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Water and solute fluxes in dry coastal dune grasslands: the effects of grazing and increased nitrogen deposition

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Abstract

A five-year monitoring study has been carried out to examine the combined effects of grazing and atmospheric nitrogen deposition on water and solute fluxes in dry coastal dune grasslands. Two vegetation types were studied: (a) a short, species-rich stand on calcareous sand (foredune site) and (b) a short, species-poor stand on partly decalcified soil on calcareous sand (innerdune site). In each stand four experimental plots were created: (1) control, (2) fertilized with nitrogen, (3) excluded from grazing by rabbits and (4) combination of fertilization and exclusion of grazing by rabbits.

Due to the large spatial variability of the soil water content, no differences between the treatments could be measured. Average soil water content at 10 cm depth is very small (3–5%) from May until October and does not increase after rainfall. However, measured soil water content at 20 cm and 50 cm depth increased after rainfall. In winter, nearly all measured soil water contents increase upon rainfall, although sometimes one soil water content remained dry till the end of the next summer.

In summer it was impossible to sample soil water for the estimation of the solute concentrations due to the very small soil water content. Therefore, only solute concentrations of the winter period could be evaluated.

Without fertilization, fluxes of nitrogen out of the soil system are below the incoming flux, due to storage in the biomass and in the soil compartment. When fertilized, 70% of the added NH_4^+-N was leached from the foredune soil profile as NO_3^--N, due to nitrification. Conversely, at the grazed innerdune site most of the added nitrogen remained in the system. Here, nitrification rates will be small due to the decalcified topsoil and NH_4^+-N is not easily leached out of the soil compartment. At the exclosures of the innerdune site, about 15% of the amount of the added fertilizer N was leached, after added NH_4^+ is taken up by the plants and partly washed out as nitrate after mineralization and nitrification of dead biomass.

Introduction

Recently, semi-natural vegetation in the Netherlands has been under increasing influence of atmospheric deposition of acidifying and eutrophicating components. This impact has led to a decrease in nature conservation values. Since the 1970s some tall perennial graminoids, notably *Ammophila arenaria, Avenula pubescens, Calamagrostis epigejos, Elymus athericus* and *Carex arenaria*, have become dominant in many originally species-rich short dry dune grasslands of the Netherlands (Vertegaal et al., 1991). As a consequence, these grasslands now show a relatively low species diversity. From the point of view of nature conservation this is considered an unfavourable situation (Westhoff, 1985). Nowadays, nature managers try to counteract this development and try to restore the original vegetation composition. This requires understanding of the processes responsible for the predominance of graminoids.

In chalk grasslands and heathlands in the Netherlands the influence of atmospheric deposition has been

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studied to support management programmes aiming at restoration of nature values (Aerts and Heil, 1993; Bobbink 1991; Bobbink et al., 1988, 1990; Heil and Diemont, 1983; Roelofs, 1986). So far, no such systematic studies were undertaken in the coastal dune area. The present study was initiated in 1988 to understand the relationships between atmospheric deposition, grazing and vegetation dynamics. Plots were investigated under grazing and non-grazing conditions, both under current atmospheric nitrogen deposition levels and increased levels. The increased atmospheric deposition was simulated by fertilization with ammonium nitrate and ammonium sulphate.

The results of the vegetation relevés showed no effect of the fertilization on the vegetation composition (Ten Harkel and Van der Meulen, 1996). It was hypothesized that the effects are absent if a major part of the added nitrogen is leached out of the soil compartment.

Nitrogen leaching has been mainly studied in intensively-managed grasslands with increased loads of fertilizer (Barraclough et al., 1984; McLay et al., 1991; Scholefield et al., 1993) and forests (Cortina et al., 1995; Koopmans et al., 1995; Tietema and Verstraten, 1992; Van Breemen et al., 1987). The processes in the dune grassland soils are comparable to those in the soils of the above mentioned grasslands and forests. Nitrogen leaching can lead to ground water concentrations which are above EU drinking water norms (Anonymus, 1984). This is also of concern in our research area, since the groundwater in this area is used for drinking water.

The determination of nitrogen fluxes in the soil compartment is hampered by the large spatial variability of the soil water content and the very small soil water content in summer. When dry in summer, the soil of the dry dunes can become very water repellent (Dekker and Jungerius, 1990; Jungerius and De Jong, 1989; Ritsema et al., 1993). Water repellency in sandy soils is caused by hydrophobic organic compounds derived from plant material or soil micro-organisms. The organic compounds occur either on the surface of sand grains or are intermixed with soil particles (Chan, 1992; Jex et al., 1985; Ma'shum et al., 1989; Miller and Wilkinson, 1977). Within a specific soil type this water repellency seems to be closely related to organic matter content (Bisdom et al., 1993; Harper and Gilkes, 1994). In general, Wallis et al. (1993) stated that it is the nature rather than the quantity of the organic matter *per se* which is the most important determinant of repellency in a soil. They found that the fulvic acid to humic acid ratio was an important parameter. Capriel et al. (1995) and Capriel (1997) characterized the degree of hydrophobicity of the soil organic matter with the aliphatic C-H to C_{org} ratio. They assumed that the hydrophobicity is caused by methyl, methylene and methine groups present in aliphatic and aromatic (olefinic) compounds.

