Vegetatio **126:** 73–88, 1996.

The restoration of species-rich heathland communities in the Netherlands

A. J. M. Jansen[1], M. C. C. de Graaf[2] & J. G. M. Roelofs[2]
[1]*Kiwa N.V. Research & Consultancy, Postbus 1072, 3430 BB Nieuwegein, The Netherlands;* [2]*Department of Ecology, Research Group Environmental Biology, University of Nijmegen, Toernooiveld, 6525 ED Nijmegen, The Netherlands*

Key words: Cirsio-Molinietum, C/N ratios, Ericetum tetralicis, Hydrology, Phosphorus availability, Sod cutting

Abstract

The wet heathland communities of the Ericetum tetralicis and the Cirsio-Molinietum have declined in the Netherlands due to acidification, eutrophication and lowering of the water table. To investigate the prospects of restoration of both communities, the effects of sod cutting and hydrological measures on vegetation and soil chemistry were studied in two nature reserves where these plant communities occurred decades ago. The combination of sod cutting and hydrological measures has restored several rare, groundwater dependent heathland communities. Sod cutting has restored the Ericetum tetralicis, but not the Cirsio-Molinietum. This might be due to the absence of viable seeds of characteristic species of the Cirsio-Molinietum and/or the absence of optimal site conditions, especially high phosphorus concentrations in the top soil. The high phosphorus concentrations might be a consequence of high mineralization rates and/or prolonged inundation with iron-poor water and the decreased flux of iron-rich groundwater into the topsoil. Restoration of the Cirsio-Molinietum only seems possible when sod cutting is carried out together with hydrological measures that counter prolonged inundation and reinforce the discharge of base and iron-rich groundwater.

Nomenclature: Nomenclature of phanerogam taxa is according to Van der Meijden (1990), that of mosses is according to Smith (1980) and that of syntaxa is according to Westhoff & Den Held (1969).

Introduction

Ericion tetralicis and Cirsio-Molinietum communities are species-rich and characteristic of wet heathlands and adjacent grasslands. Both ecosystems are found on nutrient poor, acidic to slightly acidic habitats respectively, where substrate composition, e.g. mineral or organic, seems to be of less importance. Cirsio-Molinietum communities depend on the influence of base-rich groundwater (Rodwell 1991; Westhoff & Den Held 1969). The influence of base-rich groundwater is small or absent in Ericion tetralicis communities (Westhoff & Den Held 1969).

Both communities have declined strongly in Northwestern Europe since the thirties (Buck-Sorlin 1993; De Smidt 1966; Meisel 1977; Westhoff 1978). The recent deterioration of these communities is mainly caused by atmospheric deposition and by lowering of groundwater tables (Aerts & Berendse 1988; Houdijk et al. 1993).

The increased nutrient input of atmospheric nitrogen, has resulted in a change in species composition in Ericion tetralicis communities. Dwarf shrubs like *Erica tetralix* and *Calluna vulgaris* have been replaced by the grass *Molinia caerulea* (Aerts & Berendse 1988; Pitcairn et al. 1991; Roelofs 1986). In Cirsio-Molinietum communities, *Calamagrostis canescens* and *Agrostis canina* replace the original plant species, when water tables decrease (Bakker et al. 1987; Grootjans et al., 1986; Soukupová 1992).

Many characteristic species of these communities, such as *Lycopodium inundatum*, *Gentiana pneumonanthe*, *Narthecium ossifragum*, *Dactylorhiza maculata* and *Cirsium dissectum* disappear before competition of grasses becomes obvious, probably due to soil acidification, leading to increased Al:Ca ratios and ammonium concentrations (Houdijk et al. 1993).

The reduced influence of base-rich groundwater on the top soil layer can enhance soil acidification in two ways. Firstly, the top soil becomes more acid by the increased influence of acid rain water (Bakker et al. 1987; Grootjans et al. 1988). Secondly, aerobic soil conditions stimulate mineralization and nitrification, which result in an increased production of protons and an enhanced availability of N (Grootjans et al. 1986; Berendse et al. 1994).

Restoration of these ecosystems should be aimed at diminishing the effects of soil acidification, eutrophication and lowering of groundwater tables. Since reduction of atmospheric inputs is a long term process, measures will have to be taken on a smaller, local scale, e.g. in vegetation, soil or hydrological conditions. The effects of soil acidification might be countered by increasing the amount of base cations in the soil, e.g. via liming or via reinforcing groundwater influence in the top soil (De Graaf et al. in press; Grootjans et al. this issue). Effects of nitrogen enrichment can be reduced by the removal of nutrients from the system by mowing or sod cutting (Bakker 1989; Koerselman 1992). Mowing affects dominant species, but the increase of species-diversity is a long term process (Bakker 1987). Sod cutting changes the vegetation on the short term. Species of pioneer phases often return, but the reappearance of typical litter fen species is uncertain because the seed of these species might be removed or has already disappeared from the seed bank (Bakker 1989).

The aim of this study is to evaluate the impacts of sod cutting and hydrological measures on soil and vegetation in two former groundwater fed sites in the Netherlands.

Site description and restoration measures

Stroothuizen

Stroothuizen (52 °22′N, 7 °03′E; 20 ha) is situated in the eastern part of the Netherlands (Figure 1).

During the Weichselien glacial period Stroothuizen was covered by aeolic sandy deposits and, therefore, is characterised by a mosaic of elevated and lower parts, with height differences up to 2 meters.

The soil consists of fine sands, with occasional fine gravel or loam. The soils of the elevated parts are strongly podzolized. The lower parts show an accumulation of organic material.

At Stroothuizen two aquifers are present. The second aquifer wedges from the south-east to the north-west, due to the presence of a thick impermeable layer of clay in the north-western part (Csonka 1986; WMO 1985; Figure 2). No ditches occur in the reserve Stroothuizen, but in the direct vicinity several deep ditches were dug round 1960.

Between 1944 and 1953 Cirsio-Molinietum orchietosum and Ericetum tetralicis communities were found at the north-western part of Stroothuizen (De Smidt unpublished; Westhoff & Jansen 1990). Wet heathland vegetation (Ericetum tetralicis), with species like *Erica tetralix*, *Molinia caerulea*, *Narthecium ossifragum*, *Scirpus cespitosus*, and several *Sphagnum* species had developed at the higher parts, with a Cirsio-Molinietum orchietosum community at the lower parts. In the latter community *Carex panicea*, *Dactylorhiza incarnata*, *Succisa pratensis*, and *Parnassia palustris* occurred. The lowest and flattest parts were characterised by mesotrophic fen community (Caricion curto-echinatae), and alder carr (Alnion glutinosae).

Before the restoration measures were carried out, the vegetation of Stroothuizen was highly impoverished. Large parts of the wet heathland were dominated by *Molinia caerulea*, whereas only a few scattered spots were still covered with *Erica tetralix*. Since the fifties the species-rich vegetation of the lower parts had developed into a sward dominated by *Calamagrostis canescens*, *Agrostis canina*, *Holcus lanatus*, and *Juncus effusus*. The characteristic species of the Cirsio-Molinietum disappeared in the late 1960's.

At Stroothuizen 0.5 ha of *Molinia*-dominated heathland and 0.5 ha of *Calamagrostis canescens* dominated vegetation were sod cut (10–20 cm) to the mineral soil in respectively 1986 and 1988.

Staverden

Staverden (52 °17′N, 5 °44′E; 8 ha) is situated in the central part of the Netherlands (Figure 1).

Geomorphology and soil of Staverden are comparable to Stroothuizen.

The most remarkable geohydrological feature of Staverden is the occurrence of a clay layer just below the soil surface, resulting in a perched groundwater table system (Appelo 1988) (Figure 2). At Staverden some ditches and several trenches were dug to drain the wet parts for afforestation purposes.

