Atmospheric ammonium sulphate deposition and its role in the acidification and nitrogen enrichment of poorly buffered aquatic systems

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Introduction

Acidification of aquatic environments is one of the well-known phenomena linked to the problem of acid precipitation. The first effects of water acidification were indicated by changes in biota. Nowadays many chemical data show clearly that acid precipitation has contributed to the decrease of pH in many surface waters. Particularly in Norway, Sweden, Denmark, Scotland, Belgium and the Federal Republic of Germany it has been established that acidification has occurred over the last decades[10,26,29,30].

In the Netherlands, acidification of surface waters has been recognized only very recently. The first indications were changes in desmid[8] and diatom assemblages[9]. Although only few waters had been investigated, it became clear from that time that also in the Netherlands aquatic systems were affected by the deleterious influence of acidifying components resulting from atmospheric pollution. Particularly the hydrologically isolated waters (e.g. moorland pools) appeared to be very susceptible because of their total and direct dependence on rainwater. Besides, those waters are generally situated on pleistocene sandy soils, which are poor in carbonate and nutrients. As a consequence of this the water of the pools is poorly buffered and has very low nutrient concentrations. Roelofs[23] established, by comparing historical data on the macrophyte composition of 68 waters, that 78% of those waters had been acidified since 1950. Based on the historical and present occurrence of fish species in 54 similar pools, it can be concluded that more than 67% of them are acidified[17,18].

Figure 1 illustrates the pH of surface waters in the Netherlands during 1978–1984. It is clear that most of the acid waters are situated in the middle, southern and eastern part of the country. These observations correspond with the presence of soils susceptible to acidifying components (fig. 2). Particularly in these regions many waters, such as moorland pools, small lakes and streams, which were originally poorly buffered, appear to be acidified.

One of the problems with respect to the acidification of surface waters is to establish in what way and to what extent acid precipitation contributes. In general, and particularly for the Scandinavian countries, it is assumed that acidification is the result of increased deposition of

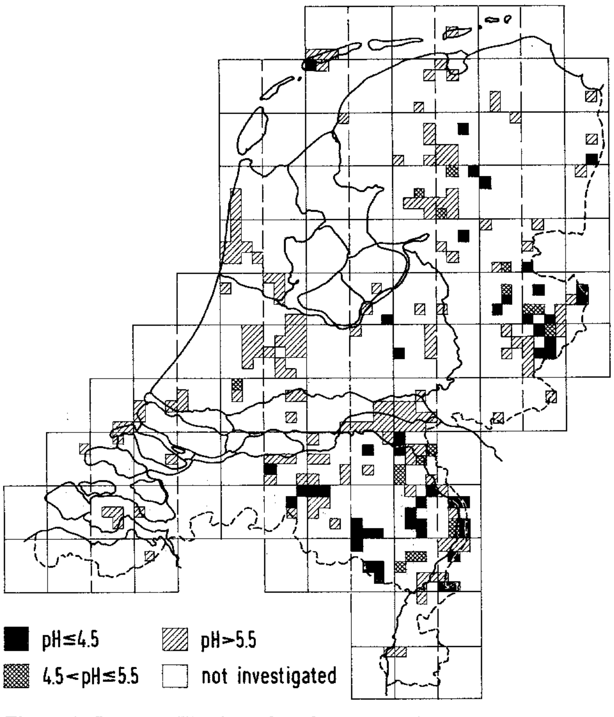

Figure 1. Lowest pH-value of surface waters in the Netherlands per square of 5 × 5 km^2 (period 1978–1984)[18].