Water repellency might lead to the formation of preferential flow paths (Raats, 1973; Ritsema and Dekker, 1996). Sections of the topsoil are bypassed and remain very dry if preferential flow occurs (Dekker and Jungerius, 1990; Ritsema et al. 1993). At the experimental site of Ritsema et al., (1993) the relatively wet areas had the form of fingers and occurred between 5 and 45 cm depth. The diameter of the vertical directed preferential flow paths varied between 5 and 20 cm at their site (Ritsema et al., 1993). The water repellency causes an increased spatial variability in soil water fluxes and resultant solute fluxes out of the soil system. The effect is dependent on whether a solute is abundant in the incoming flux or abundant in the soil system itself (McLay et al., 1991; Williams et al., 1990). In the first case solute fluxes are raised after the preferential flow occurs, the second results in smaller fluxes. Both differences are the result of bypassing part of the soil matrix by the soil water flow.

The effect of preferential water flow on sampling soil water is twofold. First, parts of the soil remain relatively dry and sampling by ceramic suction cups will be often impossible in sandy soils. Second, a soil water sample might not be representative due to the large lateral spatial variability in soil water content. These problems are less important in winter, when soil water is more equally distributed.

This paper discusses two main topics. First, soil water contents will be presented together with their spatial and temporal variability. Second, fluxes of nitrogen and other elements entering the system by bulk deposition, throughflow and fertilization with nitrogen, and leaching rates will be presented. The effects of the treatments, fertilization and excluding grazing, on soil water contents and soil water chemistry will also be reported.

Material and methods

Study sites

Bulk deposition, throughfall and soil water content and composition were measured at two sites in the

Figure 1. Location of the research area.

Meijendel dune area north of The Hague, The Netherlands (Figure 1).

The foredune site (MS1) is located on a grassland in a valley of 3 m depth at 0.5 km distance to the sea. The sandy soil is calcareous, with 2–3 wt% $CaCO_3$, and with a small organic matter content of 1.8 wt% in the 10 cm top soil. Phyto-sociologically, the vegetation at this site can be assigned to the *Festuco-Galietum maritimi* association (Westhoff and den Held, 1969). This site was monitored from July 1989 till June 1994.

The innerdune site (MS2) is located on a flat grassland just outside a small forest at a distance to the sea of 2.0 km. The soil is formed in similar calcareous dune sand as the foredune site, but is decalcified down to 40–50 cm depth. In the decalcified zone, pH_{CaCl2} increased from 4.2 at 10 cm depth to 5.4 at 20 cm depth. The 10 cm thick top soil has an organic matter content of 2.8 wt%. The site represents a poor variant of the *Violo-Corynephoretum* association (Westhoff and den Held, 1969). Monitoring at this site took place from August 1988 till June 1994.

Major industrial areas are the 'Rijnmond' area, about 30 km to the south, and the 'IJmond' area, 40 km to the north. The edge of the city of The Hague is at a distance of about 5 km.

The proximity of the sea causes a bulk deposition of sodium of 4780 mol ha^{-1} yr^{-1} at MS1 and 2960 mol ha^{-1} yr^{-1} at MS2, compared to an average of 723 mol ha^{-1} yr^{-1} for the Netherlands (RIVM and KNMI, 1989). Bulk deposition of nitrate and sulphate, corrected for sea spray, are identical at both sites and both are comparable with the average Dutch level: about 400 and 450 mol ha^{-1} yr^{-1} respectively. Ammonium bulk deposition of 400 mol ha^{-1} yr^{-1} at both sites is much smaller than the Dutch average of 925 mol ha^{-1} yr^{-1}. The smaller ammonium deposition can be explained by a distance of 75 km or more to the main source of ammonium, which is intensive husbandry, and the short travel distance of ammonium (Erisman and Heij, 1991).

Treatments

At both sites a quadrat of 2$\times$2 m with a homogeneous vegetation was selected. Each quadrat was divided into four experimental plots of 1$\times$1 m: (1) control; (2) fertilized; (3) excluded from grazing by rabbits; (4) combination of fertilization and the exclusion of grazing. Treatments were allocated randomly to the plots (randomized quadrat design).

The fertilizer was applied to simulate the effects of increased loads of atmospheric nitrogen deposition. It was hypothesised that addition of nitrogen would speed up grass encroachment with an associated loss of characteristic herbs.

From the start of the fertilization experiments in October 1988 until April 1992 the fertilizer was applied in the form of NH_4NO_3 pellets (added in spring and autumn) equal to an extra deposition of 25 kg N ha^{-1} yr^{-1}. Soil water composition collected weekly by ceramic cups showed that large amounts of this fertilizer leached from the rooted part of the soil within a few weeks. Therefore, a different method of fertilization was applied since April 1992 and the quadrats were fertilized with 1 L of a 0.0069 *M* $(NH_4)_2SO_4$ solution once every fortnight, which is equal to an extra nitrogen input of 50 kg N ha^{-1} yr^{-1}. To prevent osmosis at the plant leaves NaCl (sea salt) was added in this solution up to the same NaCl concentration as in rainwater (4150 μmol L^{-1} at MS1 and 2500 μmol L^{-1} at MS2). The non-fertilized plots obtained an equal amount of additional NaCl. The yearly amount of solution given was equivalent to an extra precipitation of 26 mm per year, which is only 3% of the average yearly precipitation. The additional fluxes of the new fertilizing method were 3600 mol NH_4^+ ha^{-1} yr^{-1} and 1800 mol SO_4^{2-} ha^{-1} yr^{-1} as fertilizer at both sites and 108 mol NaCl ha^{-1} yr^{-1} at the foredune site and 65 mol NaCl ha^{-1} yr^{-1} at the innerdune site.

Measurements and calculations

Bulk deposition is defined as the atmospheric deposition in the open field as measured with permanently open collectors at 1.5 m above the soil surface and is described in detail by Ten Harkel (1997a).