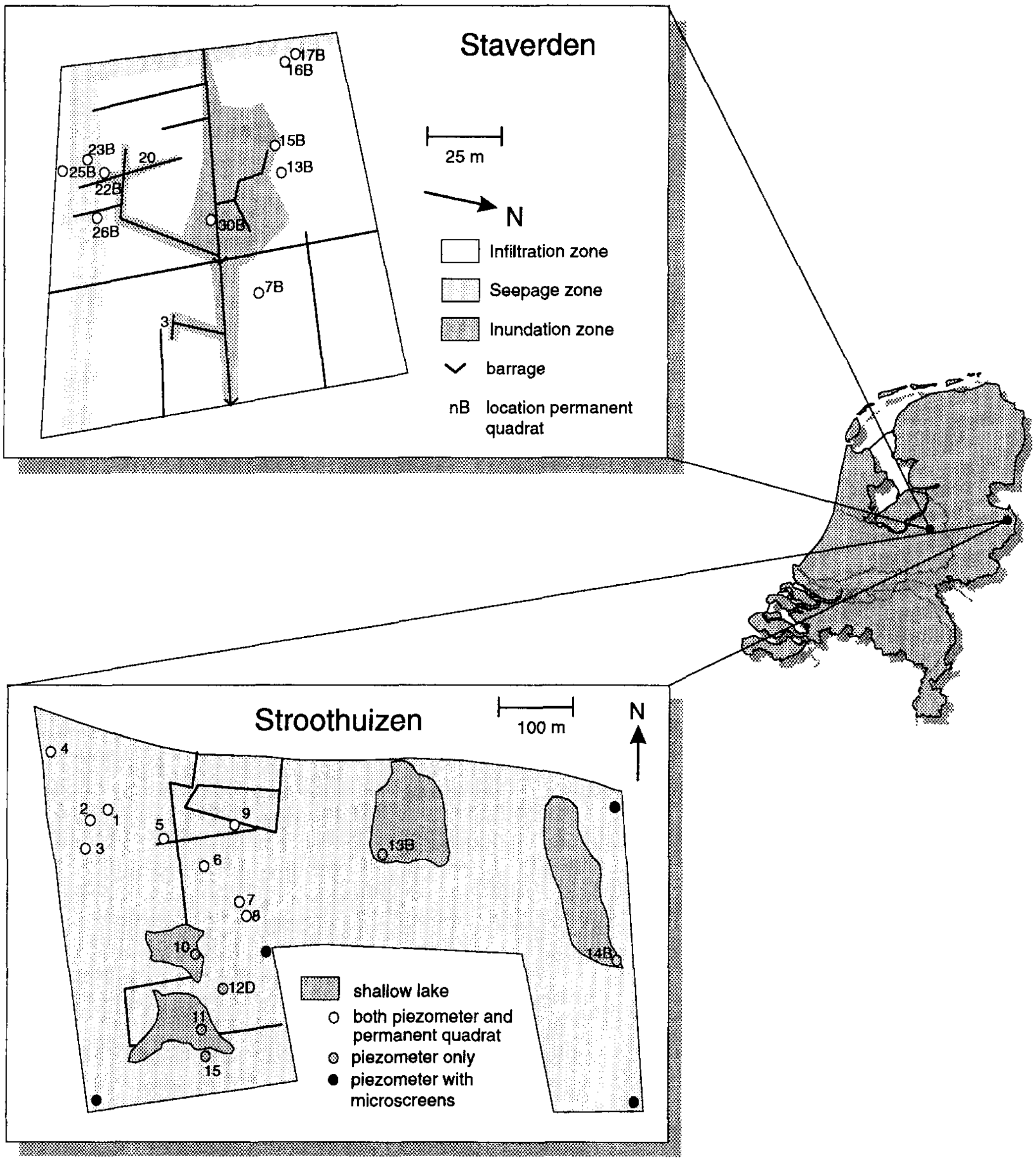

Figure 1. Location of the study areas in the Netherlands.

Both the elevated and lower parts were covered with a pine plantation before measures were carrried out. The pine trees were planted in the early sixties in a former wet heathland. In the main ditch and on its banks *Potamogeton polygonifolius*, *Scirpus fluitans*, *Carex nigra*, *Carex curta*, *Narthecium ossifragum*, *Polygala serpyllifolia*, *Juncus conglomeratus*, and *Hypericum pulchrum* were found in small numbers. In the surroundings Ericetum tetralicis orchietosum and Nanocyperion flavescentis, communities with several endangered species, are still present.

The restoration measures at Staverden were carried out during the winter of 1989/1990, and included forest clearing and removal of the disturbed organic layer down to the mineral soil. To stop artificial drainage and restore wet conditions, barrages were placed into the main ditches and most of the trenches were filled up.

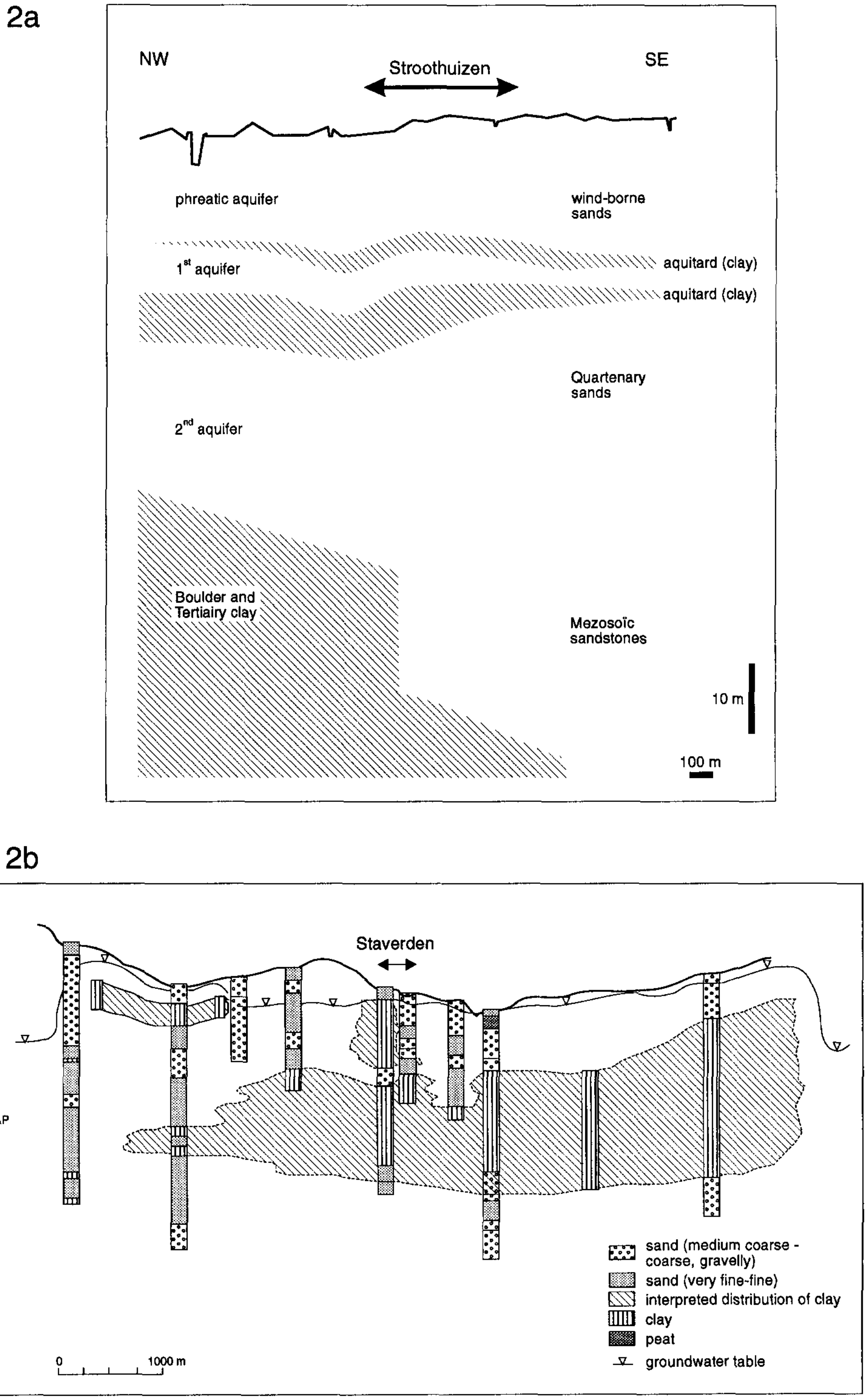

Figure 2. The geohydrological setting of the study areas and their surroundings. A. Stroothuizen (after: Csonka 1986; WMO 1985) B. Staverden (after: Appelo 1988).

Methods

Vegetation

In 1989 nine permanent plots were laid out at Stroothuizen and twelve at Staverden to cover the most important variation at the sites (Figure 1). These permanent quadrats (1 × 1 or 2 × 2 m) have been surveyed each year at Stroothuizen in July or August and at Staverden (2 × 2 m) in May and June with the exception of 1993. Numbers and cover of the species were estimated according to Londo (1976) and Barkman, Doing and Segal (1964), respectively and transformed to numerical cover.

Soil sampling

At Staverden changes in soil chemistry were monitored by annually sampling the top soil layer (0–10 cm) in the permanent plots. Sampling started in November 1989, just before restoration had started; after restoration soil sampling took place in May, except for 1994, when samples were taken in July.