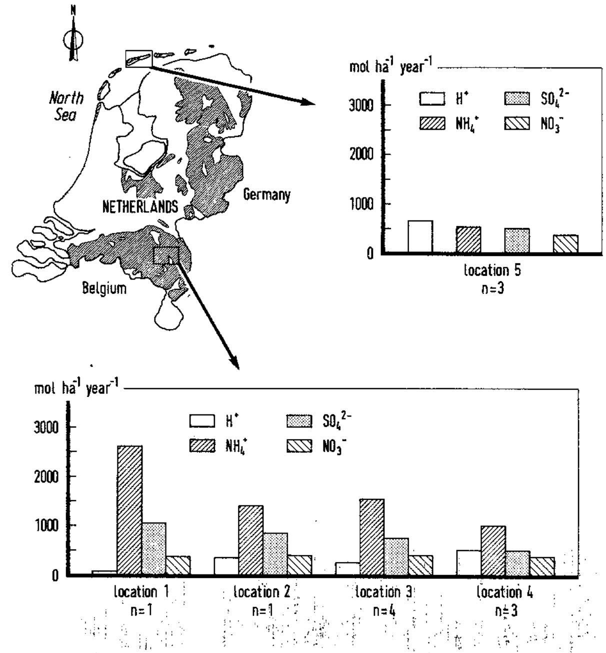

Figure 2. Wet deposition of acidifying components at different locations in the northern and southern part of the Netherlands. ▨ areas with soils susceptible to acidification. Location 1: 50 m from a poultry-breeding farm; location 2: 500 m from a concentration of breeding farms; location 3: nearby croplands loaded with manure slurry; location 4: at a distance of 2.5 km from stock-breeding activities; location 5: isle of Terschelling (seaside). n = number of sampling stations.

strong acids like sulphuric and nitric acid. According to Henriksen[15,16] the acidification of waters can be correlated with the excess of sulphate ions in rain water. In this way it has been established that sulphuric acid makes the major contribution to the decrease of alkalinity in surface waters[29,30]. In the rainwater of northern Britain and Norway there is a clear correlation between the H^+ concentration and the excess of sulphate ions. These data indicate an important contribution of sulphuric acid.[20,21]. Table 1 gives a survey of the rainwater composition and wet deposition in some northwestern European countries. These data show that rainwater composition in the Netherlands differs markedly from that of other countries. The concentrations of NH_4^+, SO_4^{2-} and NO_3^- are very high, while the mean H^+ concentration is relatively low. In this very densely industrialized area the high level of emission of sulphur and nitrogen oxides is responsible for the high concentrations of acidifying anions. The ammonium concentration appears to be enhanced by the large amount of ammonia released to the atmosphere from biological sources and fertilizers. On a national scale 70% of the emitted ammonia results from cattle manure on grassland[6]. Also in other European countries acid precipitation regularly contains large amounts of ammonium, and the ammonium concentration of wet deposition differs markedly between different locations[3,4,12,13]. Although ammonium is a recognized component of acid precipitation it is remarkable that only very little has been documented about its role as an acidifying component. The acidifying effect of precipitation is generally based on the deposition of strong acids such as sulphuric and nitric acid[4,15,16,28]. Only in the Netherlands has it been established recently that the airborne pollutant ammonium sulphate contributes to soil acidification[5,25]. Once ammonium compounds come into contact with sediment, the nitrification process will mobilize H^+ ions, according to the reaction; $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$. Because of the high level of deposition of ammonium sulphate in the Netherlands the acidifying effect of this component will be very important. Particularly in the eastern, middle and southern parts of the country the emission of ammonia is enhanced as a result of the high density of stock-breeding farms and strongly manured cropland. In the western part of the country, however, a very high emission of sulphur and nitrogen oxides occurs. As a consequence of this variation in the emission of air pollutants, the relative amount of each acidifying component in rainwater will vary from region to region. Because of the presence of susceptible and nowadays acidified aquatic systems in regions with a very high emission of ammonia it is plausible that this component has contributed to a large extent to the acidification process.

The effect of NH_3-emission on rainwater composition and the deposition of acidifying components

In intensively cultivated areas the application of nitrogen fertilizers far outweighs any effect from acid precipitation. Nitrification appears to be the most important source of H^+ input[4]. Farmers counter this acidifying action by adding lime to the croplands. Nowadays, in many countries, the production of animal manure is concentrated in areas with nutrient-poor agricultural soils. As a result of the overproduction of animal manure, most croplands are loaded with manure slurry. This manure, as well as poultry and pig farms are quantitatively the most important NH_3 sources[6,7]. The distribution of this nitrogen compound by atmospheric transport does not occur along very large distances and therefore the loading of susceptible natural environments is particularly a problem in areas where these NH_3 sources are present[1,6]. In order to study the effect of gaseous NH_3 emission on the wet deposition of acidifying components, rainwater was sampled at different locations in the Netherlands (fig. 2). The pH of the rainwater differs markedly from location to location (fig. 3). At location 5, an area relatively unaffected by NH_3, 65% of the pH-values are between 4.0 and 5.0. Close to a breeding farm (location 1), however, 75% of the pH-measurements are between 5.0 and 7.0. These data clearly show the action of NH_3 compounds as a base. The dissolution of ammonia in

