in atmospheric sources of nitrogen; however, lake water quality has not improved at a concomitant pace. In order to determine possible causes for this hysteresis effect we have attempted to identify sources of nitrogen to the watershed and have measured rates of processes in watershed soils and lake waters responsible for transformations of nitrogen. Isotopic ratios of ¹⁵N/¹⁴N or ¹³C/¹²C in vegetation, soils, and in particulates within the lakes were determined in order to identify the sources of nitrogen or carbon deposited onto a watershed and leached to the lake. Soil and vegetation samples taken from Bohemian watersheds were compared to similarly forested sites in Brenna Poland, close to the northern border of the Czech Republic near a heavily industrialized area. Results of analyses of ¹⁵N and ¹³C signatures suggest that coal burning may be a more important source of nitrogen to Polish watersheds whereas agriculture or animal feedlots may be a more important source to Bohemian watersheds. Soils in the Bohemian watersheds contained high organic matter content, which can sequester nitrogen derived from the atmosphere into forms that are only slowly decomposed. We measured rates of gross nitrogen mineralization and nitrification in the various Bohemian watersheds using the method of isotope pool dilution. Rates of nitrogen mineralization were highest in Prášílské watershed, which had been disturbed by an insect infestation causing forest die-off several years prior to this study. Nitrogen concentrations in lake water were correlated with rates of nitrogen mineralization and nitrification in the watersheds. Water column profiles of dissolved inorganic carbon, nitrous oxide, and methane were compared in the Bohemian lakes in order to determine the relative importance of respiration, denitrification, and methanogenesis. Prášílské Lake, disturbed by an insect infestation and with the highest rates of nitrogen mineralization in its watershed, had the highest concentrations of nitrous oxide, a product of denitrification. Černé Lake had the lowest rates of organic matter respiration and concentrations of nitrous oxide and thus far seems to be responding most slowly to improvements in air quality.

Key words: ¹⁵N, ¹³C, isotopes, nitrogen cycling, watershed, acidified lakes, nitrogen mineralization

Introduction

Based upon analyses of diatom assemblages in sediment cores, lakes in the Bohemian Forest have shown signs of acidification for at least 200 years. However, between 1960 and 1985 the pH declined from 5 to 4 (VESELY & al. 1993). At the same time there was a dramatic increase in nitrate concentrations in the lakes (VESELY & MAJER 1992). Acidification in the lakes of the Bohemian Forest has followed a distinctly different pattern than lakes in Scandinavia and North America. In Bohemian lakes nitrate contributes approximately 50% of the acidity whereas in other lakes sulfate is the primary anion responsible for acidification (VESELY & MAJER 1992). Based upon the high observed TN: TP ratios and the high contribution of nitrate (70%) to total nitrogen in lake waters, KOPÁČEK & al. (1995, 2000) have suggested that the Bohemian watersheds are nitrogen saturated.

Starting in the 1950's, central Europe was exposed to high levels of atmospheric nitrogen deposition. As a result, many central European forests displayed signs of nitrogen saturation. Lakes of glacial origin, such as those located in the Bohemian Forest, have shown the consequences of nitrogen saturation in their watersheds with high acidity, high total nitrogen: total phosphorous ratios and low trophic status. The Bohemian Forest lakes are all presently fishless with low abundances of metazooplankton (VRBA & al. 1996). Although during the last decade atmospheric emissions of total inorganic nitrogen (TIN) have declined by 35% (KOPÁČEK & al. 1997), Czech researchers have observed what appears to be a hysteresis effect in the recovery of these systems from nitrogen saturation at Černé Lake (KOPÁČEK, pers. com.). We hypothesize that in part this hysteresis effect may be related either to increased rates of mineralization of organic nitrogen in the watersheds or to reduced microbial processing of TIN in the lake water columns.

The primary objectives of this present study were to: (1) assess the degree of nitrogen cycling activity in forested soils at sites which show symptoms of nitrogen saturation; (2) determine whether soils, tree needles, lichens, and mosses possess distinct ¹⁵N isotopic and elemental signatures reflecting distance from sites of heavy industrial activity; (3) determine the degree to which respiration and denitrification contribute to removal of organic carbon and nitrate in the glacial lakes of the Bohemian region; (4) identify the sources of carbon and nitrogen to lake water columns.