Per plot eight subsamples were taken with an auger (diameter 3 cm), which were thoroughly mixed and stored in polyethyleen bags at 4 °C. Soil analysis was after Houdijk et al. (1993). In addition, dry soil was combusted for four hours at 550 °C in order to estimate the organic content of the soil. Total carbon and total nitrogen were determined using a CNS analyzer type NA 1500 (Carlo Erba Instruments). In Stroothuizen, samples of the top soil were taken in June 1990 (0–20 cm depth) and in June 1993 (0–10 cm) along the sides of the permanent plots. Per plot four subsamples were taken with an auger (diameter 8 cm), which were thoroughly mixed and stored in polyethyleen bottles at 4 °C.

These soil samples were air-dried (35 °C, 10–20 h) and sieved (<2 mm), after which the soil was grinded (<0.5 mm) and homogenised before analysis.

pH_{H2O} was measured after mixing 5 g air-dried soil with 12.5 ml demineralised water, using a EDT DR350 Tx-micro 2 pH meter. Organical C was determined after Haenes (1984); since this method reveals 97 to 100% of the organical C, the percentages C were multiplied by 1.03. P was measured colorimetrically, following Page (1989). For total N determination, 0.400 g air-dried soil was destructed following Novozamsky et al. (1983), after which N was determined following Merck (1983). Ca, Mg, Na and K were determined using an AAS after extraction of air-dried soil with a $BaCl_2$-solution at pH 8.2 (Houba et al. 1989).

Data concerning the effects of hydrological zone and sod cutting on soil chemistry, were statistical analysed using a Wilcoxon test. Correlations between soil parameters were tested using a Spearman rank correlation test. All statistical analyses were performed using SAS 6.0. (SAS 1985).

Ground and surface water analysis

At Stroothuizen a capped piezometer was placed, at a corner of each permanent plot, screened at a depth of 1.2–2.0 m below soil surface (Figure 1). Additional piezometers were placed near the permanent plots in shallow soil layers (0.4 and/or 0.8 m below the surface). At four locations piezometer sets in deeper soil layers were provided with micro screens at depths varying between 3 and 50 m below soil surface (Figure 1).

Water was sampled from the above-mentioned piezometers in September 1989, March 1990, June 1993 and February 1994. The piezometers were pumped before sampling until EC_{25} had stabilised.

Two 250 ml samples per filter were taken and stored in brown glass bottles without inclusion of air. pH, EC_{25}, and HCO_3^- were measured in the laboratory the same day, after which the samples were frozen at −20 °C. Within two days SO_4^{2-} and Cl^- were measured. Cations (Ca^{2+}, Mg^{2+}, Na^+, K^+ and Fe) were measured after addition of 1 ml HNO3 to 250 ml water sample, using AAS (Houba et al. 1989). Iron was only measured in September 1989 and March 1990. Anions (HCO_3^-, SO_4^{2-} and Cl^-) were measured spectrophotometrically.

Surface water was sampled in December 1989 and April 1990 at Stroothuizen and in May 1990, June 1992 and July 1994 at Staverden and analysed following the same methods as for soil extracts of Staverden.

The reliability of the analyses was checked by calculating the ionic balance and by comparing measured and computed EC_{25} according to Stuyfzand (1993). Analyses with a deviation in the ionic balance of more than 10% from electro neutrality or differing more than 15% in computed versus measured EC_{25} were discarded.

For the hydro-chemical classification of the water samples a method developed by Stuyfzand (1989) was used. The determination of a water type according to this method implies the successive calculation of the main type (by Cl^-), type (by alkalinity) and subtype (by the most important cation and anion) of a water sample, each of which contributes to the total code of the water type. The water type $F2CaHCO_3$, for instance, consists of fresh water (F), that is alkaline (2), and in which Ca^{2+} is the most important cation and HCO_3^- the most important anion.

Results

Hydrology

Stroothuizen

In Stroothuizen four hydrological zones can be distinguished, based on the chemical composition of the shallow groundwater and surface water. The first zone, characterised by shallow groundwater of a very low alkalinity (F^*CaSO_4), consists of the ridges of aeolic sand deposits and their slopes. The water levels in the ridges rise during the winter, leading to a lateral flow of shallow groundwater. This groundwater discharges at the slopes of these ridges.

The second zone, characterised by the occurrence of groundwater and stagnant surface water of a moderate and moderately high alkalinity ($F2CaHCO_3^-$ and $F3CaHCO_3^-$), is situated in the centre. It is likely that this water originates from the second aquifer, because (i) this is the only aquifer that contains water of a moderate and moderately high alkalinity (Figure 3) and (ii) hydrologically the groundwater must flow in upward direction due to the wedging of this aquifer (Figure 2).

The third zone, characterised by prolonged inundation, also occurs in the centre. Here, surface water of a low alkalinity (F0CaMIX) encloses the surface water of the second zone. The groundwater chemistry of this part of the centre is stratiform: a body of relatively HCO_3^- poor water types covering groundwater with a (much) higher alkalinity ($F1CaSO_4$, F1CaMIX, F2CaMIX, $F2CaHCO_3^-$).

The fourth zone is adjacent to the first and third zone. Here, water of a moderately low alkalinity ($F1CaHCO_3^-$), in which HCO_3^- is the dominant anion, seeps to the soil surface.

Staverden

In Staverden the surface water mainly has a very low alkalinity (F*NaCl, F*NaMIX, F*CaCl and F*CaMIX) (Figure 4). Surface water of a low alkalinity (F0CaMIX) was found only at one site. Distinct hydrological zones could not be distinguished on the basis of the chemical composition of the surface water.

Table 1. Water extractable nutrients in soil before (1989) and after (1990) restoration at Staverden. Mean values (minimum-maximum). Concentrations in μmol kg^{-1}. Significant differences in nutrient concentrations (μmol kg^{-1}) between years are indicated as follows: ***: $p<0.01$; **: $p<0.05$; *: $p<0.1$; ns: not significant. Number of measurements: 1989: 20 (Ca: 19, Mg: 17), 1990: 12. nd: not determined.

	1989	1990	
pH	4.26	4.68	**
Al	51.5	137.1	***
Ca	31.5	70.0	ns
Mg	13.7	9.8	ns
K	nd	62.0	
Fe	28.1	38.5	ns
Mn	0.32	0.04	*
Zn	1.6	0.3	***
NO_3	19.2	7.8	**
NH_4^+	29.0	123.6	***
P	0.53	1.16	ns

On the basis of field observations on water tables, iron contents and overland flow, three hydrological zones could be distinguished, namely an infiltration, a seepage and an inundation zone.

The infiltration zone consists of the ridges of aeolic sand deposits and the higher parts of their slopes, where rain water infiltrates.

The seepage zone is situated at the lower parts of the slopes of the ridges. This zone is characterised by the seepage of groundwater with a very low alkalinity, originating from the phreatic aquifer.

The inundation zone is in the centre and is characterised by prolonged inundation. Here, surface water with a very low alkalinity stagnates during winter and spring.

Soil chemistry

In Staverden, the chemical variation in the top soil was largely influenced by the restoration measures (Table 1). The mean pH has increased significantly at about 0.4 unit. With the exception of Ca^{2+}, Mg^{2+}, Fe, and P, the mean concentrations of the other ions differ significantly before and after restora-