At the exclosures, precipitation either falls directly on the ground or reaches the ground after interception by the vegetation, which is called throughfall, or by stemflow. The sum of both flows is called throughflow. The method and the measured solute fluxes are reported by Ten Harkel (1997b).

Soil water was sampled by ceramic suction cups at 50 cm beneath the soil surface of all four experimental plots of both sites in order to estimate its chemical composition. Suction cups were connected with sample bottles and held at an under pressure.

Chemical analyses used for the bulk deposition are described elsewhere (Ten Harkel, 1997a). Throughfall and soil water were collected every fortnight. Within 24 h the samples were analysed for alkalinity (titration with hydrochloric acid to pH = 4.5 and 4.2) and pH. Samples were filtered (0.45 μm) and part of it was acidified to pH = 2 for determination of K, Na, Ca, Mg and NH_4. Concentrations of K, Na, Ca, and Mg were determined with a flame atomic absorption/emission spectrophotometer. A continuous-flow auto-analyzer was used for NH_4, Cl, NO_3, SO_4 and ortho-P. The chemical measurements were carried out from June 1991 to July 1994 on MS1 and from September 1990 to July 1994 on MS2.

Automatic *in situ* volumetric soil water content measurements were carried out at the foredune and the innerdune site. At the foredune site (MS1), an 8 channel capacitive soil water content meter (CSW) (Halbertsma et al., 1987) was used from April 1992 until July 1994. Four 10 cm long CSW probes were installed horizontally at a depth of 10 cm, one in each plot. Probes were installed in one grazed and one non-grazed experimental plot at a depth of 20 and 50 cm. One 10 cm long TDR (see innerdune site) probe was installed horizontally at each depth (10, 20 and 50 cm) at all plots and measured once a week. At the innerdune site, an automated Time Domain Reflectometry (TDR) system (Heimovaara and Bouten, 1990) was used from June 1992 until July 1994. One triple-wire TDR probe of 50 cm length was installed horizontally at each depth of 10, 20 and 50 cm at all four experimental plots. In addition, 30 TDR probes of 10 cm length were installed outside the foredune plot under a vegetation similar to the grazed plots in order to determine lateral spatial variability of the soil water content. At each depth of 10, 20 and 50 cm 10 TDR probes were installed horizontally with a horizontal interval of 10 cm. Measurements were carried out weekly during the last year (July 1993–July 1994).

Mean solute fluxes out of the soil system were calculated by averaging all measured ion/chloride ratios at 50 cm and multiplying these ratios with the incoming flux for chloride. This incoming flux was the bulk deposition amount for the grazed plots and the throughflow amount for the exclosures. Solute fluxes are expressed in mol ha^{-1} yr^{-1}.

The calculated solute fluxes are only realistic if the assumption that chloride behaves as an inert ion in the soil is true. This is disputable for the exclosures, because it was shown that a substantial part of throughflow of chloride is not of atmospheric origin but washed out from the above ground parts of the plants (Ten Harkel, 1997b). An equal amount of chloride is probably entering the plant by root uptake. A second problem is that the throughfall is measured at the border of the plots and the ceramic suction cups were installed in the centre. Part of the sea-salt aerosols probably did not get into the throughfall collectors but will leave the plot by bouncing off or being blown off the plants (Ten Harkel, 1997b). This will not happen in the central part of the plots. Because of these problems the fluxes from the exclosures cannot be compared to those of the grazed plots, but comparing fluxes from the fertilized to those of the non-fertilized plots is allowed.

Results

Soil water content

Figure 2 gives a box-whisker plot for each probe at each depth of the soil water contents at the homogeneous plot at the foredune site and for each probe at each treatment plot at the foredune and innerdune site during the same measurement period as at the homogeneous plot (1 year). The box-whisker plot for each probe gives information about the temporal variation in soil water content, while comparing box-whisker plots gives information about the spatial variation. Figure 2 shows that soil water content is nearly always and everywhere small. The soil water contents averaged over the whole measurement period at the innerdune site are statistical significant ($p < 10\%$) higher than at the foredune site, except for the control