Research design and methodology

Study Sites

Studies were performed during August 1997 and September 1998. During 1997 two watersheds were sampled in Brenna Poland (PL), as described in BYTNEROWICZ & al. (1999), located along the Czech/Polish border close to industrial sources of atmospheric pollution, and three watersheds in the Czech Republic (CR), Prášílské, Plešné, and Čertovo (VESELY 1994, VRBA & al. 1996), all located in the Bohemian Forest, more isolated from sources of industrial pollution. Prášílské had undergone storm damage followed by an insect infestation several years prior to our study, which resulted in approximately a 70% loss of forest cover. During 1998 studies were done in three watersheds of the Bohemian Forest, Plešné, Čertovo, and Černé. These three lakes seem to have responded very differently to improvements in air quality. For example, although Čertovo and Černé Lakes are located on opposite sides of the same mountain, recovery of water quality in Černé has been slower than that in Čertovo.

Isotopic and elemental analyses of soil and vegetation

In 1997 five replicate samples of soil, needles, mosses, and lichens (CR only) were taken from two Brenna Poland watersheds and from Čertovo, Plešné, and Prášilské watersheds in the Bohemian Forest. Soils were sieved (2 mm) and dried at 50°C to constant weight; vegetation was air dried between 2 sheets of filter paper and all were analyzed for total carbon, total nitrogen, ¹⁵N natural abundance, ¹³C natural abundance using a VG Optima isotope ratio mass spectrometer (IRMS) coupled to a C:H:N elemental analyzer. Samples were digested using perchloric acid and analyzed by atomic emission spectroscopy (Perkin Elmer model 5000) for determinations of: phosphorous, calcium, magnesium, potassium, manganese, and zinc content.

Soil physical/chemical properties

Soils were sampled from the F (or O_e) horizon after removal of the fresh litter layer. The F horizon consisted primarily of decayed wood and fine roots. We were unable to sample the mineral layer because of rocks. During 1997 triplicate samples of soil (20 g) were removed from Čertovo, Plešné, and Prášilské watersheds, extracted with 50 ml KCl (2M) and shaken for one hour. The extractant was filtered (Gelman, 0.45 μm), frozen until analysis, and analyzed for ammonium, nitrate, nitrite, and phosphate using an Alpkem autoanalyzer. Five samples of soil removed from each of the above sites were weighed, dried at 50°C to constant weight, reweighed, and combusted at 500°C for five hours to determine soil moisture and organic content. Because subsamples of the dried soils were used for isotopic analyses, it was necessary to use a low drying temperature to prevent isotopic fractionation and loss of volatile organics. Syringes (60 ml) with ends cut off were used to take cores (three taken at randomly chosen plots per site) to a depth of 3.7 cm for determinations of bulk density. Soils were dried as described above. Soil temperature was measured at 5-cm depth. During 1998 soil and needle samples were taken in triplicate at each of three elevations (1000, 1050, 1100 m) within Černé and Čertovo watersheds and from a mid elevation site (1130 m) at Plešné (same site as in 1997). Samples were analyzed for organic content, extractable nutrient content, bulk density, total C and N, and isotopic abundances as described above.

Gross mineralization and nitrification rates in watershed soils

For determination of mineralization rates triplicate samples of soil (20 g), removed from each of the above sites during 1997 and 1998, were injected with 2.5 ml of distilled water containing 2 mM-¹⁵N (NH₄)₂SO₄ (50 at%). Samples were incubated in situ under 2 cm of soil for 0, 24, and 72 hours (1997) or in an incubator at the in situ temperature (1998). At completion of incubation samples were extracted with 50 ml KCl (2M). The extractant was filtered (Gelman Supor, 0.45 μm) and frozen until analysis. Samples were prepared for isotopic analysis as described in ANDERSON & al. (1997). Isotopic abundance was determined at the University of California, Davis, USA using an elemental analyzer coupled to an isotope ratio mass spectrometer. Rates of N-mineralization were determined using a model described by WESSEL & TIETEMA (1992) which takes into account both the change in atom percent enrichment of the ¹⁵N-labeled NH₄⁺ pool as well as the change in total concentration of the NH₄⁺ pool. For determination of nitrification samples were treated exactly as described for mineralization except that soil samples were injected with 5 ml of 1 mM ¹⁵N-KNO₃ (50 at%).

Dissolved Gas Analyses

Dissolved inorganic carbon (DIC), nitrous oxide (N₂O), and methane (CH₄) in the water column profile were determined for each of the lakes studied. During 1997 water samples

were taken from Prášilské Lake at depths of 3.5, 7, 10, 13, and 15 m; from Plešné Lake at 1, 3, 5, 7, 10, 13, and 17 m; from Čertovo Lake at 1, 4, 8, 12, 16, 20, 24, 28, and 34 m. During 1998 water was sampled from Lake Plešné at depths of 0.5, 2, 6, 10, 13, 15, 16.9 m; from Lake Čertovo at 0.5, 2, 5.5, 10, 20, 30, 33 m and from Lake Černé at 0.5, 5, 8, 20, 30, 35, 38 m. Samples were kept refrigerated in gas-tight Hungate tubes (Bellco, Inc.; 13.5 ml) preserved with 250 μ l ZnCl₂ (50% w/v). All samples were brought to room temperature prior to analysis. For DIC determinations 100 μ l samples of water were removed before injection of 7.5 ml of argon into the Hungate tubes for gas equilibration. For analyses of methane and nitrous oxide, the argon was added by syringe through a gas-tight septum displacing water into a 2nd syringe. The Hungate tube with two attached syringes was shaken for 1 min. The displaced water was reinjected displacing gas back into the syringe, and analyses for methane and nitrous oxide were performed as described below.