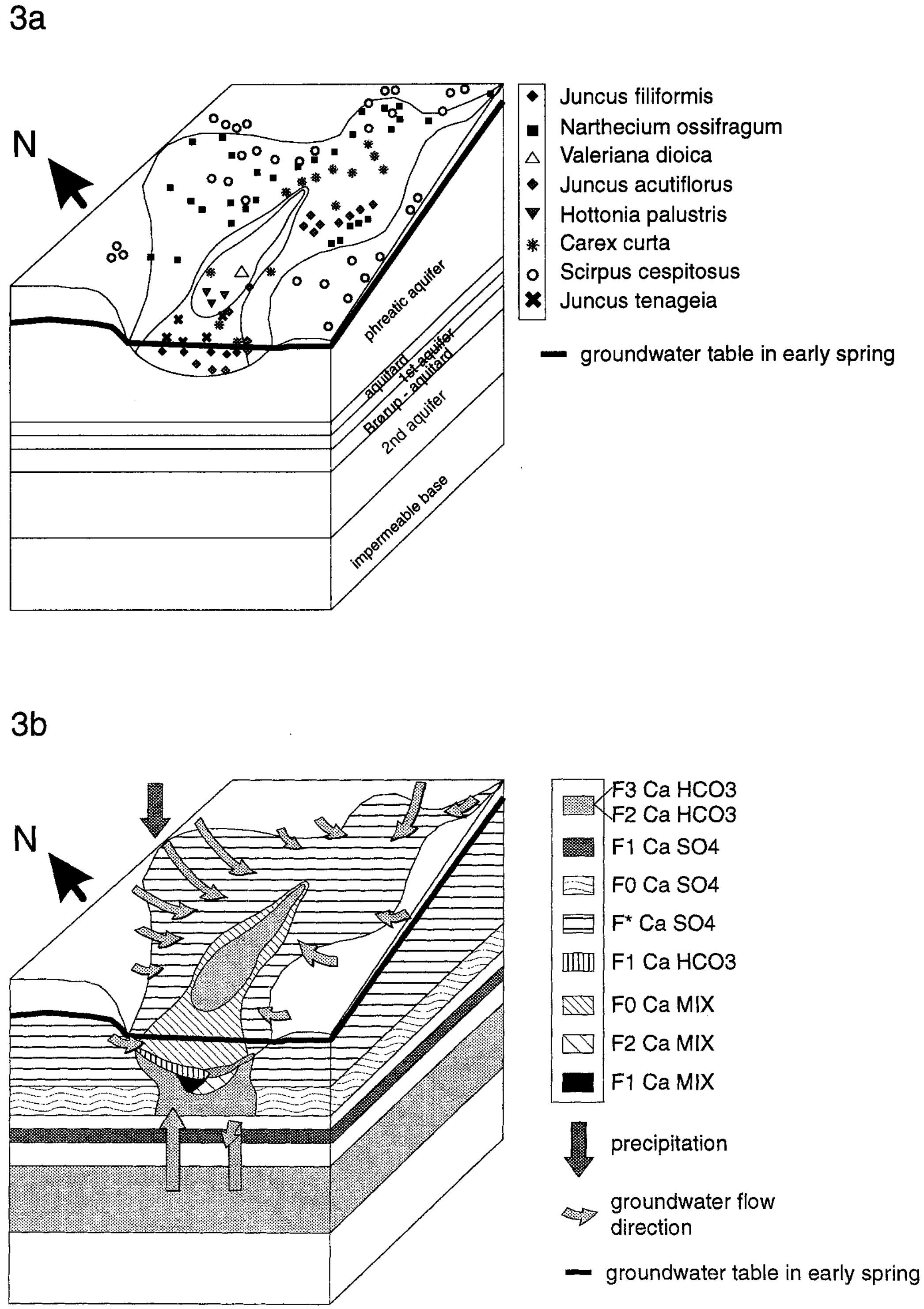

Figure 3. (a) Distribution of some characteristic plant species and (b) water types and assumed hydrological processes at Stroothuizen in 1990. The classification of chemical water types follows Stuyfzand (1989).

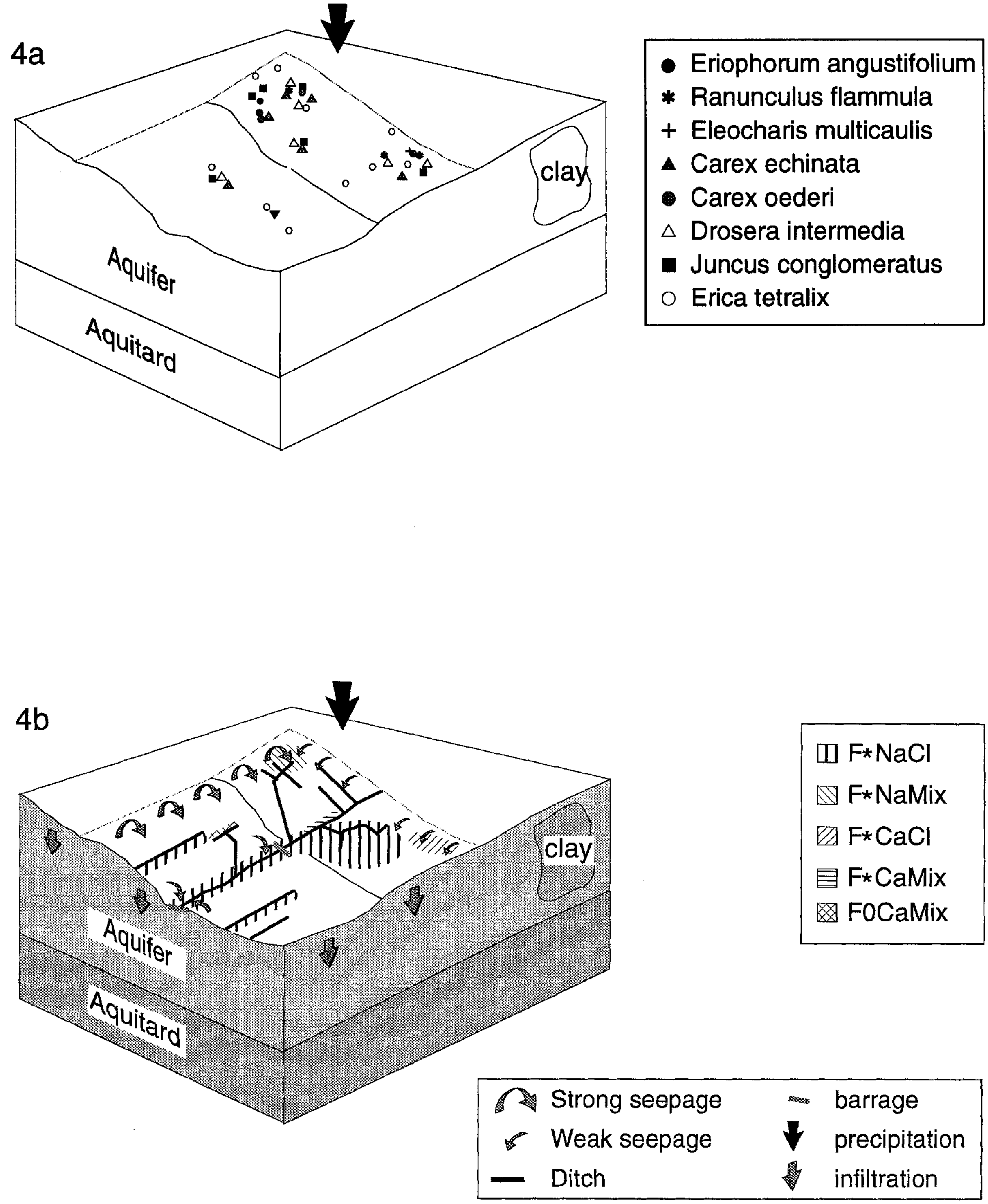

Figure 4. (a) Distribution of some characteristic plant species and (b) water types and assumed hydrological processes at Staverden in 1992. The classification of chemical water types follows Stuyfzand (1989).

Table 2. Top soil chemistry of sod cut and non sod cut parts at Stroothuizen. ***: $p< 0.01$; **: $p<0.05$; *: $p<0.1$; ns: not significant. Org. mat.: organic material, N: total nitrogen, P: water extractable phosphorus, Ca: exchangeable calcium, base cat.: sum of exchangeable Ca, Mg and K. n=number of samples.

	non sod cut	sod cut	
pH	5.24	4.93	ns
org. mat. (%)	8.7	3.3	***
C/N	12.7	14.8	ns
N (%)	0.34	0.12	***
P (μmol kg^{-1})	94.2	77.6	ns
Ca (μmol kg^{-1})	32715	7319	**
Base cat. (μmol kg^{-1})	73011	18031	**
n	18	8	

tion. The mean concentrations of Al^{3+}, and NH_4^+ have increased; those of Mn^{2+} and NO_3^- have decreased. At Stroothuizen the organic matter content, total nitrogen concentration, Ca and sum of exchangeable base cations are significantly lower in the sod cut than in the non sod cut plots (Table 2).

Both at Staverden and Stroothuizen C/N-ratios in the infiltration zones are higher, whereas pH and sum of exchangeable base cations in the infiltration zones are lower than in the other zones (Tables 3 and 4). At Stroothuizen the calcium content of the seepage zone differs significantly from those of the infiltration and inundation zone (Table 4).

After restoration of Staverden C/N-ratios in the seepage and inundation zone are higher than those of the sod cut parts of the seepage and inundation zone of Stroothuizen (Tables 3 and 5). At Stroothuizen the calcium content and the sum of exchangeable base cations in the seepage and inundation zone are mostly higher than those at Staverden (Tables 3 and 5). The concentrations of water extractable phosphorus are much higher at Stroothuizen than at Staverden (Table 3 and 5). Phosphorus concentrations are well correlated to C/N ratios and exchangeable calcium, not to pH (Figure 5).

Vegetation development after restoration

The vegetation development after restoration is demonstrated by the change in cover of characteristic species in three pairs of permanent plots at Staverden and Stroothuizen (Tables 6 and 7).

