Role of hedgerows as nitrogen sink in agricultural landscape of Wensleydale, Northern England

Živé ploty v zemědělské krajině Wensleydale (severní Anglie) jako propad emisí dusíku

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Purification role of hedgerows was assessed in nitrogen-polluted agricultural landscape of Wensleydale (North Yorkshire, United Kingdom). Air chemistry was greatly influenced here by a pig farm producing ammonia. It was found that hedges change the rainfall chemism and act as biofilters at landscape level. Their efficiency depends on their pattern within the territory and their structural parameters.

Keywords: Acid precipitation, atmospheric deposition, nitrogen compounds, throughfall, hedgerows, biofilters, ecotechnology

Introduction

Dry and wet deposition of nitrogen play an important role in vitality decrease of plants and biodiversity decrease in plant communities (e.g., Roelofs et al. 1987). Besides natural sources, atmospheric nitrogen compounds originate from industry and road-traffic (NO_x) and intensive husbandry (NH_x) – Ivens et al. (1988). In some European areas (e.g. Netherlands, Czech Republic), extremely large amounts of ammonia are emitted by agricultural sources (hundreds of kg/ha per annum). The contribution of ammonia to the total acid deposition has been frequently studied in grasslands and woodlands (e.g. Goulding et al. 1987). Data on nitrogen transport over hedgerows in agricultural landscapes are very rare. That is why we studied their role in rainfall chemism changes as rainwater passes through the hedges and changes for throughfall water.

The main aim of this part of the study was to investigate (a) the influence of ammonia emission on the properties of water that reaches the soil under the hedge vegetation structure, and (b) the spatial and temporal variability of the nitrogen deposition in hedgerows surrounding a point source of emissions.

Description of the field study area

Criteria for selection of the field site are described by Ineson (1991). Establishment of the study area has considered the previous investigation of air chemistry and throughfall enrichment around the agricultural point source of ammonia pollution in a valley in North

Yorkshire (Wensleydale, Fleets Farm near East Witton). Air chemistry in the area is dominated by ammonia, and the forests down-wind the point source (a pig farm) show a marked enrichment in throughfall concentrations and fluxes of ammonium. The synergetic co-deposition of sulphate onto forest canopies in the locality has been confirmed (Kennedy-Skipton 1992). The pig farm is located in the river Ure niveau, 100 m above the sea level. The sides of the valley rise up to 180 m a.s.l. (over 200 m a.s.l. on the south). The orientation of the valley is approx. W-E, and the prevailing winds follow also this direction. The landscape is used mainly for combined agriculture; the bottom of the valley and the declining terrains are used as sheep pastures and forests (with *Picea abies* and *Pinus sylvestris*). Traditionally present linear features are hawthorn hedgerows. The dominant *Crataegus monogyna* is intermingled with other scattered woody species, the most frequent among them being *Sambucus nigra*, see Table 3. The soils are greatly influenced by glacial drift; brown soils prevail. Geology of the bedrock is changing on the cross-section of the valley: below the upper portion sandstones and conglomerates prevail (Thomson 1992).