DIC was determined by injecting one-ml of lake water into a vessel containing 0.05N H₂SO₄, which was continuously sparged (300 ml min⁻¹) with CO₂-free N₂ into a LiCor, model 6252 infrared gas analyzer. Calibrations were performed routinely before and during analyses by injections of 1, 5, and 10 mM NaHCO₃. After equilibration, headspace (200 μ l) samples of CH₄ were injected into a Hewlett Packard model 5890 gas chromatograph equipped with a molecular sieve 13 \times column and flame ionization detector (oven \cong 80°C, detector \cong 220°C). A single point calibration of the instrument was performed routinely before and during analyses using a 9.02 ppmv CH₄ in N₂ standard (Scott Specialty Gases, Inc.). For nitrous oxide determinations five-ml samples of headspace gas were injected into a Shimadzu Model 8 gas chromatograph fitted with an electron capture detector at 330°C and Poropak Q column (2 m) at 50°C. Concentrations of all gases were corrected for temperature and gas in the dissolved phase using the Oswald coefficient as described by WEISS & PRICE (1980).

Table 1. – Soil characteristics.

Site	Organic content	NO ₃ ⁻	NH ₄ ⁺	%N	TON ^c	molar C/N
	(%)	(μ gN g soil ⁻¹)			(mg N g soil ⁻¹)	
Poland						
Catch 50	42.1	2.9 (0.78)	0.18 (0.02)	1.10 (0.10)	4.63	25.43 (0.96)
Catch 7	42.1	0.15 (0.01)	0.02 (0.01)	1.81 (0.08)	7.62	24.36 (2.02)
Czech Republic						
Prášilské		0.46 (0.06)	7.01 (6.11)	1.46 (0.06)		35.83 (2.61)
Plešné (high) ^a		0.57 (0.30)	0.22 (0.22)	1.56 (0.11)		
Plešné (high)	94.09 (1.42) ^b	0.30 (0.14)	0.48 (0.20)	1.56 (0.11)	14.68	35.42 (2.54)
Černé (low)	45.36 (9.92)	3.36 (0.4)	0.48 (0.22)			
Černé (mid)	72.22 (5.95)	3.49 (3.41)	0.36 (0.27)			
Černé (high)	36.59 (21.66)	6.66 (6.17)	0.59 (0.08)			
Čertovo (low)		1.61 (1.35)	0.34 (0.06)			
Čertovo (mid)	90.19 (3.07)	4.08 (2.15)	0.98 (0.30)	1.40 (0.09)	12.63	32.41 (1.42)
Čertovo (high)	19.17 (3.27)	7.99 (5.81)	0.33 (0.15)			