In the permanent plots representing the infiltration zone (8 of Stroothuizen and 13 of Staverden), species characteristic of the alliances Ericion tetralicis and Calluno-Genistion pilosae established at Stroothuizen and Staverden, respectively. Most of these species increased in cover.

In the seepage zone (zone 4) of Stroothuizen several rare species of the Nanocyperion were present in permanent plot 1 during the first three years after sod cutting. In this phase *Juncus articulatus* and *Ranunculus flammula* occurred in a high cover. In the next phase an impoverished, species poor community of the Junco-Molinion developed, characterised by *Carex oederi*, *Carex panicea*, *Juncus conglomeratus*, and *Molinia caerulea*, in which *Juncus effusus* and *Calamagrostis canescens* have appeared. Species valued by the nature conservation, such as *Parnassia palustris*, *Succisa pratensis* and *Dactylorhiza incarnata* did not reappear.

In the seepage zone of Staverden the vegetation development in permanent plot 17 was slower compared to Stroothuizen. Here, in 1994 a community of the Ericetum tetralicis orchietosum had developed, characterised by *Narthecium ossifragum*, *Gentiana pneumonanthe*, and *Succisa pratensis*. It is accompanied by *Juncus effusus* and some species of the *Parvocaricetea*. With the exception of *Juncus bufonius* no species of the Nanocyperion have established here.

In the inundation zones of Stroothuizen and Staverden (plot 2 and 30, respectively) the vegetation has developed into a Caricetum curto-echinatae with *Carex curta*, *Juncus acutiflorus* and several species of the Parvocaricetea. In the inundation zone of Staverden the vegetation develops more slowly, and species of the Parvocaricetea are rare. Both at Staverden and Stroothuizen *Juncus effusus* has appeared in small numbers. At Stroothuizen *Calamagrostis canescens* expanded.

Discussion

Vegetation

Successful restoration of the Ericetum tetralicis, the Cirsio-Molinietum and other groundwater dependent communities requires the restoration of their specific site conditions, such as water regime, pH, base saturation and nutrient status of the soil (Boeye & Verheyen 1994; Grootjans et al., 1986; Koerselman et al. 1990; Moore & Bellamy 1974; Niemann 1963; Succow 1988; Tüxen 1954; Wassen et al. 1989).

In the inundation zones of both reserves a Caricetum curto-echinatae has developed. This communi-

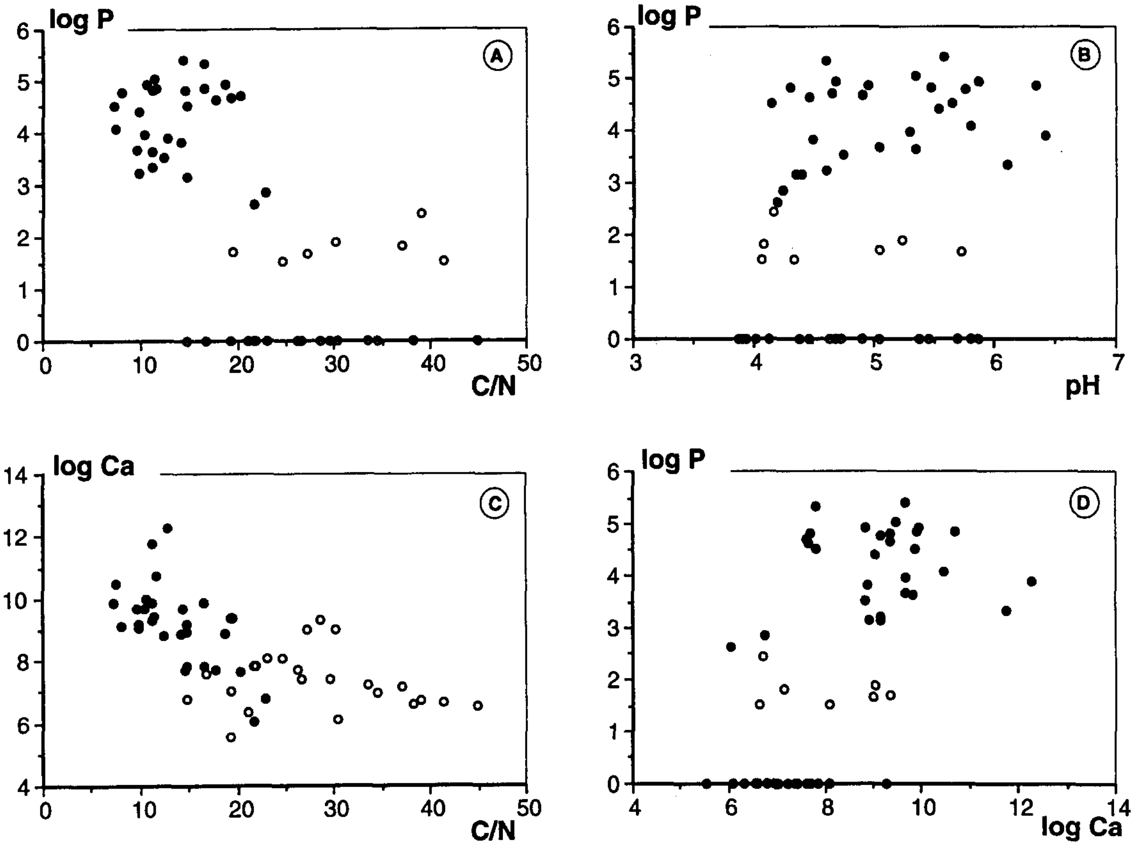

Figure 5. Scatter diagrams of A: log P versus C/N ratio, $r=-0.67$, $p<0.0001$; B: log P versus pH, $r=0.30$, $p<0.03$; C: log Ca versus C/N ratio, $r=-0.72$, $p<0.0001$; D: log P versus log Ca, $r=0.62$, $p<0.0001$. Open dots represent data of Staverden, black dots that of Stroothuizen. $N=53$. Ca and P concentrations were originally in μmol kg^{-1} DW.

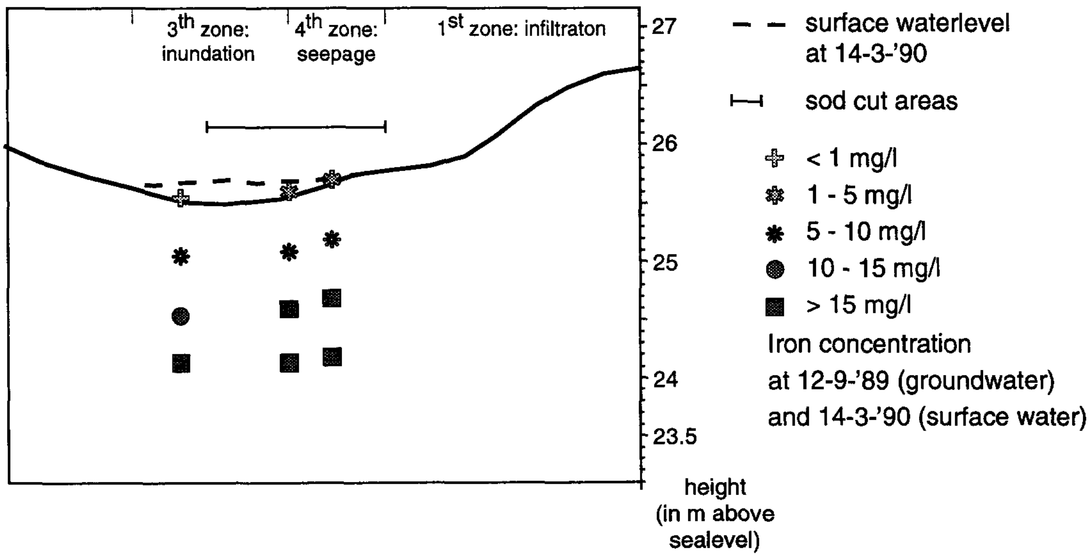

Figure 6. Iron concentration of groundwater (September 1989) and surface water (March 1990) along a transect in Stroothuizen.

Table 3. Top soil chemistry of Staverden after restoration. Means reveal measurements of 1990, 1991, 1992 and 1994 (four plots per zone; minimum and maximum values are given between brackets). Org. mat: organic material, base cations: sum of exchangeable Ca, Mg and K, n: number of samples. Significant differences between hydrological zones are indicated by different letters (p=0.05). For legend; see Table 2.