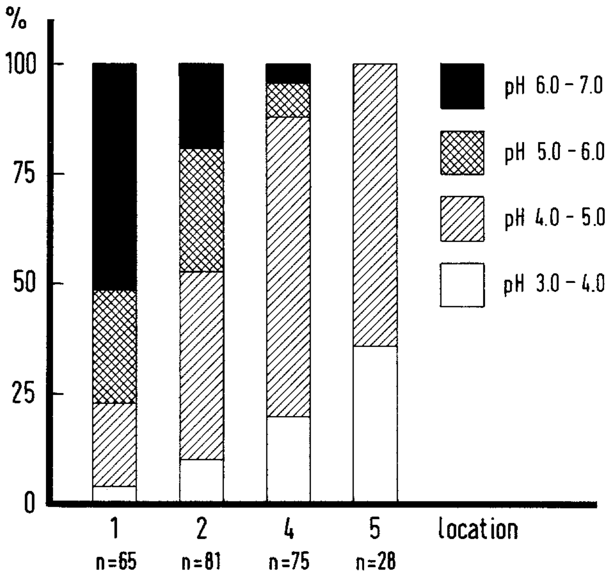

Figure 3. Relative distribution of pH-values of rainwater at different locations in the Netherlands (locations correspond with those of figure 2 and table 2; n = number of rainwater samples).

Table 1. Concentration of acid and acidifying components in rainwater and wet deposition in some northwestern European countries

Country	Period	pH	H^+	NH_4^+	SO_4^{2-}	NO_3^-	H^+	NH_4^+	SO_4^{2-}	NO_3^-
				µmoles l^{-1}			moles ha^{-1} year			
North Britain[3]	1978–80	4.2–4.7	40	19	21.5*	17	480	228	258*	204
East England[3]	1978–79	4.1–4.4	50	71	54*	57	300	426	324*	342
Mid Norway[21]	1977–79	4.2–4.5	14	8	8*	6	161	92	92*	69
South Norway[21]	1977–79	–	69	42	35.5*	41	1012	616	520*	601
The Netherlands[19]	1978–82	4.1–4.7	27	171	100	89	220	934	460	460

* Excess sulphate.

(acid) rainwater modifies the pH. It acts as a neutralizing component and raises the pH of rainwater. Therefore, it is obvious that in countries with great differences in NH_3 emission, the pH of precipitation is an ambiguous indicator of rainfall acidity. The concentrations of other acidifying components also differ at all locations (table 2). It is clear that both breeding farms and heavily-manured cropland increase the concentrations of NH_4^+ and SO_4^{2-}, whereas NO_3^- is hardly affected. Apparently NH_3 reacts mainly with sulphur oxides and sulphate ions, which leads to nearly equivalent amounts of ammonium and sulphate in rainwater. Van Breemen[5] also observed this phenomenon. Even at relatively large distances (> 2.5 km) from NH_3 sources the ammonium concentration is enhanced. Close to the seaside the concentration of sulphate is relatively high as a result of the influence of sea spray. Here, both SO_4^{2-} and NO_3^- play an important role in the acidity of rainfall and the concentrations of H^+-ions appear to be several times higher than in NH_3-affected areas.

The data of table 2 give good information on the origin of differences in rainwater composition and in what way rain is affected by gaseous NH_3 components. However, for describing the loading of the environment with acidifying components, deposition data are more useful. Figure 2 shows the wet deposition of some rainwater components at different locations in two areas in the Netherlands. Final conclusions about the origin and effect of NH_3 on the deposition are very similar to those based on the concentration data of table 2. In the NH_3-affected area in the south, deposition of ammonium varies from 0.98 to 2.63 kmoles ha^{-1} $year^{-1}$, while in the north, values may only reach up to 0.55 kmoles ha^{-1} year. However, the deposition of hydrogen-ions is clearly much higher in the northern part (table 3).