^a low, mid, and high refer to elevations of 1000, 1050, 1100 m

^b standard errors for three replicate samples given in parentheses

^c TON – total organic nitrogen

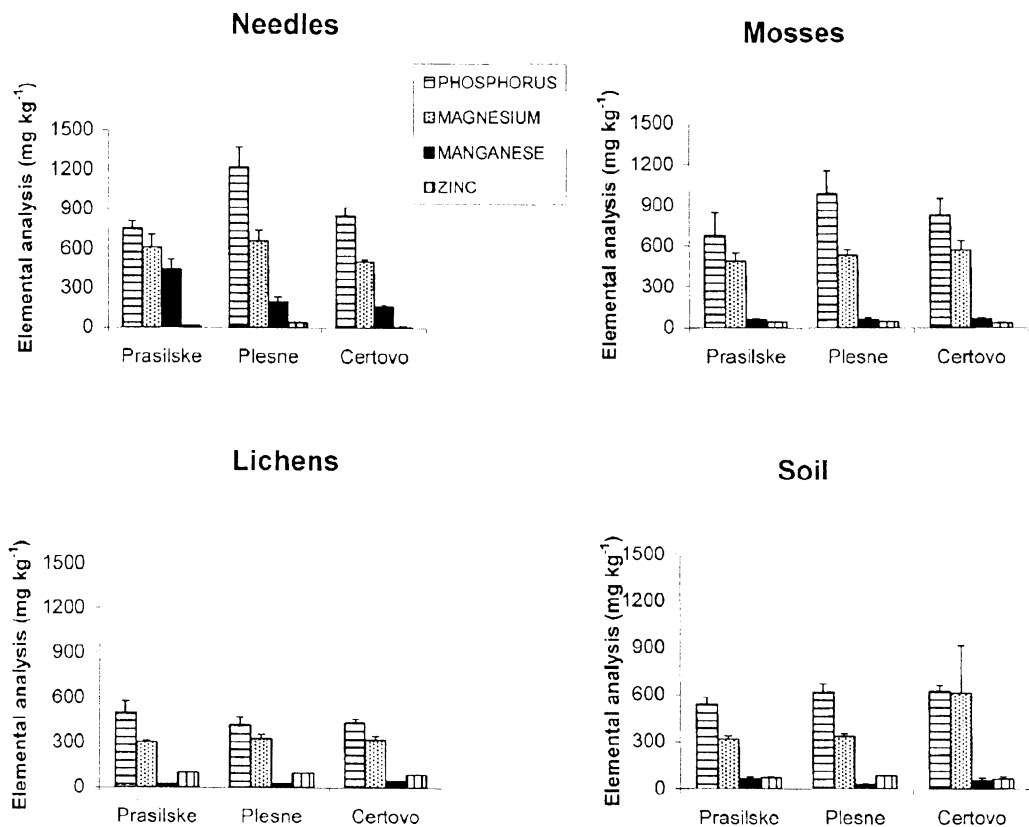


Fig. 1. – Elemental analyses of soils and vegetation – Bohemian Forest watersheds, CR (1997). Bars represent the means of triplicate samples of soils and vegetation; error bars are standard errors.

Particulate organic matter (POM) analysis

POM in the water column profiles of Čertovo, Prášílské, and Plešné was characterized for elemental composition by filtering (Gelman Supor, 0.45 μm) subsamples of the same water samples taken for analyses of dissolved gases in 1997. Filters were air dried and analyzed for total C and N and for $\delta^{15}\text{N}$ and ^{13}C with a VG Optima isotope ratio mass spectrometer (IRMS) coupled to a C:H:N elemental analyzer.

Results and Discussion

Soil bulk characteristics are shown in Table 1. Soils in all watersheds were organic rich; in Bohemian Forest watersheds organic content of soils was lowest at the highest elevation. Inorganic nitrogen content (KCl-extractable) of the soils was highest in the most disturbed of the Bohemian watersheds, Prášílské, which had undergone a beetle infestation several years prior to this study. At Prášílské most inorganic nitrogen was present as ammonium, whereas at Černé and Čertovo nitrate was more abundant.

Phosphate enrichment in Plešné Lake relative to Prášílské and Čertovo was reflected in the higher phosphorus content in both needles and in mosses sampled during 1997 in the Plešné watershed relative to other sites (Fig. 1). The bedrock of Prášílské, Čertovo, and Černé Lakes

is mica-schist (muscovite gneiss) with quartzite intrusions, while the bedrock of Plešné lake is composed of coarse-grain granites (VESELÝ 1994); more phosphate is leached out of granites than from mica-schist (KOPÁČEK & al. 1998).

In order to try to distinguish industrial sources vs. agricultural sources of nitrogen to watersheds, we compared isotopic ^{15}N signatures in soils, mosses, lichens (none present in Brenna), and needles sampled at a site in Brenna Poland, impacted by heavy industrial activity with samples from the Bohemian Forest watersheds. Results of isotopic analyses are shown in Fig. 2. Samples from the Czech Republic generally clustered together and were distinct from samples collected in Poland. Both soils and vegetation from Bohemian samples were more depleted in ^{15}N than samples from Poland. These results suggest that sources of nitrogen and carbon to watersheds in the Bohemian Forest are different from those in Poland. The isotopic values indicate that volatilized ammonia from agriculture or feedlots, which tends to be more depleted in nitrogen than samples from industrial sources (KREITLER 1975, MACKO & OSTROM 1994), may be a more important source of nitrogen to watersheds in the Czech Republic whereas coal burning or other fossil fuel combustion may be the more important source to watersheds in Brenna Poland.

During both 1997 and 1998 gross nitrogen mineralization was measured in soils from two watersheds in Brenna Poland and four watersheds in the Bohemian Forest. All soils were incubated in situ with water added so that soil moisture was at field capacity. Results are shown in Table 2. Soil temperatures during our 1997 study were 16–18°C, whereas during 1998 they averaged 9°C. Rates of gross N mineralization were highest at the most disturbed site, Prášílské. This is to be expected since sources of easily decomposable organic matter would be more available at Prášílské than at other sites. In 1998 soils at Černé demonstrated the highest rates of nitrification. Mean concentration of nitrate in surface waters of Lake Černé over the period 1986–1994 was higher in Černé than in Čertovo even though the lakes are very close geographically (on opposite sides of the same mountain) (VRBA & al. 1996).