Zone	pH	org. mat. (%)	C/N	N (%)	P μmol kg^{-1}	Ca mmol kg^{-1}	Base cat. meq kg^{-1}
Infiltration	4.05a	5.49 a	37.3a	0.12 a	2.98a	0.95a	3.10a
zone	(3.8–4.3)	(3.9–8.8)	(30.3–44.9)	(0.06–0.27)	(0.00–10.46)	(0.43–1.39)	(1.39–6.57)
Seepage	5.50b	4.17a	25.3ab	0.10a	1.64a	3.05a	8.98b
zone	(4.07–5.86)	(0.87–7.16)	(14.8–30.1)	(0.02–0.17)	(0.00–8.71)	(0.49–10.80)	(2.56–24.47)
Inundation	4.96b	3.01a	20.9b	0.07a	7.12a	2.30a	6.13ab
zone	(4.38–5.70)	(1.25–6.33)	(16.8–26.6)	(0.03–0.21)	(0.00–26.60)	(0.25–11.63)	(0.74–27.18)
n	20	8	8	8	16	16	16

Table 4. Top soil chemistry of hydrological zones at Stroothuizen, including sod cut and non sod cut parts. Significant differences between hydrological zones at the 0.05 level are indicated by different letters. Number of measurements: infiltration and seepage zone: 8 (base cations: n=4) , inundation zone: 10 (base cations: n=5). Legend: see Table 3.

Zone	pH	org. mat. (%)	C/N	N (%)	P μmol kg^{-1}	Ca mmol kg^{-1}	Base cat. meq kg^{-1}
Infiltration	4.69a	5.61a	17.3a	0.17a	109a	6.36a	16.3a
zone	(4.20–5.59)	(2.5–13.2)	(11.5–22.8)	(0.07–0.35)	(13–223)	(0.43–15.55)	(2.2–33.8)
Seepage	5.91b	8.90a	10.0b	0.38a	81a	61.57b	134.9b
zone	(5.35–6.42)	(1.2–22.5)	(7.3–12.8)	(0.07–0.68)	(27–139)	(9.45–216.5)	(22.2–445.7)
Inundation	4.90a	6.75a	12.8ab	0.26a	80a	10.40a	24.8a
zone	(4.15–5.53)	(1.1–14.7)	(9.7–19.3)	(0.07–0.69)	(24–129)	(2.25–19.7)	(5.9–46.6)

ty tolerates prolonged inundation (Grootjans & Ten Klooster 1980) and is related to water of a base-poor composition (Grootjans et al. 1988). Such site conditions occur in the inundation zones of both reserves due to the stagnation of water with very low and low alkalinity.

In the infiltration zone of Stroothuizen the Ericetum tetralicis sphagnetosum has developed with species such as *Narthecium ossifragum*, *Rhynchospora alba* and several *Sphagna*. In the infiltration zone of Staverden species of the alliance Calluno-Genistion pilosae have established. At both reserves, the site conditions in the most acid parts, the infiltration zones, are suitable for the development of acid and nutrient poor heathland communities (Bannister 1966; Hayati & Proctor 1990; Houdijk et al. 1993; Rodwell 1991; Summerfield 1974).

In the seepage zone of Staverden the restoration of the endangered heathland community of the Ericetum tetralicis orchietosum with species like *Carex panicea*, *Gentiana pneumonanthe*, *Succisa pratensis*, and *Narthecium ossifragum* is successful. The soil of this zone is nutrient poor and moderately acid. Similar relations between the occurrence of these species and soil chemical conditions have been found by several authors (Boeye & Verheyen 1994; De Graaf et al. 1994; Hayati & Proctor 1990; Houdijk et al. 1993).

In the seepage zone of Stroothuizen sod cutting does not restore the Cirsio-Molinietum orchietosum, an almost extinct plant community in the Netherlands, that occurred in that zone until the 1950's, but resulted in the development of an incomplete community of the Junco-Molinion. However, the presence of several endangered species of the Nanocyperion in the seepage zone of Stroothuizen in the first years after sod cutting, was an unexpected success.

The incomplete development of the Cirsio-Molinietum

A complete Cirsio-Molinietum has not developed, although, water tables seem to be high enough (Table 8), the pH and the base cation concentrations of the soil are high and nitrogen concentrations are low in the sod cut part of the seepage zone of Stroothuizen (Table 5). The incomplete development of the Cirsio-Molinietum at Stroothuizen could be due to:

Table 5. Top soil chemistry of hydrological zones at Stroothuizen after sod cutting. Means reveal samples of 1990 and 1993; minimum and maximum values are given between brackets. Number of samples: 3, except in plot 8+9 and plot 10+11 where n=6. Org. mat: organic material, base cations: sum of exchangeable Ca, Mg and K.

Hydrol. zone	pq	pH	org. mat. (%)	C/N	N (%)	P μmol kg^{-1}	Ca mmol kg^{-1}	Base cations meq kg^{-1}
infiltration zone	8+9	4.3 (4.1–4.6)	4.0 (2.3–7.0)	20.5 (16.5–25.2)	0.11 (0.06–0.199)	60.8 (12.9–206.4)	1.20 (0.4–2.4)	4.7 (1.5–10.1)
seepage zone	1	5.5 (5.3–5.8)	3.5 (1.2–5.4)	10.3 (8.1–12.5)	0.14 (0.07–0.21)	63.4 (35.5–116.1)	15.6 (9.4–18.9)	35.4 (22.2–42.4)
inundation zone	2	5.4 (5.3–5.5)	3.1 (1.0–4.6)	10.3 (9.9–10.6)	0.12 (0.07–0.17)	61.3 (38.7–80.6)	13.5 (8.5–16.6)	30.8 (20.7–37.1)

(1) the removal of germinable seeds of characteristic species, such as *Parnassia palustris*, *Dactylorhiza incarnata* and *Succisa pratensis*, by sod cutting. This is not likely, because these species had already disappeared at about the late 1960's and have a short-term persistent seed bank type (Maas & Schopp-Guth 1995). On sod cut areas, the re-establishment of these species is, therefore, only possible when these species are still present nearby, as is indicated by the reappearance of *Succisa pratensis* at Staverden, where this species occurs at about 100 metres from the reserve.

(2) the high phosphorus levels in the top soil. According to Grootjans et al. (1986) the Cirsio-Molinietum is at least during a part of the year limited by phosphorus. Since P concentrations in the seepage zone of Stroothuizen are high, it is unlikely that P will be limiting (Table 5).

Phosphorus availability

At Stroothuizen the high P concentrations might be the result of:

(1) high mineralization rates:

P availability is influenced by several processes, such as decomposition and mineralization. Low C/N-ratios (<15–20) are known to favour mineralization in many ecosystems (Gundersen & Rasmussen 1990; Swift et al. 1979). The correlation, that exists between low C/N-ratios and high P concentrations, points to high mineralization rates at Stroothuizen, and, therefore, could explain high P availability.

In aquatic sediments an increased bicarbonate concentration results in increased decomposition rates (Kok & Van de Laar, 1991). We assume that an increase in decomposition rate will positively influence mineralization, and that it is likely that the same stimulation can occur in the seepage zone of Stroothuizen, where bicarbonate is supplied to the soil by groundwater.

(2) prolonged inundation with iron-poor water and the decreased flux of iron-rich groundwater into the topsoil:

Patrick & Khalid (1974) show the importance of iron in sorbing P in slightly acidic soils. They stress that the formation of phosphorus-iron complexes is of greater importance than is the immobilisation of P by calcium or magnesium, especially under anaerobic circumstances. Hence, we suggest that the low iron concentrations of the shallow groundwater and the surface water might be the cause for the high P concentrations in the seepage and inundation zone of Stroothuizen.

However, at greater depth high iron concentrations occur in the groundwater of the seepage and inundation zone of Stroothuizen (Figure 6). The deficiency of iron in the top soil zone might, therefore, be caused by interferences in the water management in the vicinity of the reserve, such as the digging of a 1.50 meter deep ditch at the edge of the reserve and the construction of a bank along this ditch, both round 1960. This has led to a decreased discharge of base and iron-rich groundwater and prolonged stagnation of base and iron-poor surface water behind the bank.

Furthermore, stagnation leads to anaerobic conditions under which Fe^{3+} becomes reduced to Fe^{2+}. Because P is much stronger bound to Fe^{3+}-hydroxides than to Fe^{2+}-hydroxides, stagnation also results in higher P concentrations (Patrick & Khalid 1974).

Sod cutting or hydrological measures?