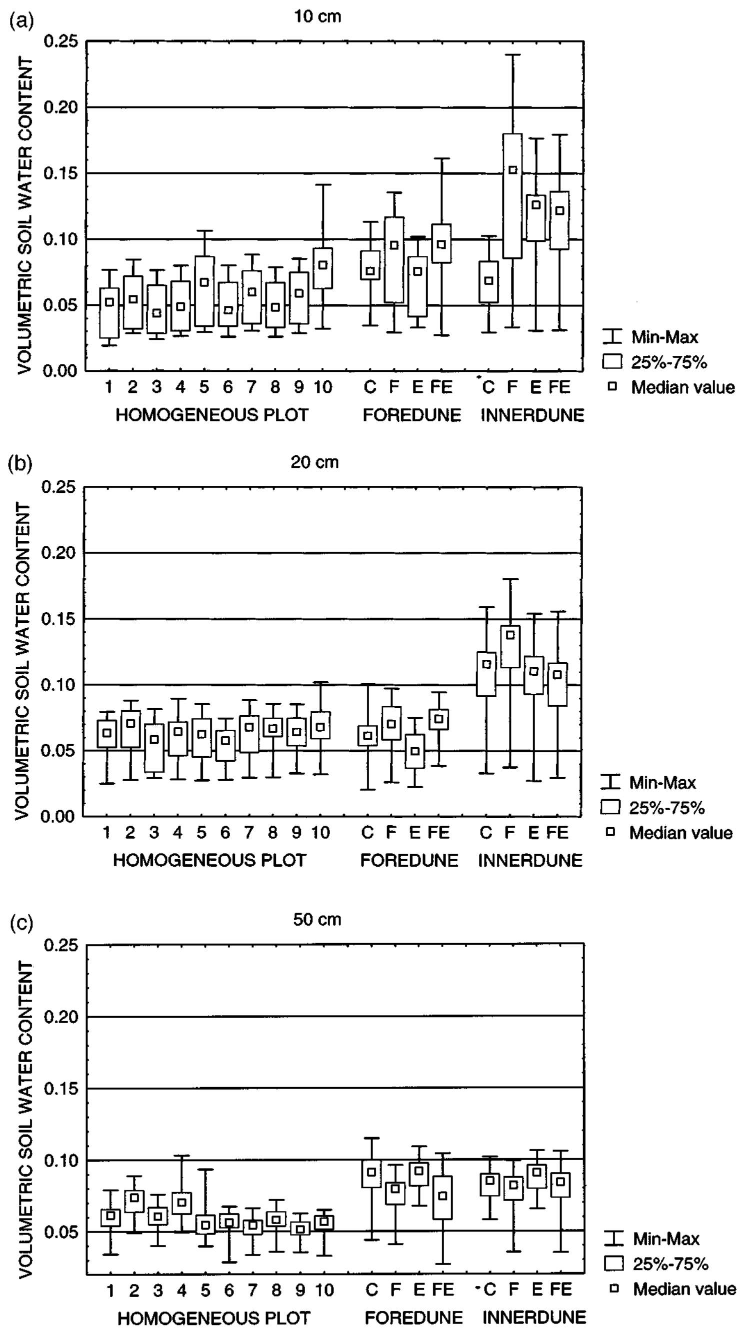

Figure 2. Box-whisker plots for three depth (10, 20, 50 cm) of the measured soil water content of the homogeneous plot, the foredune site and the innerdune site. C= control, F = fertilzed, E = exclosure and FE = fertilzed exclosure.

at 10 cm depth. The differences are probably due to differences in organic matter content (1.8% at MS1 and 2.8% at MS2 in the upper 10 cm of the soil). The differences between treatments are not larger than as found on the homogeneous plot.

In general, measured soil water content at 10 cm depth decreased to about 3% in May and showed no increase after rainfall (Figures 3 and 4). However, at 20 cm and 50 cm depth this reaction was seen. In October soil water content at 10 cm increased again, although one measured soil water content remained sometimes small during the winter. If the soil was wet again at 10 cm depth, measured soil water content increased after rainfall.

Figure 5 gives two examples of the measured soil water contents: (a) in a soil with a small soil water content at 10 cm depth and (b) with a relatively large soil water content at 10 cm depth. Soil water content at 10 cm depth is constant about 0.04 m^3 m^{-3} in the first example (Figure 5a), while soil water contents at 20 and 50 cm depth were still between 0.05 m^3 m^{-3} and 0.09 m^3 m^{-3}. Although the soil water content at 10 cm depth remained stable after rainfall, it did increase at the depths of 20 and 50 cm. Visual inspection of a bare soil in the surrounding of the innerdune site just after rainfall, showed a uniformly wet topsoil of just a few centimetres above a soil layer with dry and wet parts, which corresponds with the measures as found by Ritsema et al. (1993). This supports the concept of preferential flow, by which sections of the soil below the upper few centimetres remain dry and are not influenced by rainfall, while in the subsurface soil a more normal infiltration pattern exists. In November soil water contents and reaction to rainfall are largest at 10 cm depth (Figure 5b). Soil water content at 50 cm depth is between 0.07 m^3 m^{-3} and 0.09 m^3 m^{-3} in the dry as well as in the wet period (Figure 5).

Summarizing, it can be concluded that soil water contents in the months May till October show a large spatial variability, due to irregular wetting and the probable occurrence of preferential flow. In the other months, the soil water is much more homogeneously distributed in the different soil horizons. However, some parts of the soil remain dry even during the winter months. It seems that the treatments had no systematic effect on the soil water content distribution. The consequence for soil water composition is that soil water in some parts of the soil has no direct relation with rainfall composition when preferential flow occurs. A second effect is that components in the precipitation can easily flow through the soil, with little retention.

Average solute fluxes in the soil

The ceramic soil moisture suction tubes did not sample any soil water at volumetric soil water contents below 5–6%. Below this soil water content air is entering the ceramic cups. This occurs during the summer months, and even sometimes in winter, in large parts of the soil. Therefore, no complete sample programme was possible during summer periods. To compare the chemical fluxes of the various plots, the averages of the months October to May during the measurement periods of both sites are given (Table 1).

Despite the above-mentioned limitation, some major points can be raised with respect to the solute fluxes in soil water (Table 1).

It is not really possible to compare the grazed and non-grazed plots because the measured chloride levels in throughflow of the non-grazed plots are too small due to sea salt bouncing off or being blown from the vegetation, and chloride in throughflow is not completely of atmospheric origin because part of the chloride in the throughflow is pumped around by the vegetation and not leached out of the soil compartment. This last feature is illustrated by a sodium flux out of the soil compartment (Table 1) which is much larger than the throughflow flux at the exclosures, while at the grazed plots these fluxes are about equal to the bulk deposition flux. The overestimation of the input flux of chloride at the exclosures causes an overestimation of the other solute fluxes out of the soil compartment.