Also in other European countries the deposition of acidifying components varies between different parts. Both in the southern part of Norway and the eastern part of England the deposition of all components in clearly higher than in the northern parts[3,13]. It is well known that in these areas the higher industrial acitivities are responsible for these local variations. However, the observed higher NH_4^+-deposition may originate from agricultural activities, although increased SO_2-concentrations may also enhance the deposition of $(NH_4)_2SO_4$. A recent study on the emission of NH_3 resulting from animal manure production in Europe shows that in the Netherlands, Denmark, Belgium, the western part of the FRG and in some parts of France very high NH_3 concentrations occur[7]. Therefore, it is plausible that rainwater composition may be affected in a similar way to that in the Netherlands. It is, however, remarkable how little attention has been paid to the deposition of ammonium in those countries. It may be expected that also there, ammonium sulphate is an important component of acid precipitation.

Table 2. Mean volume-weighted pH and concentration (μmoles l^{-1}) of acidifying components in rainwater* at five locations** with different NH_3-loading

Location	pH	H^+	NH_4^+	SO_4^{2-}	NO_3^-
1	5.0	9	382	154	55
2	4.4	38	152	90	44
3	4.5	34	213	100	54
4	4.2	65	123	62	45
5	4.0	105	86	81	61

*Samples were taken fortnightly from March 1983 till October 1984; ** all locations correspond with those of figure 2.

Table 3. Wet deposition of acidifying components (moles ha^{-1} $year^{-1}$) in the northern and southern part of the Netherlands

	North (n = 3)	South (n = 4)
H^+	547–703	62– 517
NH_4^+	473–546	978–2626
SO_4^{2-}	478–508	496–1061
NO_3^-	364–371	360– 405

n = number of sampling-stations; all data are derived from figure 2.

The relative importance of ammonium sulphate in the deposition of acidifying components has been reported by Roelofs et al[25]. In areas with a high NH_3 emission, more than 80% of the H^+-input in non-agricultural soils may be a result of airborne ammonium components. Particularly in non-acidic environments ammonium salts may be an important source of acid production[2,11]. For the purposes of this paper it is essential that the maximum potential acidifying effect of precipitation be established. Therefore a consideration of two components of precipitation is essential: a) H^+ concentration, by which the direct acid input can be calculated, and b) NH_4^+ concentration, the potential acidifying influence of which is important. With respect to these assumptions the potential acidifying effect of wet deposition can be calculated according to: $H^+ + 2 \times NH_4^+$. It will be obvious that in areas with a high NH_3 loading the importance of ammonium as an acidifying component of rainwater may be very high. In table 4 some data are shown. In the southern part of the Netherlands the potential acidifying effect of wet precipitation may reach values of more than 5 kmoles ha^{-1} $year^{-1}$, while ammonium contributes 79–99%. In Norway and Great Britain this contribution is relatively low, while the acidifying effect of precipitation is also much lower. However, it is obvious that the potential acidifying effect of ammonium sulphate far outweighs the importance of the deposition of hydrogen ions. The resemblance to data given by the EEC-report[4] is remarkable: it is stated that on strongly fertilized soils, the nitrification process supplies 65–80% of the H^+ input. In Belgium it has also been established that ammonium fertilizers play a very important role in decreasing the pH of agricultural soils and that acid rain is of minor importance[31].

The figures presented in tables 1–4 concern wet deposition. It has been established, however, that in several northwestern European countries both wet and dry deposition contribute in equal proportions to the total deposition of acidifying components[1,4]. This must be taken into

Table 4. Potential acidifying effect (P.A.E.) of wet deposition and the relative contribution of ammonium

	P.A.E. (moles H^+ ha^{-1} $year^{-1}$)	NH_4^+(%)
The Netherlands (south)	2473–5314	79–99
The Netherlands (north)	1614–1787	59–67
Norway	354–2244	53–55
Great Britain	936–1152	49–74

account when calculations are made on the maximum acid loading of ecosystems.

Preliminary studies on the role of ammonium sulphate as an acidifying component

Field observations on the deposition of acidifying components as well as the level of acidification of poorly buffered aquatic environments in some west European countries give indications about the possible role of $(NH_4)_2SO_4$ as a potential acidifying source. Therefore it is interesting to establish in what way ammonium sulphate may have contributed to the acidification process. It is generally known that the conversion of ammonium to nitrate by the nitrification process may act as a H^+ source. However, in most aquatic systems no clear effects will be noticed, as a consequence of the high acid neutralizing capacity of water (HCO_3^-) and sediment (lime, clay and organic particles). In these aquatic environments the nitrification process is often mentioned to account for changes in N-conditions. However, in Belgium, Denmark, the Federal Republic of Germany and the Netherlands, many hydrologically isolated pools occur on carbonate- and nutrient-poor soils and thus are very susceptible to acidification. Therefore, it is remarkable that in these countries, so far, hardly any experiments have been carried out on this phenomenon. Until now, only a little experimental work has been conducted in order to establish the role of ammonium components as an acidifying factor in hydrologically isolated pools. Within the scope of this paper it will be useful to outline these experiments.