At Staverden a pH gradient developed after restoration, which has not been measured before. This has to be ascribed to the hydrological measures taken, which

Table 6. Cover of some characteristic species (in%) at three distinguished hydrological zones of Stroothuizen during the period 1989–1994). The permanent plots are representative of the vegetation development after sod cutting.

hydrological zone	seepage						inundiation						infiltration					
permanent plot	1	1	1	1	1	1	2	2	2	2	2	2	8	8	8	8	8	8
year	89	90	91	92	93	94	89	90	91	92	93	94	89	90	91	92	93	94
Ericion tetralicis/																		
Calluno–Genistion pilosae																		
Calluna vulgaris	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	1	1	1
Erica tetralix	1	1	1	1	1	–	–	–	–	–	–	–	7	17	20	40	40	30
Molinia caerulea	1	1	5	3	2	1	–	–	–	–	–	–	–	1	1	1	1	1
Narthecium ossifragum	–	–	–	–	–	–	–	–	–	–	–	–	40	40	40	40	50	60
Drosera intermedia	0	1	1	1	–	–	–	–	–	–	–	–	1	1	1	1	1	1
Gentiana pneumonanthe	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	1	1	1
Lycopodium inundatum	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Rhynchospora alba	–	–	–	–	–	–	–	–	–	–	–	–	1	1	1	1	1	1
Parvocaricetea/																		
Caricetum curto–echinatae																		
Juncus articulatus	1	20	20	1	5	1	3	30	10	1	1	1	–	–	–	–	–	–
Agrostis canina	1	5	30	20	5	3	10	10	10	40	10	5	–	–	–	–	–	–
Ranunculus flammula	1	12	3	3	3	3	20	20	3	30	20	1	–	–	–	–	–	–
Hydrocotile vulgaris	–	–	–	–	–	–	1	1	1	–	–	–	–	–	–	–	–	–
Carex curta	–	–	–	–	–	1	–	–	–	–	1	30	–	–	–	–	–	–
Carex echinata	–	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–
Eriophorum angustifolium	–	–	–	–	–	–	–	–	–	1	1	3	–	1	1	–	1	–
Nanocyperion																		
Juncus bufonius	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Juncus tenageia	7	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Scirpus setaceus	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Radiola linoides	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Cicendia filiformis	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Junco–Molinion																		
Carex oederi	1	1	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–
Carex panicea	–	–	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–
Juncus conglomeratus	–	–	3	10	10	30	–	–	–	–	–	–	–	–	–	–	–	–
Juncus acutiflorus	–	–	–	–	–	–	–	–	–	1	5	20	–	–	–	–	–	–
Other species																		
Juncus bulbosus	1	3	–	–	–	–	7	1	1	–	–	3	–	–	–	–	–	–
Juncus effusus	1	1	1	1	2	2	–	–	–	1	2	3	–	–	–	–	–	–
Calamagrostis canescens	1	1	1	5	10	1	1	1	1	1	1	20	–	–	–	–	–	–

have resulted in an enlarged influence of seepage and inundation water. Together with the low nitrogen concentrations that have been obtained by sod cutting, optimal conditions for the development of a varied nutrient poor vegetation were established at Staverden.

The combination of sod cutting and hydrological measures has led to the restoration of the Ericetum tetralicis orchietosum, here. The zone in which this plant community has developed, is characterised by discharging groundwater, that flows superficially to

Table 7. Cover of some characteristic species (in%) at the distinguished hydrological zones of Staverden during the period 1989–1994). The permanent plots are representative of the vegetation development after sod cutting.

hydrological zone	seepage					inundiation					infiltration				
permanent plot	17	17	17	17	17	30	30	30	30	30	13	13	13	13	13
year	89	90	91	92	94	89	90	91	92	94	89	90	91	92	94
Ericion tetralicis/															
Calluno-Genistion pilosae															
Calluna vulgaris	–	–	–	–	–	–	–	–	–	–	–	–	2	2	8
Erica tetralix	–	–	–	2	2	–	–	–	–	–	–	–	2	2	2
Molinia caerulea	–	–	3	2	8	–	1	2	1	8	–	2	–	4	37
Narthecium ossifragum	–	–	–	1	3	–	–	–	–	–	–	–	–	–	–
Drosera intermedia	–	–	–	1	3	–	–	–	–	1	–	–	–	–	–
Gentiana pneumonanthe	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Lycopodium inundatum	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Rhynchospora alba	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–
Juncus bulbosus	–	2	–	37	8	–	–	–	37	19	–	–	–	–	–
Parvocaricetea/															
Caricetum curto–echinatae															
Juncus articulatus	–	–	2	2	–	–	–	–	4	–	–	–	–	–	–
Agrostis canina	–	–	–	1	–	–	–	–	1	–	–	–	–	–	–
Ranunculus flammula	–	–	–	1	2	–	–	–	–	–	–	–	–	–	–
Hydrocotile vulgaris	–	–	1	2	3	–	–	–	–	–	–	–	–	–	–
Carex curta	–	–	–	1	–	–	–	–	1	2	–	–	–	–	–
Carex echinata	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–
Nanocyperion															
Juncus bufonius	–	–	–	–	2	–	–	–	–	2	–	–	–	–	–
Junco–Molinion															
Carex oederi	–	–	2	–	19	–	–	–	–	–	–	–	–	–	–
Carex panicea	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Juncus conglomeratus	–	–	–	–	3	–	–	–	–	3	–	–	–	–	–
Juncus acutiflorus	–	–	–	–	3	–	–	2	4	19	–	–	–	–	–
Succisa pratensis	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Other species															
Juncus bulbosus	–	2	–	37	8	–	–	–	37	19	–	–	–	–	–
Juncus effusus	–	–	8	8	3	–	–	2	4	3	–	–	–	–	–

the lowest part of the reserve. Hence, no stagnation of base-poor surface water occurs in this seepage zone.

In the seepage zone of Stroothuizen the restoration of the Cirsio-Molinietum is only appropriate after hydrological measures have been taken, which ensure the impact of base- and iron-rich groundwater in the root zone of the soil. This can be reached by hydrological measures that reinforce the discharge of base- and iron-rich groundwater to the soil surface, such as filling up the ditches in the direct vicinity of the reserve that in the present situation drain the base and iron-rich groundwater from the second aquifer. Filling up ditches will result in increased groundwater heads in the second aquifer, which promote groundwater discharge to the soil surface. Such measures ought to be combined with measures that prevent stagnating water on the soil surface.

At Staverden hydrological measures, causing a sufficient supply of base cations, in combination with sod cutting have shown to be successful measures to coun-

Table 8. Groundwater table characteristics (in cm below soil surface) of the Cirsio-Molinietum orchietosum in the nature reserve 'Stelkamps Veld' (eastern part of The Netherlands) and of the frame community of the Junco-Molinion (adjacent to piezometer 1) in Stroothuizen. - = water table above the soil surface, x = mean water table, M = median water table,%I =% inundation, max = maximum water table, min = minimum water table.

year Stelkamps Veld	x	M	% I	max	min
1980	22	20	10	−1	57
1980	19	14	40	−1	62
1982	36	35	10	−1	83
1982	38	31	5	−1	91
1985	22	21	0	4	48
1988	47	45	0	13	97
Stroothuizen (piezometer 1)					
1990	13	1	45	−9	74
1991	22	26	35	−8	89

terbalance the effects of atmospheric acidifying and eutrophying compounds on plant communities of subneutral pH conditions.

Whether or not sod cutting and hydrological measures will be effective to prevent the impact of continuous nitrogen input in the long term (10–20 years), is still unknown.

Acknowledgments

We thank A. Th. W. Eysink (Staatsbosbeheer) and A. J. M. Roozen (Het Gelders Landschap) for providing field facilities and measuring the water tables, and T. H. M. Croese and P. J. M. Verbeek for surveying the vegetation. Comments on the manuscript by R. Bobbink, A. P. Grootjans, P. C. de Hullu, Prof. C. den Hartog, C. Maas, G. van Wirdum, and the referees are gratefully acknowledged. Our research was financed by the Netherlands Waterworks Association (VEWIN) and the Dutch Ministry of Agriculture, Nature Conservancy and Fishery.

References

Aerts, R. & Berendse, F. 1988. The effect of increased nutrient availability on vegetation dynamics in wet heathlands. Vegetatio 76: 63–69.

Appelo, C. A. J. 1988. Beïnvloeding van de waterkwaliteit in het Hierdense Beekgebied (NW-Veluwe). Report, Free University, Amsterdam.

Bakker, J. P. 1987. Restoration of species-rich grassland after a period of fertilizer application, pp. 185–200. In: Van Andel, J., Bakker, J. P. & Snaydon, R. W. (eds): Disturbance in grasslands. Junk Publishers, Dordrecht.

Bakker, J. P. 1989. Nature management by grazing and cutting: on the ecological significance of grazing and cutting regimes applied to restore former grassland communities in the Netherlands. Thesis, Kluwer Academic Publishers, Dordrecht.

Bakker, J. P., Brouwer, C., Van den Hof, L. & Jansen, A. J. M. 1987. Vegetational succession, management and hydrology in a brookland (the Netherlands). Acta Bot. Neerl. 36: 39–58.