The solute fluxes leaving the soil compartment at 50 cm depth (Table 1) are highly influenced by dissolution of carbonates. The ratio of the solute flux in the soil water to the input flux is between 10 and 30 for calcium and about 2.5 for magnesium. The increase of the solute flux of weak acids is from 0 to about 2000 mol ha^{-1} yr^{-1} at the grazed plots and from about 50 to about 2500 mol ha^{-1} yr^{-1} at the grazed plots (Table 1). The increase in magnesium flux relative to the input flux (350–1700 mol ha^{-1} yr^{-1}) is between 4% and 12% of the increase in calcium flux (10–17 kmol ha^{-1} yr^{-1}). This would be expected if the magnesium content of calcium carbonate is taken into account. The increase in the fluxes of weak acids (17–30 kmol ha^{-1} yr^{-1}) are between 160% and 240% of the increase of the fluxes of calcium and magnesium after passage of the soil (11–18 kmol ha^{-1} yr^{-1}). This

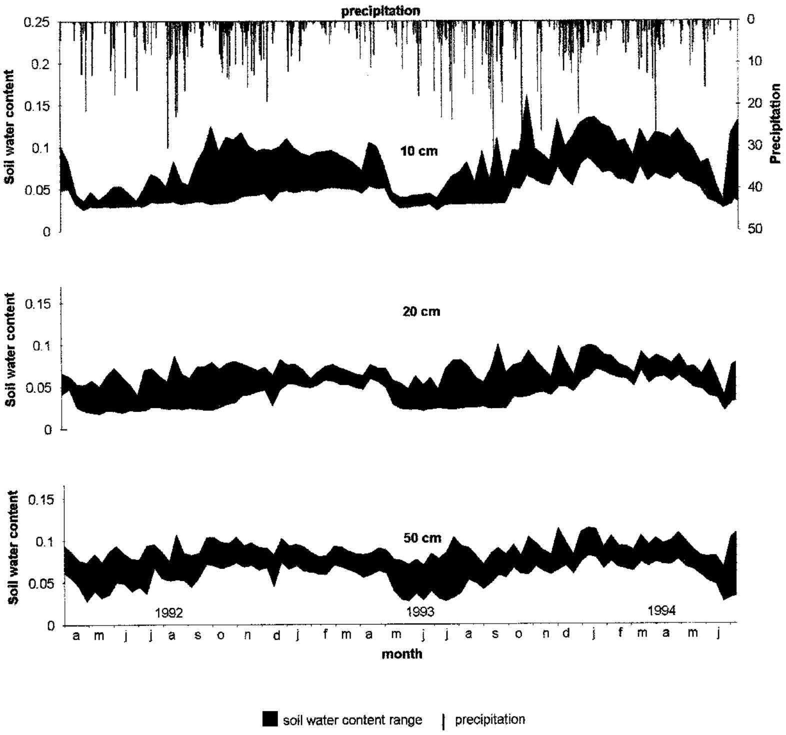

Figure 3. Range of measured volumetric soil water content (m^3 m^{-3}) at three depths at the foredune site (MS1) from April 1992 to July 1994.

is due to the fact that at the pH of this soil system the dissolution of carbonates produces two mol HCO_3^- for every mol Ca^{2+} or Mg^{2+}.

Nearly all the SO_4^{2-} added as fertilizer is leaving the system. Increases of this flux after an extra input of about 1800 mol SO_4^{2-} ha^{-1} yr^{-1} were between 1400 and 1800 mol ha^{-1} yr^{-1} (Table 1). Only the exclosures of the foredune had an equal flux of SO_4^{2-} in the soil compartment, which could be due to some measurements in a dry soil. The first measured sulphate concentrations at 50 cm after the summer period without soil water samples were 4.2 times larger than later on in the winter. This is probably an example of measurements done in a relatively dry part of the soil without hardly any interaction with the infiltrating water. The other ions, except nitrate and ortho phosphate, had concentrations in these first samples between 1.6 and 4.2 times larger than later on in the winter.

About 70% of the added NH_4^+ at the foredune site leaves the soil as NO_3^- due to the raised nitrification rates in the calcareous soil of this site. No nitrogen of the fertilizer is lost through the soil at the grazed innerdune plot and only 13% at the exclosure of the innerdune site. The larger flux at the foredune site might be due to a raised nitrification rate in the calcareous soil with a higher pH at the foredune site (Dancer et al., 1973; Killham, 1990; Nyborg and Hoyt, 1978). The larger flux at the fertilized exclosure at the innerdune site compared to the grazed and non-fertilized exclosure was possibly due to fertilizer taken up by the vegetation and subsequent mineralisation and nitrification of senescing leaves and dead standing biomass. The throughflow is indeed larger at the fertilized exclosure (100 μmol L^{-1}) compared to the exclosure (50 μmol L^{-1}). Differences were largest in April and in October–November. The first period coincides with the start of the growing season, when temperatures and decomposition of the dead biomass increase. Smallest differences occur in May–June when the dunes become dry and decomposition becomes smaller. The second period with large differences is when the leaves are senescing and nitrate is washed out. No dead biomass existed at the grazed plots and amount of living biomass is small. The fertilizer nitrogen left the system at the grazed plots due to grazing by rabbits or is incorporated in the biomass.