Dissolved gas profiles measured in the Bohemian Forest lakes during 1997 and 1998 are shown in Fig. 3. Dissolved inorganic carbon (DIC) profiles reflect the integrated rate of net ecosystem metabolism in the hypolimnion since spring overturn. The higher DIC concentra-

Table 2. – Soil mineralization and nitrification (all units in $\mu\text{g N g soil}^{-1} \text{ d}^{-1}$).

Site	Gross mineralization	SE	Gross nitrification	SE	Net mineralization
Poland-Catch50 ^a	3.20	0.70	0.11	0.16	
Poland-Catch7 ^a	2.60	0.30	0.60	0.32	
Prášílské ^a	28.40	16.80	0.08	0.05	
Plešné-high ^a	8.70	0.30	0.46	0.11	
Plešné-high ^b	2.75	0.77	0.51	0.61	0.29
Čertovo-low ^b	3.40	0.40	1.02	0.34	0.04
Čertovo-mid ^b	4.56	1.29	0.00	0.65	0.12
Čertovo-high ^b	6.38	0.82	1.65	4.60	0.0
Černé-low ^b	3.52	0.61	2.19	1.22	0.01
Černé-high ^b	3.57	1.10	3.58	1.56	-0.02
Černé-mid ^b	5.30	1.93	3.08	2.40	-0.09

^a Soils incubated at 16–18°C, September 1997

^b Soils incubated at 9°C, September 1998 (see Table 1 for elevations)

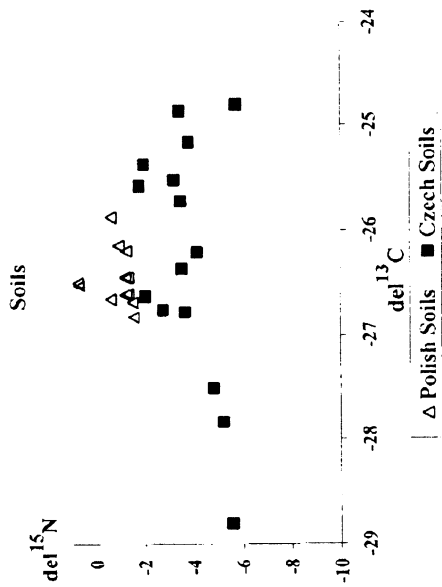
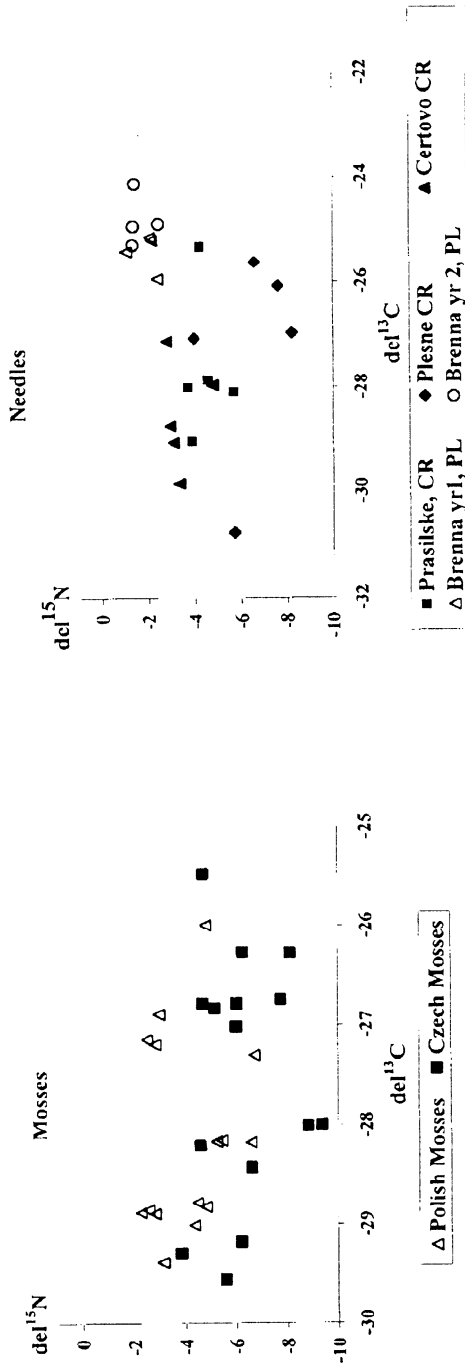