In two experiments the effect of ammonium sulphate on the pH-development of water was studied. One experiment was set up to establish dose-effect relations, the other was carried out to gain information about the processes which are involved. In both experiments field situations were simulated by using carbonate-poor sandy sediment and media with a composition similar to rainwater. The first experiment was set up in a greenhouse where light and temperature were comparable to outdoor conditions. The greenhouse itself served as a shelter from ambient gaseous pollutants and for the reduction of the background level of nitrogen deposition.

In total, 550 mm of rainwater was added during the first year. Therefore, the deposition of NH_4^+ corresponded to the values of total deposition at various locations (undisturbed, highly affected) in the Netherlands. The following scheme reflects the experimental set up.

Rainwater treatment* of the simulated poorly-buffered pools

Treatment	Rainwater pH	$(NH_4)_2SO_4$ µM	Deposition NH_4^+ kmoles ha^{-1} year
1	5.6	0	0
2	5.6	125	1.4
3	5.6	250	2.8
4	5.6	750	8.5

* All treatments correspond to field observations; treatment 1: reference; treatment 2: overoll loading in the Netherlands; treatment 3: total deposition of NH_3/NH_4^+ in an area with a high density of intensive stockbreeding; treatment 4: maximum loading in an area with stockbreeding activities.

The initial alkalinity of the water is 0.09 meq l^{-1} and remains unaffected in the reference treatment. Figure 4 shows that all ammonium treatments caused a reduction of pH, whereas the reference treatment showed a slight pH increase. The most rapid acidification occurred during the highest ammonium treatment; already in March, alkalinity was zero and pH decrease continued slowly. In treatment 3, alkalinity reached the zero point in June. The acidifying influence of treatment 2 appeared not to be sufficient to decrease alkalinity to the zero point and therefore the pH remained relatively high. The pH devel-