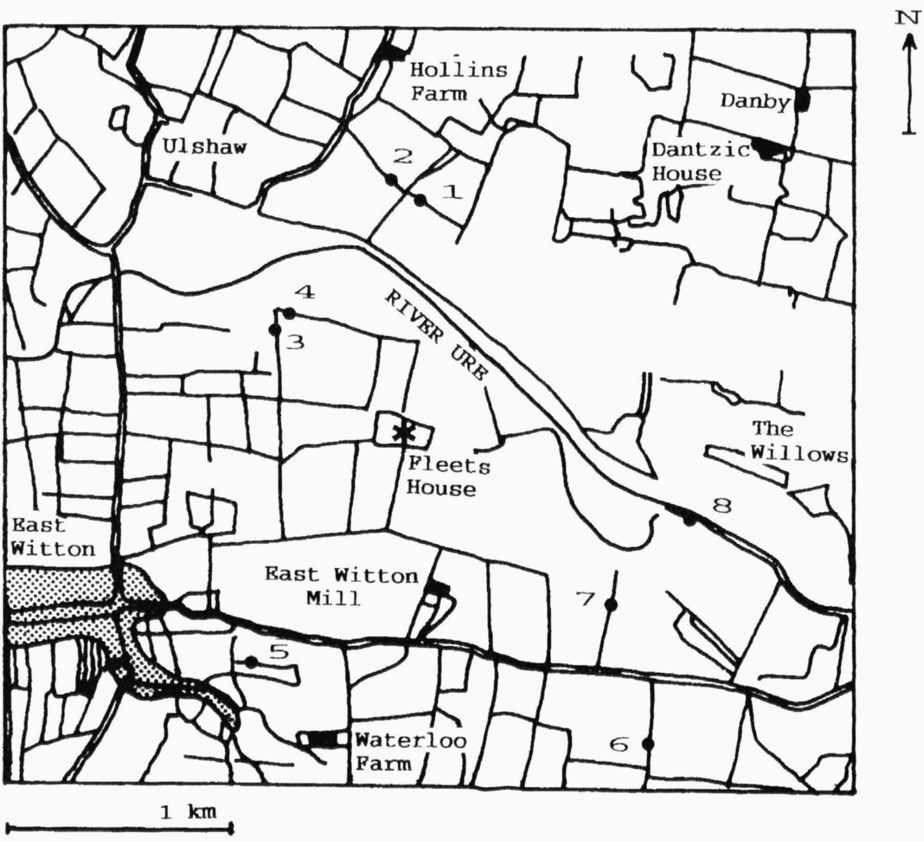

Fig. 1. – Map showing the location of the source of N pollution (pig farm of Fleets House marked by the asterisk) in the middle, and of the measuring sites (Nos. 1–8) around. The hedge network is clearly seen (full lines).

Table 1. – Data on measuring sites (hedgerows) in Wensleydale. Exposure to wind: crosswise -, lenghtwise + to the wind direction. Orientation of the hedge was considered with respect to the farm: crosswise +, lenghtwise -. Neighbourhood: field -, pasture +. Leaf biomass (kg) and area (m^2) are given per 5 m of the hedge length. Water for measuring pH was collected at the hedge top and bottom. Chemical characteristics represent averages of four values.

Site	1	2	3	4	5	6	7	8
Orientation	N	N	NWW	NWW	SSW	SSE	SEE	E
Distance from the farm	700	700	500	500	800	1100	700	800
Exposure to wind	-	-	-	-	-	+	+	+
Orientation of the hedge	+	+	+	-	+	-	+	-
Hedge trimming	-	+	+	+	-	+	+	+
Neighbourhood	+/-	+/-	-/-	-/-	+/+	+/+	+/+	+/+
Number of species	8	5	6	5	11	13	6	13
Hedge width (cm)	300	80	100	100	300	65	80	80
Hedge height (cm)	450	120	130	130	450	210	130	150
Leaf layer thickness (cm)	300	45	45	45	300	100	40	55
Leaf biomass (kg)	48.0	5.22	7.18	7.18	48.0	7.83	4.18	6.26
Leaf area (m^2)	740	65.8	90.5	90.5	740	98.7	52.9	79.0
pH – hedge top	4.79	4.79	4.87	4.87	4.87	4.87	4.99	4.99
pH – hedge bottom	7.08	6.69	6.76	6.92	7.01	6.47	6.60	6.88
NH_4/NO_3 – hedge top	1.21	1.21	1.00	1.00	1.00	1.08	1.16	1.16
NH_4/NO_3 – hedge bottom	1.67	1.19	2.34	1.46	3.87	1.51	2.88	1.38

Methods

Eight measuring sites were chosen within the hedgerows in different distances and directions from the farm (Fig. 1). The following parameters were assessed for each site (Table 1): hedge trimmed/non-trimmed (the hedges were always composed of *Crataegus monogyna*; other woody species were sporadically present: *Sambucus nigra, Fraxinus excelsior, Ulmus scabra, Acer pseudoplatanus, Prunus spinosa, Corylus avellana*); distance from the farm, orientation (within quadrants), location with respect to the farm from the point of view of prevailing winds, exposure of the hedgerows to the prevailing winds (transversely or lengthwise) and to the farm, hedge width, hedge height, thickness of the leaf layer (canopy), biomass and leaf area per 5 m of the hedge length, neighbouring field/pasture.

Four gauges (6 cm in diameter and 8 cm high) were set up at each site at the hedge bottom, under the hedge canopy on the soil surface, in the first half of June. In each of the four quadrants, a set of the same gauges was fixed at the hedge top level, under the open sky. The retained water samples of rainfall and throughfall were collected weekly (in case that precipitation was present). Out of the total 7 measuring intervals, 4 yielded water samples during the time of monitoring from June 12 to August 8). The water samples were analyzed for pH and the two forms of nitrogen, NH_4-N and NO_3-N, using automated simultaneous colorimetry (auto analyzer). Nitrate (plus nitrite) was reduced to nitrite by alkaline solution of hydrazine sulphate with copper as catalyst. With sulphanilamide and naphthyl-ethylendiamine dihydrochloride, it produced a dye which was measured colorimetrically. Ammonium was analyzed using the sensitive sodium salicylate – hypochlorite method with nitroprusside as catalyst (Gentry et Willis 1988).

Notched box-and-whisker plot (Figs. 3–8) give the following information: The central box encloses, between the upper and the lower quartile, the middle 50 % of the data values with median in the middle. The "whiskers" extend within 1.5 interquartile ranges from the quartile. Outstanding data values are plotted as separate points. Notches correspond to 95 % confidence interval for the median, and the width of each box is proportional to the square root of the number of observations. Pairwise comparisons is performed by examining whether the two particular notches overlap. Two data sets are supposed to be significantly different if their confidence intervals do not overlap. As few as six figures of this type were selected (Figs. 3–8); the remaining ones were presented only as a brief comment, if needed.