Fig. 2. – Isotopic signatures in soils and vegetation from Czech and Polish watersheds. Needles sampled in the Czech Republic were all from the 1-yr age class; Brenna Poland needles were sampled from both the 1-yr and 2-yr age classes.

tions observed in the hypolimnion of Prášilské, Plešné, and Čertovo Lakes relative to Černé suggest a higher rate of dissolved organic matter respiration than in Černé. This may reflect either the lower concentration of DOC in Černé relative to the other lakes as observed by KOPÁČEK & HEJZLAR (1998), or it may result from differences in the lability of the DOC present. Methane (CH_4) concentrations are highest when the lake water column is anaerobic, and anaerobic conditions result from high levels of organic carbon respiration. Methane producing bacteria consume organic carbon when dissolved oxygen and other potential electron acceptors are at low levels. Note that methane concentrations at depth in Černé were much lower than in the other lakes, reflecting the lower respiration rates in Černé relative to the other lakes. The presence of high concentrations of nitrous oxide (N_2O) in the hypolimnion of these stratified lakes where dissolved oxygen concentrations were low suggests that denitrification was occurring, thereby removing nitrate from the system. Highest concentrations of dissolved N_2O were observed in Prášilské Lake, most likely resulting from high rates of denitrification of inorganic nitrogen leached from watershed soils. Although peaks in N_2O occurred at Čertovo (below 30 m), and at Plešné (below 10 m), there was no peak observable in Černé Lake, suggesting that nitrate, although shown to be in high concentrations, was not being removed by denitrification. More work is required to understand why Černé and Čertovo Lakes behave so differently.

Particulates were filtered from the same water as sampled for dissolved gas analyses. Sampling depths in the water columns of Lakes Plešné, Prášilské, and Čertovo were as listed above. Particulates were analyzed for isotopic abundances of ^{15}N and ^{13}C (Fig. 4) and for organic carbon/total nitrogen molar ratios (Fig. 5). For the most part isotopic signatures of particulates from each lake clustered together suggesting that the sources of these particulates were different. The ^{13}C isotopic signature demonstrated sharp changes with depth in Lakes Plešné and Čertovo but not Prášilské. In the epilimnion the $\delta^{13}\text{C}$ signatures were more enriched and were similar to the $\delta^{13}\text{C}$ of particulates in the watersheds of these lakes. It is not clear why the $\delta^{13}\text{C}$ of Prášilské lake particulates was so different. KOPÁČEK & HEJZLAR (1998) observed lower inputs of soluble aluminum (Al) to Prášilské than to the other lakes. They also showed that within the lakes alkalinity generated by nitrate and sulfate reduction caused Al to precipitate as colloidal Al hydroxides which complexed with high molecular weight dissolved organic matter derived from watersheds.

In the hypolimnion of both Lakes Plešné and Čertovo the $\delta^{13}\text{C}$ signal was depleted relative to that in the epilimnion. This depleted signal may have resulted from low temperature (approx. 5°C) and slow growth rates below the thermocline. GOERICKE & al. (1994) reported that at temperatures below 5°C the $\delta^{13}\text{C}$ of POM in oceanic systems was depleted relative to that at higher temperatures. Close to the bottom the $\delta^{13}\text{C}$ of POM sharply increased in both Lakes Plešné and Čertovo. Increased enrichments of these ^{13}C signatures occurred at the same depths in which methanogenesis was shown to occur (Fig. 3). MACKO (unpubl. data) observed similar enrichments of POM in pure cultures of methanogens. Methane concentrations in Lake Plešné were much higher than in Lake Prášilské, perhaps explaining why POM in Prášilské did not show a similar increase in enrichment as that observed in the other lakes. An alternative explanation for the enrichment in ^{13}C in bottom waters is that it represents POM- Al complexes resuspended from the bottom sediments.

The enrichments of $\delta^{15}\text{N}$ in the epilimnion of Lakes Plešné, Prášilské, and Čertovo may have resulted from phytoplankton uptake of nitrate derived from atmospheric and watershed sources. In the hypolimnion the $\delta^{15}\text{N}$ signature in Lakes Prášilské and Čertovo became more depleted resulting perhaps from bacterial uptake of remineralized ammonium as has been observed by MACKO & al. (1987). The pattern of $\delta^{15}\text{N}$ signatures observed in Lake Plešné particulates is more complex and requires further investigation.