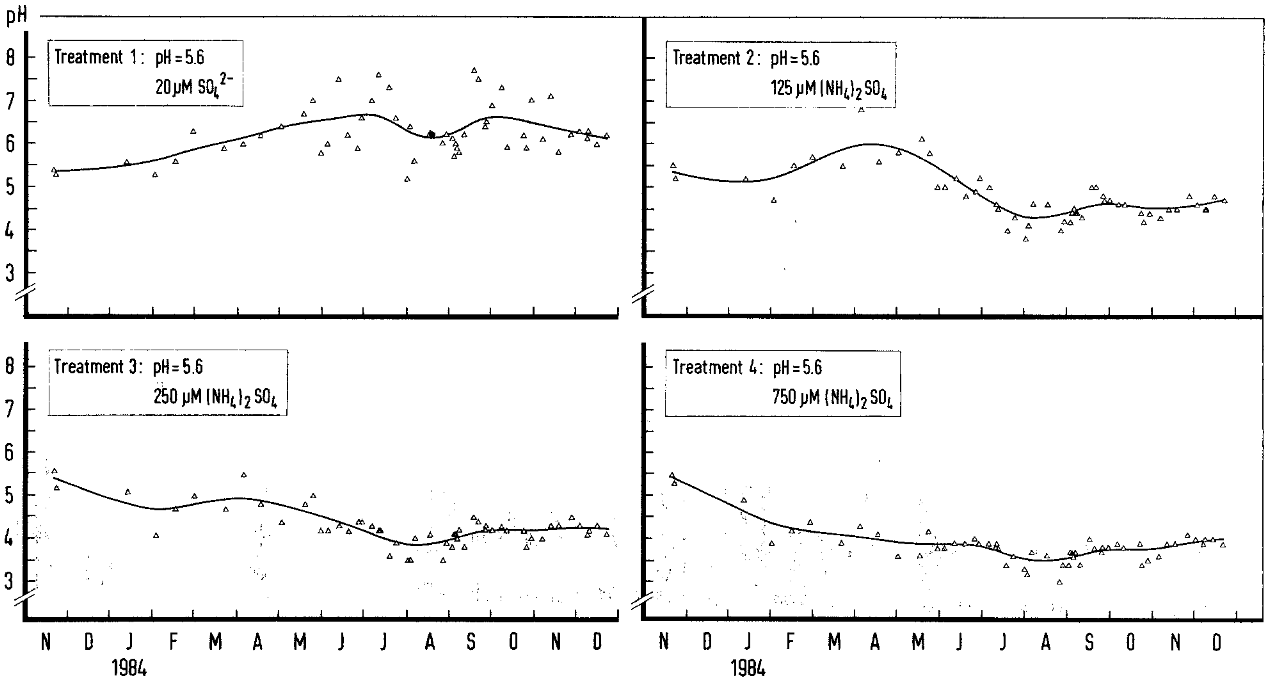

Figure 4. The effect of different rainwater treatments on the pH development of simulated, poorly buffered pools (greenhouse experiment).

opment of all treatments differs significantly (Rank-correlation test of Friedman; $p < 0.001$). After a starting period of several months pH-values are relatively stable and are respectively 6.2; 4.8; 4.2 and 3.8 for the different treatments. Apparently, after the macrophytes have developed well in June and July, an equilibrium is reached in which the hydrogen-ion production and consumption are balanced. This situation is primarily determined by the ammonium sulphate concentration of the rainwater. Both biochemical and physicochemical processes are responsible for the maintenance of the different pH-values. Particularly the buffer complexes which originate from the sediment may play an important role. The results of this greenhouse experiment show clearly that ammonium sulphate may cause a severe reduction of alkalinity, a decrease of pH and changes in nitrogen conditions. Under these simulated field conditions continued ammonium sulphate addition to acidified water leads to an accumulation of ammonium. Particularly this N-enrichment causes an eutrophication enabling the biomass of shore macrophytes to become extremely high.

In order to gain more detailed and causal information on the processes which underly these chemical changes in water composition, (soil-water) column experiments were performed. The experimental set up is given below:

Experimental set up of the column experiment*

	A			B		
Column	1	2	3	4	5	6
$NaHCO_3$ (µM)	500	500	500	2000	2000	2000
pH	6.8	6.8	6.8	7.5	7.5	7.5
$(NH_4)_2SO_4$ (µM)	0	250	500	0	250	500

*All six soil-water columns were incubated in the dark at 20° C; each column was filled up with soil and medium in a volume ratio of 1:3; two different HCO_3^- concentrations (A and B), and three different (0, 250, 500 µM) ammonium sulphate concentrations were used as the initial situation of the medium; during 12 weeks the changes in pH, HCO_3^-, NH_4^+ and NO_3^- concentrations were monitored.

Table 5 shows some data which express the importance of the nitrification process in the observed acidification of the media. The conversion of ammonium to nitrate results in a strong reduction of the HCO_3^- level. The production of nitrate is equivalent to the loss of ammonium and twice the loss of bicarbonate. These observations fully support the importance of the nitrification process in which each converted NH_4^+ ion produces 2 H^+ ions. This affects the HCO_3^- level and subsequently the pH. The somewhat lower nitrate concentrations may be a result of anaerobic denitrification.

The effect of an acid-producing process on the decrease of pH depends mainly on the presence of buffer substances. The ultimate level of pH decrease depends both on ammonium sulphate concentration and bicarbonate level. In this experiment, HCO_3^- acts as pH-buffer as long as it is present. Figure 5 illustrates that under bicarbonate-poor conditions (A), the pH is hardly affected during the first 13 days. However, acidification can be observed by the decrease of the HCO_3^- concentration (table 5). When all HCO_3^- has been used and ammonium is still present, the pH decreases very rapidly. Under bicarbonate-poor conditions this point is reached after 12 days. However, after 20 days the decrease of pH proceeds only very slowly. This is a consequence of an inhibition of the nitrification process below pH = 4.5. The level of acidification is apparently determined by the available amount of ammonium. The ultimate pH at which no further nitrification occurs depends on the initial NH_4^+ concentration and is reached after 70 days. These pH-values for the water are respectively 4.2 and 3.8, and at those points no further conversion of ammonium occurs. Subsequently the ammonium concentration will not decrease any further and NH_4^+ accumulates (table 6). At low HCO_3^- concentrations, the high NH_4^+ concentrations are responsible for a severe pH-decrease.