Leaf samples of the species composing hedges (apart from sites 1–8) as listed above were collected from a hedge volume of 20 × 20 × 40 cm (i.e. 0.016 m^3) for rough estimates of biomass, leaf area, and pH, NO_3-N and NH_4-N concentrations in the fresh leaf samples crushed with deionized water (10.0 g of fresh mass plus 100 ml deionized water, mixed; pH measured immediately and the two forms of N after filtration).

Results and discussion

Fig. 1 presents a map showing the location of the source of pollution (a pig farm) in the centre, and the measuring sites bearing numbers (corresponding with numbers in other figures and tables, Table 1). Sites Nos. 1 and 2 north from the farm lie close together, both hedges are equally oriented and possess also similar parameters. The main difference between them is the trimming: No. 1 is a non-trimmed hedge with *Sambucus nigra* and *Prunus spinosa*, while No. 2 is a trimmed hedge (formed by *Crataegus monogyna*). Sites Nos. 3 and 4 are in the greatest proximity to the farm and at the lowest position in the alluvium, with nearly equal parameters of the hedges; the main difference between them is in orientation (they lie crosswise each other). Site No. 5 is also in the W quadrant, more towards the south, and higher from the bottom of the niveau. It is one of the non-trimmed hedges (comparable to No. 1). Site No. 6 is the most distant one, on the SE slope. Sites Nos. 7 and 8 lie in the river niveau, in the E quadrant, as counterparts to Nos. 3 and 4.

The primary data on the two forms of N are plotted for all the hedge sites in Fig. 2 (both the input: hedge top and the output: hedge bottom values). It is not only the course of concentrations of NH_4-N and NO_3-N in the rainwater and throughfall water plotted against time, but also their ratios both for rainfall and throughfall, offering information on changes of water quality under the influence of the hedge (numbers in brackets show the number of measurements from which the average value was calculated).

The pH ratio is also presented for both the rainfall and throughfall, for each site. The relative distance, direction and orientation of the hedge is shown for each site as well as the proportional schemes for every hedge (which was non-trimmed in two cases).

The most striking is the high concentration of NH_4-N in the throughfall water from the sites Nos. 5 and 7. It is also reflected in the high NH_4-N/NO_3-N ratios (3.87 and 2.88, opposite to the prevailing values around 1.0). It refers to the higher deposition of the N emissions on these sites (we can hypothesize that the interception was increased by the higher leaf volume of the non-trimmed hedge at the site No. 5, and by the relative proximity of the farm at the site No. 7). In general, all the sites from the S and E quadrants show somewhat higher values of N retained, and also higher fluctuation of values which suggest greater impact of the meteorological characteristics (precipitation, wind, location of the

Table 2. – Significance of differences between samplings, quadrants and sites in the respective characteristics (pH, NH_4-N, NO_3-N and the ratio of the latter two) of the rainfall (hedge top) and throughfall (hedge bottom) water and its ratio. Results of ANOVA: * $P < 0.05$, ** $P < 0.01$, x – not measured.

	Hedge top				Hedge bottom				Hedge bottom/top			
	pH	NH_4-N	NO_3-N	NH_4/NO_3	pH	NH_4-N	NO_3-N	NH_4/NO_3	pH	NH_4-N	NO_3-N	NH_4/NO_3
Sampling	**	**	**	**	**	**	**	**	**	**	**	**
Quadrant	*	*	*	*	*	**	*	**	*	**	**	
Site	x	x	x	x	**	**	**	**	**	**	**	**

source of pollution) on them – configuration of the river valley, its exposure and orientation support this view.

Comparison of the input (hedge-top) concentration values

Differences were noted among the data sets from the particular sampling dates (June 1–30, July 2–7, 3–14, 4–21), for the NH_4-N values and, adequately, for the NO_3-N values (Fig. 2, see also Table 2). In both cases, higher values were measured on the first sampling date than on the three remaining ones. In spite of the similarity of data arrangement in time for both NH_4-N and NO_3-N input values, the picture changes when the ratios of NH_4-N and NO_3-N are compared. By far the greatest values of significance are found at the third sampling which means that there was a prevailing proportion of ammonium-N compared to the nitrate-N (Fig. 2 also suggests that after the dry period before the first sampling, when high values of the two nitrogen forms were measured, there was a higher proportion of nitrate-N, presumably from dry deposition, cf. Hicks 1989). The input pH data are limited due to the low amounts of water sampled; anyway, the available averages for the particular sampling dates are as follows: 1. – 3.69, 2. – 4.86, 3. – 4.98, 4. – 4.89. The very low pH on the first sampling date could be influenced with numerous factors – apart from a high NO_3-N level, also with sulphur ions (see Kennedy-Skipton 1992).