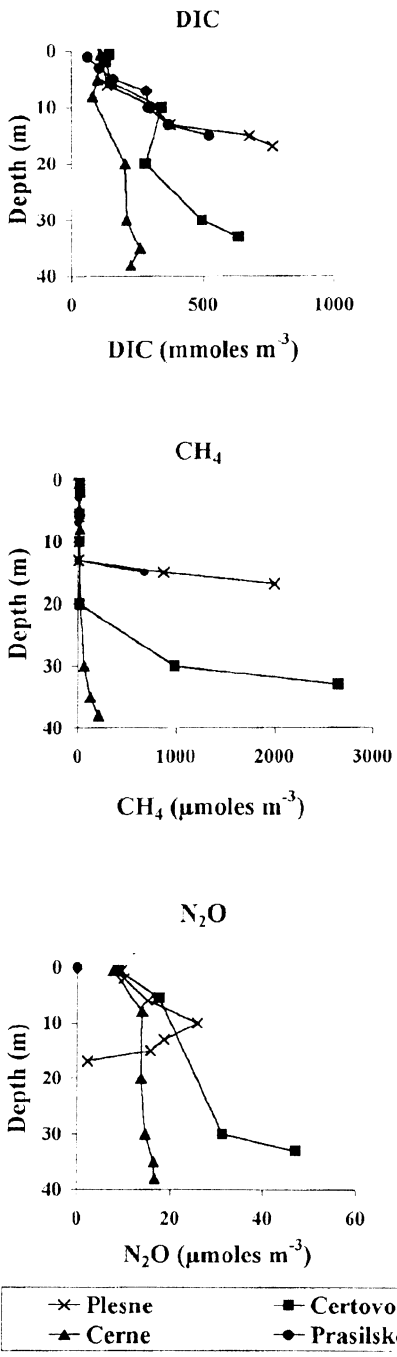


Fig. 3. – Dissolved gas profiles in Bohemian Forest lakes. Gas profiles in Prášilské Lake were performed in September, 1997; remaining profiles were performed in September, 1998.

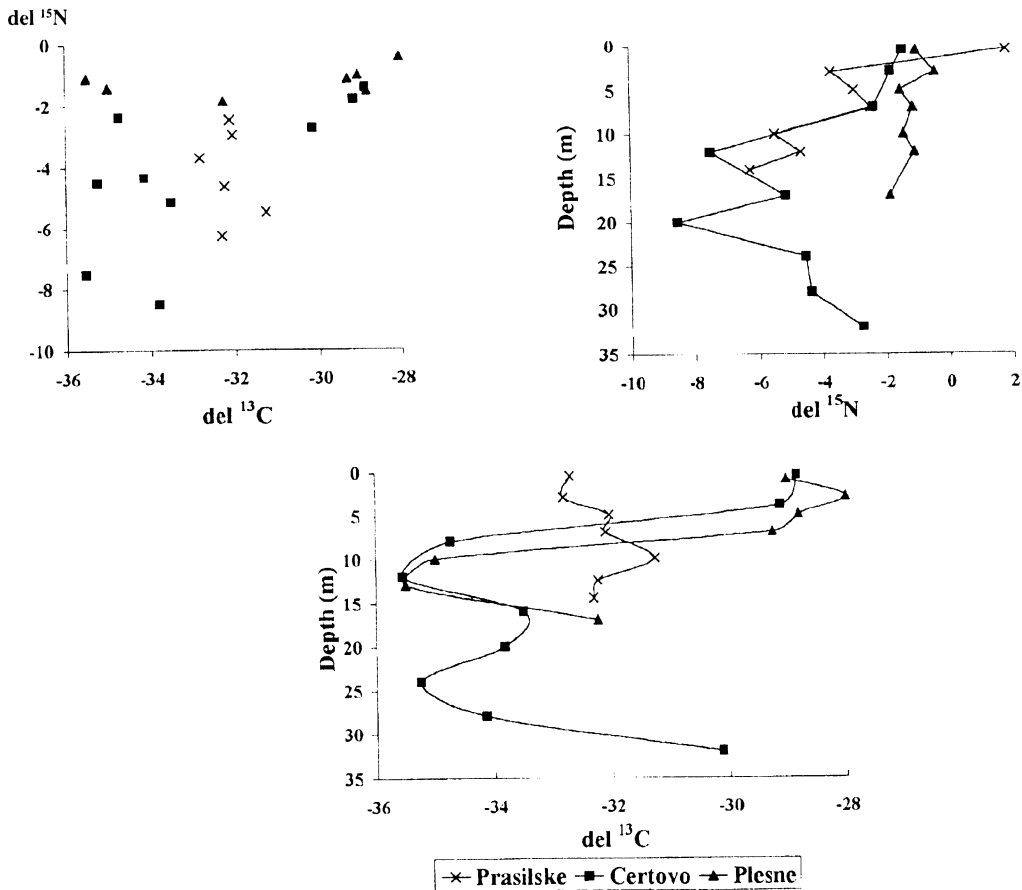


Fig. 4. – Isotopic signatures of suspended particulates in lake water columns.