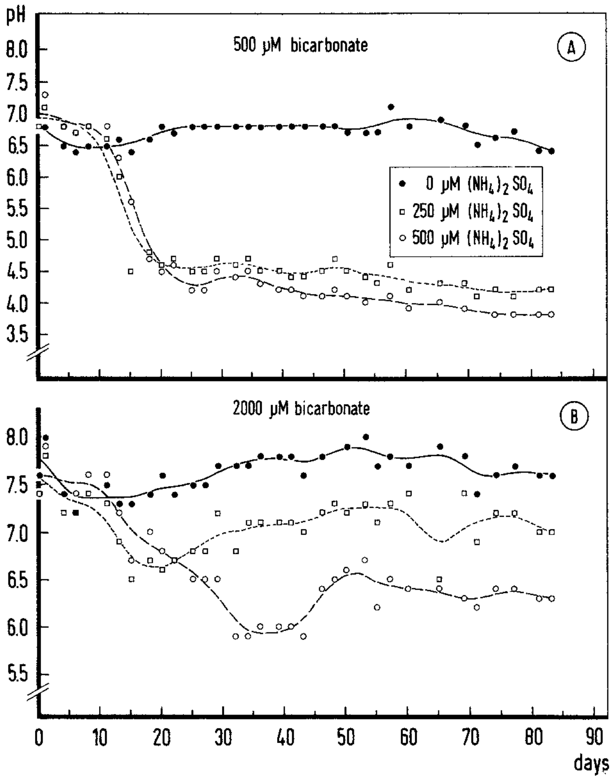

Figure 5. pH-development of water in columns with different $(NH_4)_2SO_4$ concentrations under low (A) and high (B) bicarbonate conditions of the medium (column experiment).

Under bicarbonate-rich conditions the final result of the process involved is different. Although similar processes take place the ultimate pH is primarily determined by the high HCO_3^- concentration. The acidifying action of the nitrification process is buffered by the high amount of

Table 5. Loss (−) and gain (+) of ammonium, nitrate and bicarbonate* (µmoles l^{-1})

Situation	NH_4^+	NO_3^-	HCO_3^-
A	− 240	+ 225	− 480
B	− 940	+ 800	− 1950

*Data are obtained from column experiment (see also fig. 5 and table 6).

Table 6. The initial and ultimate values* of some parameters in four columns with low (A) and high (B) bicarbonate concentration

	Initial				Ultimate			
	NH_4^+	HCO_3^-	NO_3^-	pH	NH_4^+	HCO_3^-	NO_3^-	pH
A	460	480	0	6.8	20	0	390	4.2
	960	480	0	6.8	250	0	525	3.8
B	460	1950	0	7.5	0	450	400	7.1
	940	1950	0	7.5	0	0	810	6.3

*Concentration expressed as µmoles l^{-1}.

bicarbonate and therefore no severe pH-decrease takes place (fig. 5). If the initial NH_4^+ concentration is 500 µM the decrease of pH already stops after 20 days. At this point all ammonium is converted and no further pH-decrease occurs. The final pH (7.0) is strongly influenced by the remaining amount of bicarbonate. If the initial NH_4^+ concentration is 1000 µM, pH-decrease stops after 35 days. At this point both bicarbonate and ammonium are fully utilized as a result of the nitrification process (tables 5 and 6). In this situation, when bicarbonate is not present any more, the ultimate pH (6.3) is determined by the prevailing physico- and biochemical processes in the soil-water column.

Both experiments show clearly that the acidifying influence of ammonium sulphate far outweighs any other possible acidifying process. At a high $(NH_4)_2SO_4$ concentration, pH decrease reaches down to pH = 3.8. At this pH value nitrification is fully inhibited and ammonium will accumulate.

Extrapolation to the field situation

Particularly during the last few years observations in several west European countries indicate that airborne $(NH_4)_2SO_4$ may play a role in the changes in natural environments caused by acid precipitation. In the Netherlands it has been established that both dry and wet deposition of ammonia compounds lead to decreased vitality of pine trees and to acidification of forest soils[5,25]. The strongly increased growth of grasslike plant species in heathlands also appears to be a consequence of the high deposition of nitrogen compounds[14,24]. In south Sweden the decreased vitality of pine forests may also be a result of ammonia deposition (Hultberg, personal communication).