Bannister, P. 1966. Biological flora of the British Isles: *Erica tetralix L.* J. Ecol. 54: 795–813.

Barkman, J. J., Doing, H. & Segal, S. 1964. Kritische Bemerkungen und Vorschläge zur quantitativen Vegetationsanalyse. Acta Bot. Neerl. 13: 394–419.

Berendse, F., Oomes, M. J. M., Altena, H. H. & De Visser, W. 1994. A comparative study of nitrogen flows in two similar meadows affected by different groundwater levels. J. appl. Ecol. 31: 40–48.

Boeye, D. & Verheyen, R. F. 1994. The relation between vegetation and soil chemistry gradients in a ground water discharge fen. J. Veget. Sci. 5: 553–560.

Buck-Sorlin, G. 1993. Ausbreitung und Rückgang der Englischen Kratzdistel – *Cirsium dissectum (L.)* – in Nordwestdeutschland. Tuxenia 13: 183–191.

Csonka, J. 1986. Onderzoek Denekamp Noord-Beuninger Achterveld. DGV-TNO, Delft/Oosterwolde.

De Graaf, M. C. C., Verbeek, P. J. M., Verheggen, G. M., Bobbink, R. & Roelofs, J. G. M. in press. Experimental liming of acidified heathlands and grasslands: effects on soil chemistry and vegetation. Proceedings symposium Ecosystem Manipulation, UK, 1994.

De Smidt, J. 1966. The inland-heath communities of the Netherlands. Wentia, 15: 142–166.

Grootjans, A. P. & Ten Klooster, W. Ph. 1980. Changes of groundwater regime in wet meadows. Acta Bot. Neerl. 29: 541–554.

Grootjans, A. P., Schipper, P. C. & Van der Windt, H.J. 1986. Influence of drainage on N-mineralization and vegetation response in wet meadows II. Cirsio-Molinietum stands. Acta Oecologica/Oecologia Plantarum 7: 3-14.

Grootjans, A. P., Van Diggelen, R., Wassen, M. J. & Wiersinga, W. A. 1988. Dynamics in trophic gradients along small rivers in relation to distribution of plant species. Vegetatio 75: 37–48.

Grootjans, A. P., Sival, F. P. & Suyfzand, P. J. 1996: Hydro-chemical analysis of a degraded dune slack. Vegetatio, this issue.

Gundersen, P. & Rasmussen, L. 1990. Nitrification in forest soils: effects from nitrogen deposition on soil acidification and aluminium release. Rev.Environ. Contam. Toxicol. 113: 1–45.

Haenes, D. L. 1984. Determination of total organic C in soils by an improved chromic acid digestion and spectrophotometric procedure. Communication in Soil Science and Plant Analysis 15: 1191–1213.

Hayati, A. A. & Proctor, M. C. F. 1990. Plant distribution in relation to mineral nutrient availability and uptake on a wet-heath site in South-west England. J. Ecol. 78: 134–151.

Houba, V. J. G., Van der Lee, J. J., Novozamsky, I. & Wallage, I. 1989. Soil and Plant analysis. Part 5: Soil analysis Procedures. Vakgroep Bodemkunde en Plantenvoeding. L.U. Wageningen.

Houdijk, A. L. F. M., Verbeek, P. J. M., Van Dijk, H. F. G. & Roelofs, J. G. M. 1993. Distribution and decline of endangered herbaceous heathland species in relation to the chemical composition of the soil. Plant and Soil 148: 137–143.

Koerselman, W. 1992. The nature of nutrient limitation in Dutch dune slacks. pp. 189–199. In: Curtis, T. F. H & Sheehy-Skeffington, M. J. (eds), Coastal dune; geomorphology, ecology and management for conservation. Balkema, Rotterdam.

Koerselman, W., Bakker, S. A. & Blom, M. 1990. Nitrogen, phosphorus and potassium budgets for two small fens surrounded by heavenly fertilized pastures. J. Ecol. 78: 428–442.

Kok, C. J. & Van de Laar, B. J. 1991. Influence of pH and buffering capacity on the decomposition of *Nymphea alba* L. detritus in laboratory experiments: a possible explanation for the inhibition of decomposition at low alkalinity. Verh. int. Ver. Limnol. 24: 2689–2692.

Londo, G. 1976. The decimal scale for relevés of permanent quadrats. Vegetatio 33: 61–64.

Maas, D. & Schopp-Guth, A. 1995. Seed banks in fen areas and their potential use in restoration ecology. In: Wheeler, B. D., Shaw, S. C., Fojt, W. J. & Robertson, R. A. (eds), Restoration of Temperate Wetlands. Wiley & Sons, Chichester.

Meisel, K. 1977. Die Grünlandvegetation nordwestdeutscher Flusstäler und die Eignung der von ihr besiedelten Standorte für einige wesentliche Nutzungsansprüche. Schriftenreihe für Vegetationskunde 11: 1–121.

Merck 1983. Schnelltest Handbuch, Darmstadt.

Moore, P. D. & Bellamy, D. J. 1974. Peatlands. Elek Science, London.

Niemann, E. 1963. Beziehungen zwischen Vegetation und Grundwasser, ein Beitrag zur Präzisierung der ökologischen Zeigerwertes von Pflanzen und Pflanzengesellschaften. Archiv für Naturschutz und Landschaftsforschung 3: 3-37.

Novozamsky, I., Houba, V. J. G., Van Eck, R. & Van Vark, W. 1983. A novel digestion technique for multi-element plant analysis. Communication in Soil Science and Plant Analysis 14: 239–248.

Page, A. L. 1989. Methods of soil analysis. Part 2: Chemical and microbiological properties. American Society of Agriculture, Madison.

Patrick, W. H. Jr. & Khalid, R. A. 1974. Phosphate release and sorption by soils and sediments: effect of aerobic and anaerobic conditions. Science 186: 53–55.

Pitcairn, C. E. R., Fowler, D. & Grace, J. 1991. Changes in species composition of seminatural vegetation associated with the increase in atmospheric inputs of nitrogen. Final report to Nature Conservancy Council, Institute of Terrestrial Ecology, Edinburgh.

Rodwell, J. 1991. British plant communities Volume 2: Mires and Heaths. Cambridge University Press, Cambridge.

Roelofs, J. G. M. 1986. The effect of airborne sulphur and nitrogen deposition on aquatic and terrestrial heathland vegetation. Experimentia 42: 372–377.

SAS 1985. SAS User's Guide, Statistics. Version 5 Edition. Cary NC, SAS Institute Inc.

Smith, A. J. E. 1980. The moss flora of Britain and Ireland. Cambridge University Press, Cambridge.

Soukupová, L. 1992. *Calamagrostis canescens*: population biology of a clonal grass invading wetlands. Oikos 63: 395–401.

Stuyfzand, P. J. 1989. A new hydrochemical classification of water-types. IAHS Publication 182: 89–98.

Stuyfzand, P. J. 1993. Hydrochemistry and hydrolgy of the coastal dune area of the western Netherlands. Thesis, Free University of Amsterdam.

Succow, M. 1988. Landschafsökologische Moorkunde. Gebrüder Borntraeger, Berlin/Stuttgart.

Summerfield, R. J. 1974. Biological flora of the British Isles: *Narthecium ossifragum* (L.) Huds. J. Ecol. 46: 247–253.

Swift, M. J., Heal, O. W. & Anderson, J. M. 1979. Decomposition in terrestrial ecosystems. Studies in Ecology, Volume 5. Blackwell Scientific Publications, Oxford.

Tüxen, R. 1954. Pflanzengesellschaften und Grundwasser Ganglinien. Angewandte Pflanzensociologie 8: 64–98.

Van der Meijden, R. 1990. Heukels' flora van Nederland. Wolters-Noordhoff, Groningen.

Wassen, M. J., Barendregt, A., Palczynski, A. De Smidt, J. T & De Mars, H. 1990. The relationship between fen vegetation gradients, groundwater flow and flooding in an undrained valley mire at Biebzra, Poland. J. Ecol. 78: 1106–1122.

Westhoff, V. 1978. Bedrohung und Erhaltung seltener Pflanzengesellschaften. pp. 285–310. In: Tüxen, R. (ed), Werden und Vergehen von Pflanzengesellschaften. Cramer, Vaduz.

Westhoff, V. & Den Held, A. J. 1969. Plantengemeenschappen in Nederland. Thieme, Zutphen.

Westhoff, V. & Jansen, A. J. M. 1990. Vegetatiegegevens uit de jaren veertig van Noordoost-Twente. Kiwa-report SWE 90.025, Nieuwegein.

WMO 1985. Nieuw waterwingebied Denekamp: inventarisatieonderzoek. WMO, Zwolle.