Comparison of the output (hedge/bottom) concentration values

Fig. 2 shows that the concentration values for NH_4-N at the output – after the rainwater had passed through the hedge canopy – are generally higher than the input values of rainfall. Rainfall chemistry is strongly episodic (Unsworth et Fowler 1987). This could suggest that the hedge structure cummulated immissions of N that were leached out during rainy episodes (analogically, the forest floor is considered the largest pool of nitrogen within forest ecosystems – e.g., Driscoll et Schaefer 1989). Our trimmed hedges were composed of old plants with slow growth rate (hawthorn, *Crataegus monogyna*) which implies that plant absorption and utilization of NH_4-N was relatively low and transport from the leaf surface to the soil was the leading mechanism of the N-movement (cf. Reisenauer 1978). Fig. 3 gives comparison in rainfall NH_4-N concentration for all the eight sites sampled. Site No. 7 yielded the highest values. It is the site closest to the polluting source in the eastern quadrant, i.e. in the direction of the prevailing winds that

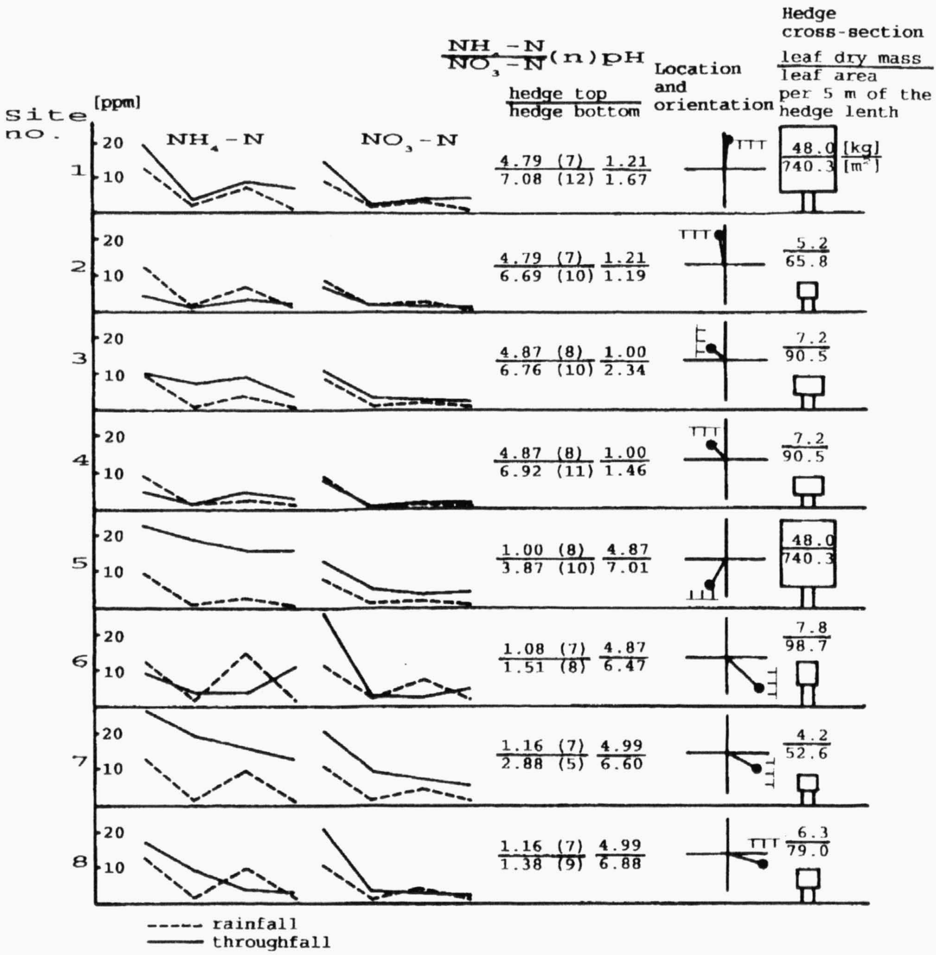

Fig. 2. – NH_4-N, NO_3-N, their ratios, and pH measured in rainfall and throughfall at eight measuring sites (hedges) and four sampling dates. Location and orientation with respect to the pig farm is given, as well as the schematical cross-section of the hedge, its leaf dry mass and leaf area

are drawn within the slightly bending valley of the Ure river towards SE. Another significant increase show sites Nos. 1 and 5 and the following explanation is available here: these are the only two non-trimmed hedges with a voluminous leaf layer with high leaf surface per unit area, through which the rainwater has to pass through and leach out the deposit on the leaf surface.

When the sampling data sets for ammonium-N were compared, only the first sampling showed higher values but the difference was not so great as for inputs. The buffering effect of the vegetation canopy is obvious.

The comparison of nitrate-N (Fig. 4) is analogous; the only one difference (reciprocal and negligible) was between the sites No. 5 and 6. Similar results were also obtained by comparison of the sampling dates. In general, variability of nitrate-N within the data sets was lower than that of ammonium-N.