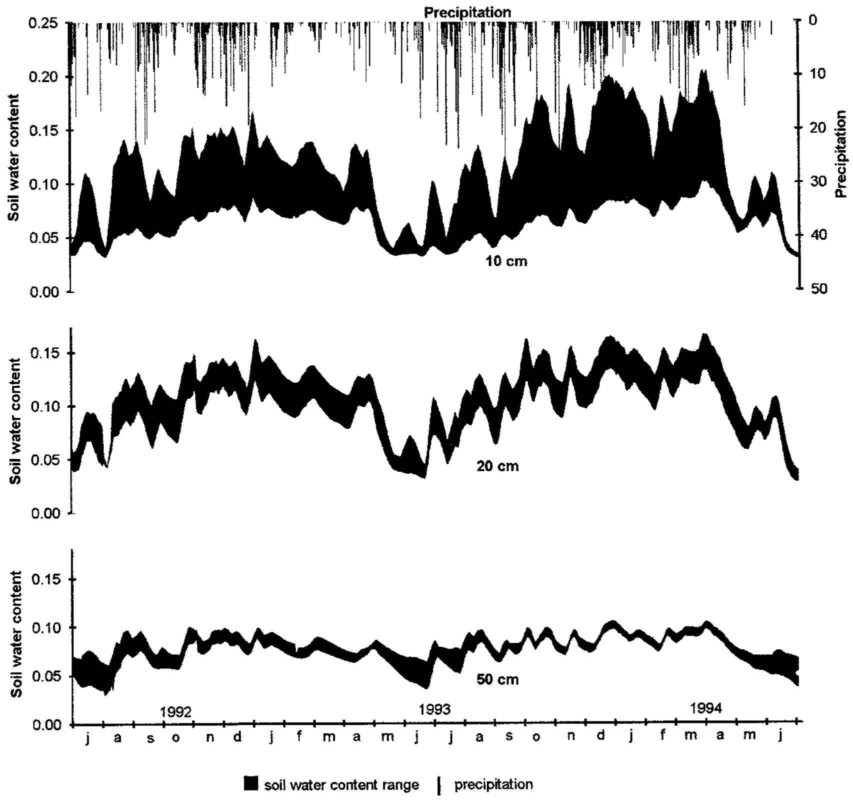

Figure 4. Range of measured volumetric soil water content ($m^3\ m^{-3}$) at three depths at the innerdune site (MS2) from July 1992 to July 1994.

Effect of ignoring summer solute fluxes

During the summer of 1993, soil water could be sampled. Figure 6 shows the sum of all the equivalent solute fluxes at 50 cm depth for both the measurement sites and averaged for all the treatments. The fluxes of all solutes are of course smallest in summer and largest in winter. In summer, readily soluble material accumulates, which is leached in winter (Foster and Walling, 1978). Figure 6 shows also the trends of soil temperature and soil water content at 50 cm depth. The fluxes have the same seasonal trend as the soil water content. This trend is inverse to the trend of the soil temperature. The high temperatures cause small soil water contents and consequently small solute fluxes.

Calculating average year fluxes of solutes in the soil water without the soil water samples of summer 1993 gives about 30% larger fluxes for all solutes in the period November 1992 till June 1994, except for nitrate and sulphate, of which the fluxes are 50% and 15% larger, respectively.

Differences between the sites have been discussed already. Only differences in nitrogen fluxes between the sites need some further explanation. These differences are very small in the summer months and increased in the autumn (Figure 7). During winter these differences exist because of the raised nitrification rates at the calcareous foredune site (Dancer et al., 1973; Killham, 1990; Nyborg and Hoyt, 1978). Consequently, the ammonium flux is the smallest, while the nitrate flux is the largest at the foredune site (MS1). Relatively high soil temperature in summer (about 18 °C) should cause relatively large mineralization rates (Freijer, 1994; Stanford et al., 1973) and nitrification rates (Emmer and Tietema, 1990; Killham, 1990). Emmer and Tietema (1990) found in a forest soil an optimum for nitrification at 25 °C. However, mineralization and nitrification in summer are very small due to very small soil water contents (Figures 3 and 4). Myers et al. (1982) found a linear relationship between net nitrogen mineralization rate and soil water content and some nitrifying soil microbes are very sensitive to water stress (Killham, 1990).