In the epilimnion one would expect the C/N ratio of particulates to resemble phytoplankton with a molar ratio of 6.6. The high C/N ratios observed in all the lakes suggest that allochthonous particulates derived from the watershed were a significant component of the total particulates in the epilimnion. The molar C/N ratios were lowest for Plešné particulates and increased in the lower part of the hypolimnion. Phytoplankton biomass represented as chlorophyll *a* was at least 2-fold higher in Plešné than in the other lakes (VRBA & al. 1996). In Prášilské the C/N ratio rapidly increased with depth to a maximum at 10 m and then decreased with increased depth. In Čertovo particulates had relatively high C/N ratios throughout the water column. These data can be explained by a scenario in which phytoplankton with a low C/N ratio in the epilimnion is decomposed and the DOM respired leaving behind a more recalcitrant fraction of particulates derived from watershed sources and with a higher C/N ratio. We, therefore, speculate that the watershed is a likely source of much of the carbon observed in water column particulates in the Bohemian Forest lakes. The mechanism of transfer of carbon from the watershed to lake particulates is not known and may occur by direct transfer of particulates or by precipitation or bacterial uptake of DOC leached from the watershed.

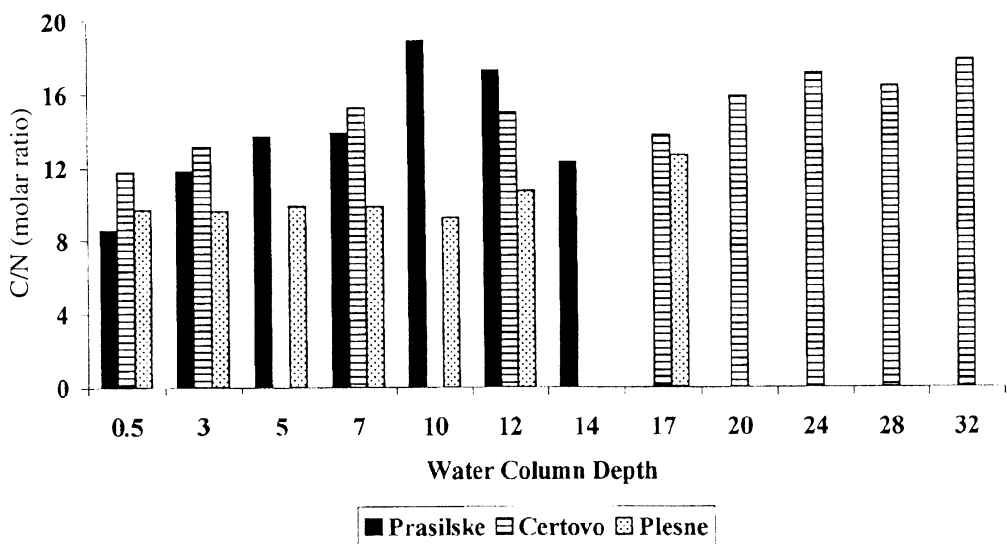


Fig. 5. – Particulate carbon/nitrogen in Bohemian Forest lakes.

Conclusions

The results presented above suggest that likely causes of the hysteresis in recovery of Bohemian Forest lakes from nitrogen saturation are:

1) Continued mineralization of soil organic nitrogen in the watershed. Disturbance may increase mineralization of organic nitrogen. This was observed in the Prášílské watershed, which had suffered storm damage followed by a beetle infestation several years prior to this study. Of the watersheds studied, Prášílské soils had the highest measured rates of gross nitrogen mineralization (Table 2). Production of inorganic nitrogen by mineralization may have been coupled to nitrification, producing nitrate, which can readily be leached from soils to lakes in surface water runoff and groundwater.

2) As atmospheric nitrogen deposition derived from fossil fuel combustion has declined (KOPÁČEK & al. 1997), more localized sources, including agriculture or animal husbandry may have become more important. The nitrogen found in Bohemian Forest soils and vegetation (Fig. 2) was more highly depleted in ^{15}N than was nitrogen from watershed soils and vegetation located in Brenna, Poland, which is close to a heavily industrialized area. One possible source of depleted nitrogen was ammonia volatilized from animal feed lots. Although speculative, volatilized ammonia is a well-known, isotopically depleted substance in the atmosphere. Further study is required to understand how sources of nitrogen to watersheds vary both on short time scales (seasonal) and over longer annual to decadal time scales.

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