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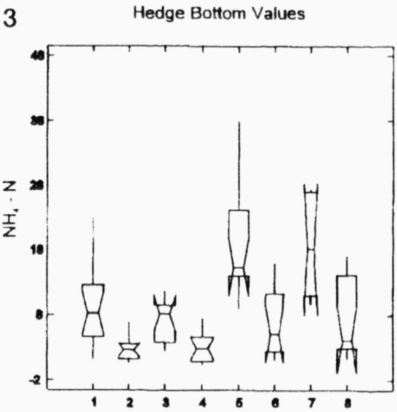

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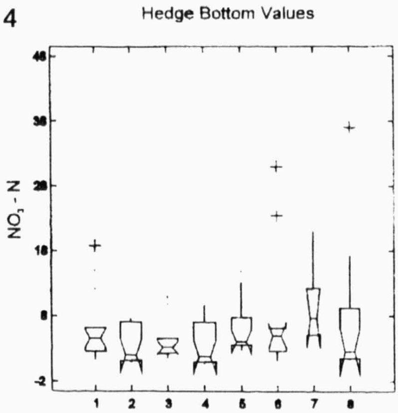

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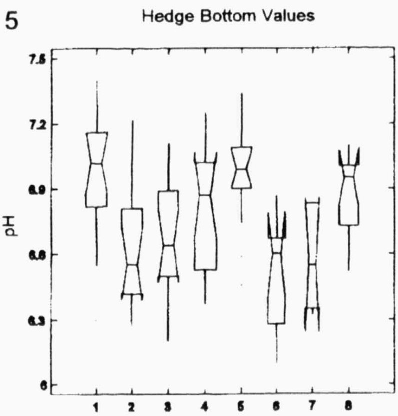

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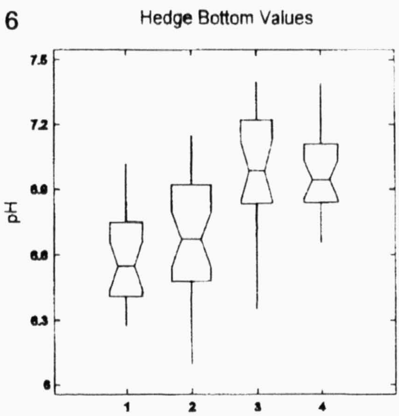

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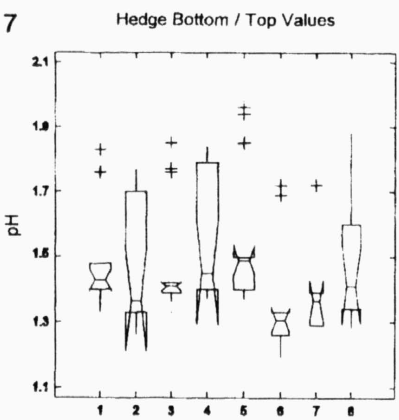

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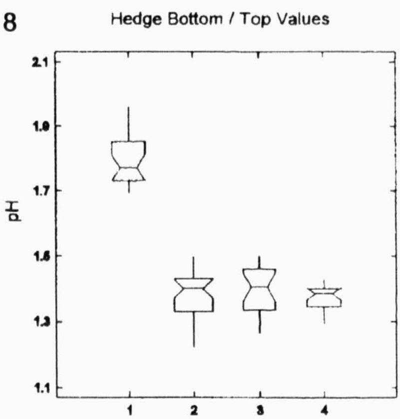

Fig. 3.–8. – Notched box-and-whisker plots comparing the partial data sets including their variability (for more detailed description see the Methods). Abscissa in Figs. 3, 4, 5 and 7 presents sampling sites and in Figs. 6 and 8 sampling dates.

The pH data (Figs. 5 and 6) complete the information supplied by N concentrations values. The consistently lowest pH values with low variability were measured at the site No. 7 (close to the source, in the direction of the prevailing winds), Fig. 5. The highest pH output values were measured under the two non-trimmed hedges (Nos. 1 and 5) where high retention capacity could be expected (dry deposition). Another possibility of explanation demanding further testing (see below, and Table 3) is the occasional presence of *Sambucus nigra* in these two hedges. The fast metabolism and supposedly higher nutrient (bases) ammounts leached from the leaf canopy might have influenced the resulting pH.

Comparison of pH between the sampling dates (Fig. 6) shows difference of higher significance between the first two and the second two sampling dates (by approx. 0.5 unit) which could coincide with the longer dry period before the first sampling date and with the intensity of rainwater leaching, approximately in the middle of the overall sampling period.

Comparison of the relative (hedge bottom/top) concentration values

Both forms of N, NH_4-N either in space and in time and NO_3-N in space and time showed a similar scheme of the ratios bottom/top (Table 2). When the stands were compared, the bottom/top ratio was greatest for Nos. 5 and 7, i.e. at completely different parameters (non-trimmed and trimmed hedge, SW and E orientation related to the source).

Differences between the sampling dates were not much distinct; however, an indication of a "cummulative" trend within time appears, i.e. increase of the bottom/top ratios.

The greatest output/input pH difference occurs in the two non-trimmed hedges (Nos. 1 and 5), but also in the hedge close to the farm (site 4), Fig. 7. The smallest difference was for the site No. 6, a hedge trimmed and influenced by an intense pasture, not far from the farm, towards the east (while the change of NH_4-N and NO_3-N is the greatest here, see the above comments).