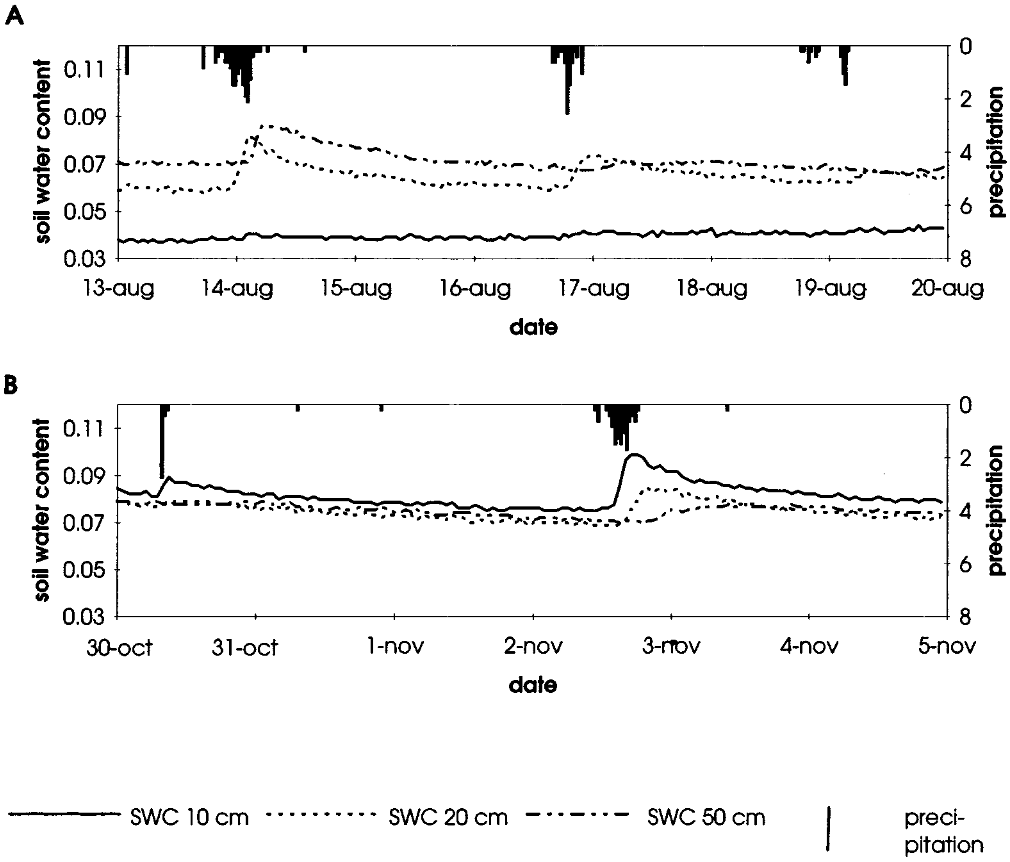

Figure 5. Volumetric soil water contents ($m^3\ m^{-3}$) at 10, 20 and 50 cm depth and cumulative amount of precipitation (mm) on the fertilized plot at the foredune site (MS1) between (a) 08-13-92 and 08-20-92 and (b) between 10-30-92 and 11-05-92.

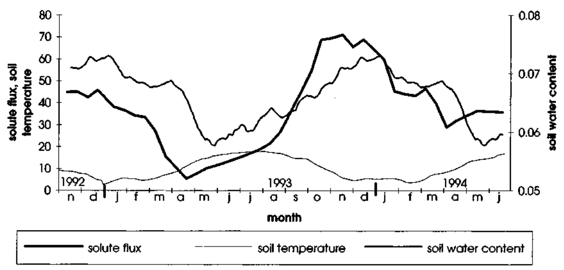

Figure 6. Two month moving average of total solute flux in the soil water averaged for the foredune site (MS1) and the innerdune site (MS2) in $kmol_c\ ha^{-1}\ yr^{-1}$, soil temperature (°C) and soil water content ($m^3\ m^{-3}$) at 50 cm depth.

Discussion

The absence of a reaction of the vegetation upon nitrogen fertilization can only partly explained by the leaching of nitrogen from the soil compartment. At the foredune site about 70% of the added nitrogen is leached from the soil. However, at the innerdune site this nitrogen is accumulating in the soil under grazed conditions or only 13% is leached under the exclosures. Therefore, nitrogen leaching cannot be the main reason for no reaction of the vegetation upon fertilization at the innerdune site. The vegetation at these grasslands might be phosphorous limited. Phosphorous is the second most important nutrient in dry dune grasslands (Boorman and Fuller, 1983; Dougherty et al., 1990; Kachi and Hirose, 1983; Milton, 1940, 1947; Willis, 1963). A second reason might be that an adaption of the vegetation in latter successional stages to a higher nutrient availability might take more than five years, as was proposed by DiTomasso and Aarsen (1991) and Morecroft et al. (1994).

To compare the measured solute fluxes with literature data on solute fluxes in coastal dune ecosystems (De Vries et al., 1994; Dopheide and Verstraten, 1995;

Table 1. Input (bulk deposition or throughflow) and output (soil water at 50 cm depth) solute fluxes in mol ha^{-1} yr^{-1} at the foredune site (MS1) and the innerdune site (MS2)

	Grazed plots				Exclosures			
	Non-fertilized		Fertilized		Non-fertilized		Fertilized	
	Bulk deposition	Soilwater flux	Bulk deposition	Soilwater flux	Throughflow	Soilwater flux	Throughflow	Soilwater flux
MS1								
H^+	150	0	150	0	10	0	30	0
Na^+	6300	6300	6300	6000	5700	7800	6600	8200
K^+	200	90	200	350	500	100	600	90
Ca^{2+}	450	11000	450	17900	950	10700	1400	11200
Mg^{2+}	700	1600	700	2000	850	1200	900	1700
NH_4^+	350	100	3900	100	700	100	3400	90
Cl^-	6700	6700	6700	6700	7600	7600	8200	8200
NO_3^-	400	1100	400	3500	550	350	500	3000
SO_4^{2-}	750	1400	2500	3200	1200	2900	3100	2900
P ortho	6	5	6	6	20	20	10	3
WA[a]	0	23000	0	29700	450	17300	300	20100
inorg. N[b]	750	1200	4300	3600	1250	450	3900	3100
MS2								
H^+	150	0	150	0	10	0	20	0
Na^+	3800	4200	3800	4600	3100	6300	3000	4900
K^+	150	150	150	100	950	100	950	100
Ca^{2+}	350	11300	350	14100	800	11500	1000	12600
Mg^{2+}	400	1700	400	2100	600	1500	750	1600
NH_4^+	400	150	4000	150	900	100	2500	100
Cl^-	4300	4300	4300	4300	4800	4800	4500	4500
NO_3^-	350	150	350	150	1000	150	1300	700
SO_4^{2-}	600	1700	2500	3100	1000	2000	2000	3800
P ortho	7	40	7	20	90	3	50	10
WA[a]	0	21500	0	30100	400	28000	600	23200
inorg. N[b]	750	300	4350	300	1900	250	3800	800

[a] Weak Acids (HCO_3^- + organic anions).
[b] NH_4^+ + NO_3^-.