For poorly buffered pools in the Netherlands, the role of $(NH_4)_2SO_4$ has already been demonstrated, by means of deposition data and some experiments. However, field observations of the changes in chemical composition of acidified waters also indicate the influence of airborne NH_4^+ compounds. Acidified waters are generally characterized by a low pH (mean 3.8–3.9) and, in contrast to the originally poorly-buffered waters, ammonium is the dominant form of nitrogen[18,23]. This alteration of the nitrogen condition is coupled with the expansion of macrophytes which are stimulated by NH_4^+-enriched acid conditions[18,23,27].

In more buffered waters, where pH is hardly altered, the alkalinity has decreased more than 1 meq l^{-1} since 1950[18]. In other countries, where high atmospheric NH_3-concentrations occur, similar effects have been noticed. Rebsdorf[22] reports a severe reduction of alkalinity in slightly alkaline lakes in central Jutland, while pH has decreased up to 1 unit over a period of 12–25 years. Also in Germany, lake acidification to pH 3.9 has been detected in the Erzgebirge and Thüringer Wald[4,26], while in Belgium acidification of bog pools in the Campine area has occurred together with a lowering of the HCO_3^- concentration[28-30]. Acid sulphur-rich precipitation has reduced the pH of those pools down to 3.8. Particularly the Belgian, German and Danish environmental conditions are very similar to those of the Dutch situation. In these countries also, many hydrologically isolated waters are present on sandy sediments poor in carbonate and nutrients. Both the high atmospheric NH_3-concentrations and high level of acidification (pH = 3.8–3.9) indicate that $(NH_4)_2SO_4$ is very important. It is, however, strange that this component of acid precipitation has been neglected so far. For all these countries it would be useful to pay more attention to the deposition of NH_3 compounds and changes in nitrogen conditions of waters which are becoming acidified.

Final conclusions

– The atmospheric transport of NH_3, emitted from breeding farms and strongly manured cropland, causes a severe loading of neighboring non-agricultural environments. Particularly the wet deposition of ammonium sulphate is enhanced, while the pH of rainwater is only slightly acidic.

– Due to the variation of gaseous air pollutants over the Netherlands large differences are noticed in the relative contribution of each acidifying component in rainwater. In areas with high atmospheric NH_3 concentrations, ammonium sulphate contributes the major part to the potential acidifying influence of wet deposition.

– Preliminary experiments show a causal relation between ammonium sulphate and water acidification, ammonium enrichment and the expansion of ammonium tolerant shore macrophytes. For the Dutch situation it is clear that, particularly in areas with enhanced atmospheric NH_3 concentrations, the deposition of NH_3 and SO_2 derived compounds has provided the major contribution to acidification and N-enrichment of hydrologically isolated, poorly buffered pools.

– In all countries, particularly in areas with high NH_3 emission, it will be useful to pay more attention to the environmental impact of airborne ammonium sulphate deposition.

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The response of plants to acid soils

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Summary. Interactive effects between acid deposition and the rest of the environment are the key to further understanding. Although this article deals only with plant growth in relation to the chemical state of the soil and not with aerial effects, it is still possible to illustrate a number of interactions and patterns of response among both vascular and non-vascular components of vegetation. Evidence is examined with regard to plant age, pre-treatment and the nature of nutrient supply. It includes consideration of both effects of soil on plants and of plants on soil, notes both antagonisms and symbioses, and draws attention to inducible defence systems.

Key words. Aluminium; ammonium N; ion efflux; metal toxicity; mucilage; mycorrhizae; nodulation; nutrient deficiency.

Introduction

There is considerable concern over the effects of acid deposition on vegetation both by direct contact with aerial parts and through changes in the chemical state of the soil down the profiles in which plants root. This article will deal with plant growth in relation to the chemical state of the soil volume that is occupied and not with aerial effects. It should be stated at the outset that there is no single pattern of response shown by plants. Most common crop plants have been selected and bred for rapid growth under fertile conditions and they lack the tolerance mechanisms necessary for survival in very acidic conditions.

Within the native populations of plants worldwide, however, there are those that are tolerant of a wide range of soil chemical conditions, including the suite of factors found in acidic soils.

Even within acidic soils the degree of acidity and the extent of associated toxicities varies according to the