The greatest difference with respect to the other sampling dates shows the first data set (Fig. 8), where the average pH was increased by 1.8 (while in other cases only by 1.4). Buffering capacity of hedges against acidification is very distinct.

Comparison of the input (hedge top) and output (hedge bottom) total amounts of the two forms of N

The absolute N values sampled in the rain and throughfall water (both for NO_3-N and NH_4-N) are plotted for all eight sites and for the four sampling dates (Fig. 9). Both forms of N in rainfall (hedge top) are shown above, and in throughfall (hedge bottom) below the abscissa. It is evident that the variability within the rainfall amounts of N (in mg/m^2) is very low. Variability of the throughfall values is, on the other hand, quite high (in one case – sampling on 14 July, site No. 7 – data are lacking since the collectors were destroyed by cows).

These results support the evidence from the analysis of the relative values (concentrations) of N sampled (see the previous text); however, they give the finishing touches to the whole picture and are even surprising in some cases. Thus, maximum values of

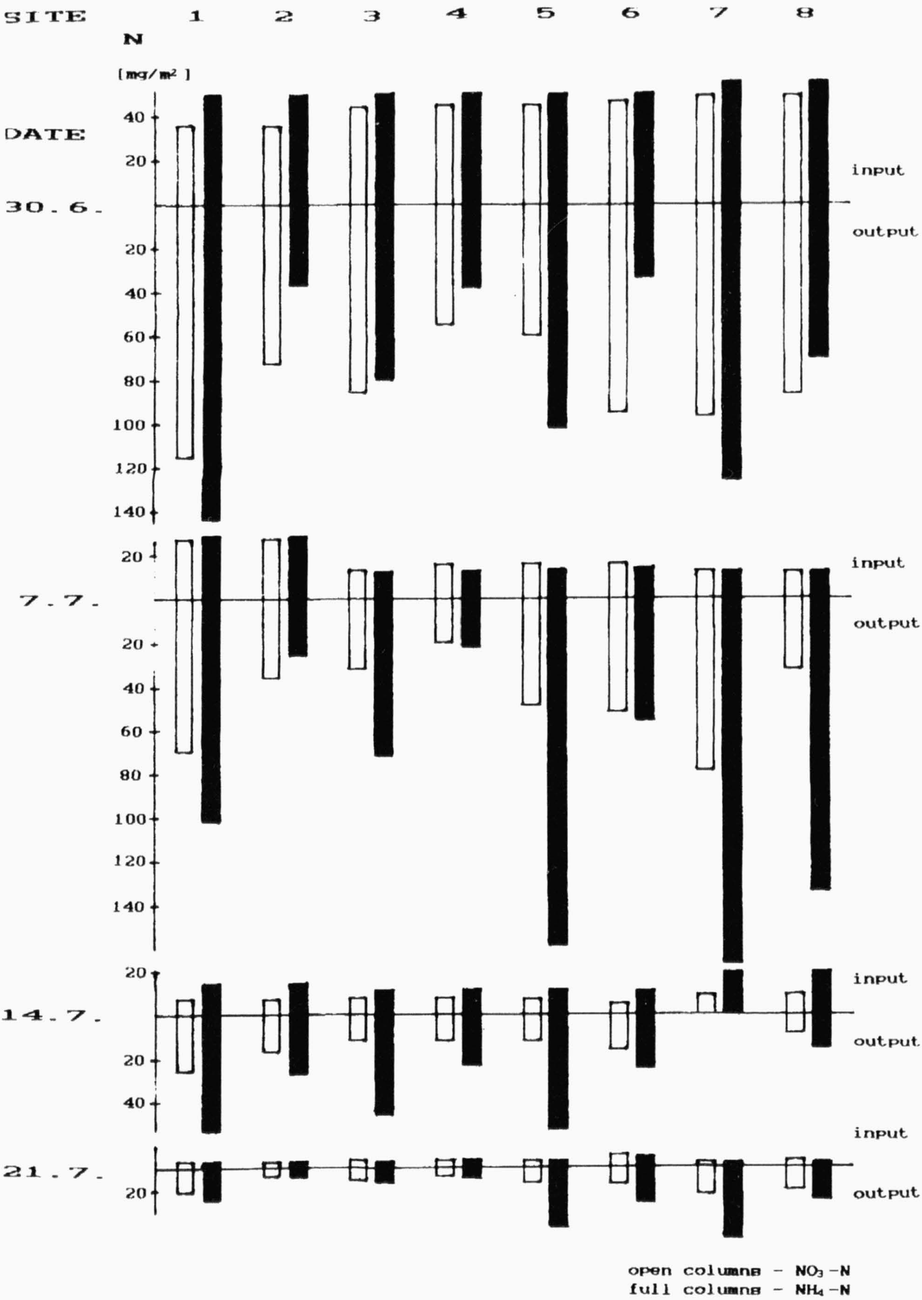

Fig. 9. – Absolute values of NH_4-N and NO_3-N for all eight sites and the four sampling dates

throughfall in sites Nos. 1 and 5 (non-trimmed hedges) and No. 7 (downwind trimmed hedge close to the farm, in E direction) are followed by those of No. 8 (downwind, trimmed), and are in agreement with the up-to-now conclusions. It is interesting to compare the sites Nos. 3 and 4 (in the W quadrant) which differ only in orientation. No. 3 is a hedge lying crosswise to the wind while No. 4 is oriented to the wind lenghtwise. This could perhaps explain the increased amounts of N, especially NH_4-N, in the throughfall from the site No. 3 hedge which is more efficient in rainwater interception due to its orientation. Opposite to it, site No. 4 hedge was even lower in throughfall NH_4-N than in rainfall NH_4-N at the first sampling date.