James and Wharfe, 1989; James et al., 1986; Kellman and Roulet, 1990; Stuyfzand, 1984, 1993), the ratio of solute flux in the soil water to incoming flux (bulk deposition or throughflow) is used (Table 2). These ratios show that the solute fluxes as measured at both the measurement sites are comparable to those found in literature. The ratios for nitrate, except the grazed MS1, and potassium are smaller. For nitrate this can be explained by a small nitrification rate at MS2 and an increasing amount of biomass at the exclosures by which nitrogen is fixed. The large variability in ratios for calcium is due to a very small input flux compared to the soil solute flux. Small differences in the input flux have an increased impact on the ratio. The smallest ratio for calcium of 0.6 (Dopheide and Verstraten, 1995) is due to a non-calcareous soil.

EC drinking water norms

EC drinking water norms for ammonium of 11 μmol L^{-1} are reached in the soil water. The limit for nitrate,

Table 2. Ratio of solute fluxes in the output flux at 50 cm depth to those in the input flux (bulk deposition or throughfall) at both sites and as found in literature

Reference	Vegetation	Na	K	Ca	Mg	NH_4	Cl	NO_3	SO_4	PO_4
This research, MS1	grazed	1.0	0.5	24.7	2.3	0.3	1.0	3.0	1.9	0.9
This research, MS1	exclosure	1.4	0.2	11.1	1.4	0.2	1.0	0.6	2.4	0.9
This research, MS2	grazed	1.1	1.0	33.8	4.0	0.3	1.0	0.5	2.8	5.7
This research, MS2	exclosure	2.0	0.1	14.7	2.5	0.1	1.0	0.2	1.9	0.0
De Vries et al., 1994	shrub and grass		31.2		0.1		2.8	1.6		
Dopheide and Verstraten, 1995	heathland	1.0	0.7	0.6	0.9	0.4	1.0	1.8	1.2	
James and Wharfe, 1989	grass and bare	1.0	1.2	14.0	2.5					
James et al., 1986	grass and bare	0.9	0.8	11.2	2.1					
Kellman and Roulet, 1990	pioneer	2.1	0.4	8.3	10.0	0.1		0.0		0.2
Kellman and Roulet, 1990	shrub	6.6	0.6	11.1	12.5	0.3		0.1		0.2
Stuyfzand, 1984	bare	1.1	4.7	28.3	2.2	0.0	1.1	3.6	1.9	0.2
Stuyfzand, 1984	shrub	1.9	3.1	33.7	2.7	0.0	2.1	3.7	2.7	0.1
Stuyfzand, 1993[a]	mosses	0.9	3.1	15.9	1.2	0.3	0.8	4.2	2.6	7.6

[a] Based on weighted mean concentrations.

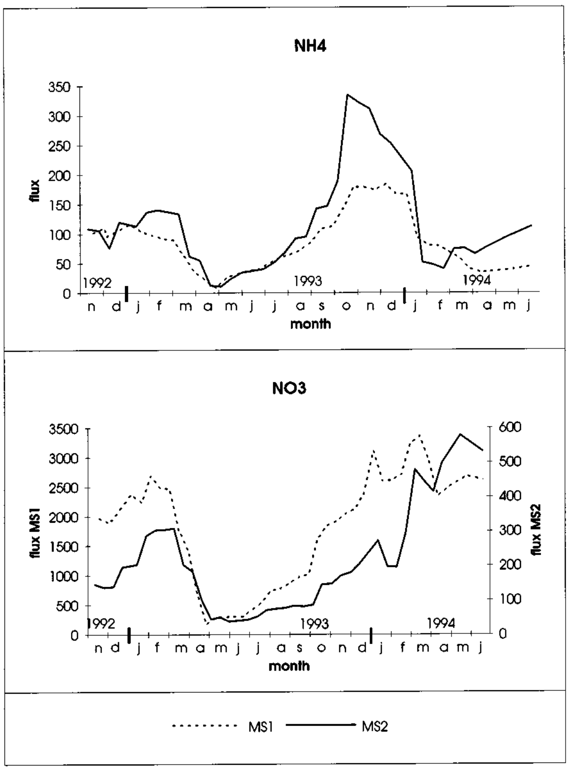

Figure 7. Two month moving average of the fluxes of NH_4^+ and NO_3^- in the soil water at the foredune site (MS1) and the innerdune site (MS2) in mol ha^{-1} yr^{-1}.

807 μmol L^{-1}, is not exceeded, even at the fertilized plots. Therefore, drinking water limits for nitrate will not be exceeded in the ground water despite of raised loads of atmospheric nitrate deposition or nitrification in the soil compartment.

Conclusions

The soil water contents of the soil in the dry coastal dunes were highly variable, especially in summer if wetting took place after a dry period. Some spots in the soil remained dry for more than one year. The measurements of the soil water content gave much evidence for the occurrence of preferential flow at both sites.

Nearly all the SO_4^{2-} added as fertilizer is leached out of the soil at 50 cm depth. An exception is the exclosure on the foredune site, possible due to some deviating measurements. At the foredune site, about 70% of the added NH_4^+-N is lost as NO_3^-. At the innerdune site only the exclosure lost about 13% of the added NH_4^+-N as NO_3^-. The leaching of nitrogen at the foredune site could explain why the vegetation did not react to the fertilization as was found by Ten Harkel and Van der Meulen (1996). However, at the innerdune site little or no leaching was measured and still the vegetation did not change after fertilization with ammonium sulphate. This is probably due to phosphorous limitations (Kooijman et al., 1997).

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