Overall trend from the first to the last sampling date shows a remarkable decrease in amounts, relatively higher in throughfall (the last two sampling dates). In this context, it is necessary to notice a factor not mentioned yet – the effect of bird excrements spotted over hedge branches, as the source of N. Apart from that, caterpillars were also present (small eggar – *Eriogaster lanestris*) in huge amounts on the hawthorn. This factor could have influenced the first two sampling values before becoming pupae, and shortly afterwards, till the beginning of July.

The values of ammonium N measured here are in agreement with other data from this area (Ineson 1991, Thomson 1992, Kennedy-Skipton 1992). They vary in rainfall from several units to tens (maximum nearly 60 mg/m^2) on the first sampling date while the amounts in throughfall reach about hundreds of mg/m^2, especially on the first two sampling dates. It seems that while there is a negative relationship in forest stands between the throughfall ammonium N and the canopy coverage (Ivens et al. 1988, Kennedy-Skipton 1992), the hedge data suggest an opposite relation.

Comparison of N concentration and pH in leaf biomass of the hedge woody species

From Table 3, it is obvious that one species, *Sambucus nigra*, largely exceeds the values of pH and both the ammonium and nitrate N measured in the leaves of other woody species. This is an evidence for the hypothesis that the foliage nutrients leached out of this species contributed to the increased amounts of N measured in throughfall water samples under the hedge where elder was present (see site 1, Fig. 5, increased throughfall pH values).

Sambucus nigra is known as a species of ruderal strategy (Grime 1979): it is one of the dominants of the alliance *Sambuco-Salicion capreae* Tüxen et Neumann in Tüxen 1950. Its communities frequently occupy abandoned sites, covering ruins of buildings and walls on substrates rich in nutrients.

According to Chapin (1980, 1983), species could be divided basically into two groups considering their physiology: (1) those of ruderal-type, possessing high relative growth rate, high growth response to nutrient addition, higher efficiency of nutrient use; also the nutrient losses from the ecosystems formed by these species are greater, due to a higher rate of nutrient cycling, than the losses from the ecosystems formed by (2) plants with low relative growth rate, low efficiency of nutrient use, low growth response to nutrient addition, luxury consumption, mycorrhizal association, better survival at nutrient stress, the prolonged life of shoots and roots, the synthesis of anti-herbivore defense compounds, the high translocation within plants. *Sambucus nigra* obviously belongs to the first group

Table 3. – Selected characteristics of the hedge species (the first three parameters relate to the analysis of the fresh crushed leaves). Mean values (n = 4) are shown. T – trimmed hedge, N – non-trimmed hedge

		pH	NH_4-N (ppm)	NO_3-N (ppm)	Leaf parameters per 1 m^3 of hegde volume	
					dry mass (g)	area (m^2)
Crataegus monogyna	T	5.73	5.3	4.2	2.61	32.9
Crataegus monogyna	N	5.85	5.5	1.4	1.08	16.5
Sambucus nigra	T	6.21	10.0	75.6	2.35	11.9
Fraxinus excelsior	T	5.98	7.5	3.2	3.17	38.9
Ulmus scabra	T	5.98	6.8	3.5	1.60	34.4
Corylus avellana	N	5.45	3.2	2.1	0.99	31.0
Prunus spinosa	T	4.76	7.0	1.8	0.94	16.6
Acer pseudoplatanus	T	4.29	5.7	2.2	1.67	19.7

of species with a fast nutrient turnover. Its relatively soft leaves also suggest to a higher nutrient leaching with rainwater than the firmer leaves of hawthorn.

Conclusions

Table 2 shows high significance of differences at 99 % probability level for both sampling dates (hedge-top, hedge-bottom, hedge bottom/top) and sites (hedge-bottom, hedge bottom/top). Equally high significance of differences for quadrants is only for NO_3-N and pH.

The overall area pattern of N flows is better illustrated when the two forms of N, both in rainfall and throughfall, are expressed in terms of absolute amounts per unit area. The high retention role of hedges is evident, especially of those with thick leaf canopy and those lying downwind and oriented crosswise to the wind. From the point of view of ecotechnology, hedges may be used as biofilters. The N values in the range of tens and hundreds of mg per m^2 of hedge cover area prevail. The amount of N which leaches down through the hedge to the soil surface is positively related with the coverage, quite opposite to the forest stands.

Concerning the high nitrate and ammonium N concentrations in elder leaves, we suggest that leaf nutrient leaching is the main factor influencing the elevated pH and N values in throughfall water samples collected at the bottom of the hedge where *Sambucus nigra* was a component species.

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Souhrn

Živé ploty hrají významnou filtrační roli v krajině zachycováním a zadržováním kyselých polutantů včetně sloučenin dusíku. Zároveň tak ve zkoumaném typu anglické zemědělské krajiny představují zásobník, v němž je dusík vázán. Změny v chemickém složení dešťové vody dopadající na povrch živého plotu a dešťové vody proteklé živým plotem charakterizují následující závislosti:

(1) Obecně, živý plot s dominantní dřevinou *Crataegus monogyna* významně pufruje kyselost srážek, jež byly ovlivněny dusíkem emitovaným z farmy pro chov vepřů (v průměru činí zvýšení 2 stupně pH).

(2) Živý plot mění poměr amoniakálního ku nitrátovému dusíku v dešťové vodě proteklé jeho větvovím a listovím v závislosti na rozmístění v území (depozičně nejúčinnější jsou ploty na východ od zdroje znečištění, tj. ve směru převládajícího větru) a v závislosti na mocnosti listového zápoje (dusík účinněji zachycují nestříhané živé ploty). Z hlediska ekotechnologie mohou živé ploty v krajině sloužit jako biofiltry vzdušného znečištění.

(3) *Sambucus nigra* (allochtonní komponenta živých plotů) silně ovlivňuje v úseku svého výskytu chemismus proteklé dešťové vody (pH a koncentrace amoniakálního a nitrátového dusíku v důsledku vyplavování živin z listů stoupá).

References

Chapin III F. S. (1980): The mineral nutrition of wild plants. – Ann. Rev. Ecol. Syst., Palo Alto, 11:233–260.

Chapin III F. S. (1983): Adaptation of selected trees and grasses to low availability of phosphorus. – Pl. Soil 72:283–287.

Driscoll C. T. et Schaefer D. A. (1989): Overview of nitrogen processes. The role of nitrogen in the acidification of soils and surface waters. – In: Malanchuk J. L. et Nilsson J. [red.], Proc. Internat. Workshop, Copenhagen, 3–4 October 1988, Miljorapport, p. 10, Stockholm.

Gentry C. E. et Willis R. B. (1988): Improved method for automated determination of ammonium in soil extracts. – Commun. Soil Sci. Pl. Anal. 19:721–737.

Goulding K. W. T., Johnston A. E. et Poulton P. R. (1987): The effect of atmospheric deposition, especially of nitrogen, on grassland and woodland at Rothamstead Experimental Station, England, measured over more than 100 years. – In: Mathy P. [red.], Air pollution and ecosystems. Proc. Int. Symp., Grenoble, 18–22 May 1987, p. 841–846, D. Reidel Publ. Company, Dordrecht.

Grime J. P. (1979): Plant strategies and vegetation processes. – John Wiley & Sons, Chichester.

Hicks B. B. (1989): Overview of deposition processes. The role of nitrogen in the acidification of soils and surface waters. – In: Malanchuk J. L. et Nilsson J. [red.], Proc. Internat. Workshop, Copenhagen, 3–4 October 1988, Miljorapport, 10, Stockholm.

Ineson P. (1991): The effects of air pollutants on the chemistry and biological activity of soils. – Ms. [Dept. Environm. Progress Report, ITE, Merlewood Res. Stn., Grange-over-Sands.]

Ivens W. P. M. F et al. (1988): Dutch forests as air pollutant sinks in agricultural areas. A case study in the central part of the Netherlands on the spatial and temporal variability of atmospheric deposition to forests. – Ms. [Dutch priority programme on acidification, Report 37–09.]

Kennedy-Skipton H. (1992): The codeposition of ammonia and sulphur dioxide: A case study. – Ms. [M.Sc. thesis, Lancaster University].

Reisenauer H. M. (1978): Absorption and utilization of ammonium nitrogen by plants. Nitrogen in the environment. – In: Nielsen D. R. et MacDonald J. G. [red.], Soil-plant-nitrogen relationships. Vol. 2, p. 157–170, Academic Press, New York..

Roelofs J. G. M., Boxman A. W. et van Dijk H. F. G. (1987): Effects of airborne ammonium on natural vegetation and forests. – In: Mathy P. [red.], Air pollution and ecosystems, Proc. Intern. Symp., Grenoble, 18–22 May 1987, p. 876–880, D. Reidel Publ. Company, Dordrecht.

Thomson P. (1992): Anthropogen verursachter Stickstoffeintrag in Waldökosysteme des Lower Wensleydale/ Nordengland. – Ms. [M.Sc. thesis, Tübingen University].

Unsworth M. H. et Fowler D. (1987): Deposition of pollutants on plants and soils; principles and pathways. – In: Mathy P. [red.], Air pollution and ecosystems, Proc. Intern. Symp., Grenoble, 18–22 May 1987, p. 68–84, D. Reidel Publ. Company, Dordrecht.

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