The distribution and interconversion of ammonium and nitrate in the Skallingen salt marsh (Denmark) and their exchange with the adjacent coastal water

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Abstract

The potential nitrogen sources for the primary production in the intertidal area are nitrogen compounds obtained from mineralization in the sediment and the water column, nitrogen fixation, outflow from rivers and groundwater seeping from the mainland.

The available inorganic nitrogen in the adjacent coastal waters decreases from 50–80 μmol NO_3^-/l and 6–15 μmol NH_4^+/l in early spring to ca one tenth during the growing season. In the sediment of the tidal flats available ammonia and nitrate vary between 50 and 100 μmol/l pw. In the salt marsh available ammonia increases from 200–300 nmol NH_4^+/g fwt to approximately double the amount, and the available nitrate varies from 100–300 nmol NO_3^-/g fwt (250–750 μmol NO_3^-/l pw) to ca one third during the growing season.

The exchange of NH_4^+, NO_2^- and NO_3^- across the sediment water interface has been estimated during tidal cycles under light and dark conditions on the tidal flats. The flux of nitrogen was dependent on the flora and fauna as well as the time of the year.

The tidal activity, frequency and length of inundation are considered the driving force in a two-way process between salt marshes and adjacent coastal waters. The role of marsh sediment, tidal water and sediments of the tidal flats as sites of accumulation, consumption and remineralization of organic matter is emphasized. The possible exchange of ammonia and nitrate between the salt marsh and the different compartments of the tidal water is discussed.

Introduction

Salt marshes are characterized by environmental gradients mainly determined by the tide. Salt marshes are not subject to extreme diurnal fluctuations of salinity associated with the tidal water because they normally lie between the upper limit of high water at spring tide and the upper limit of high water of neap tides (Chapman, 1960). In spite of their apparent stability the salt marshes are subject to extreme seasonal fluctuations and long-term changes. The origin and development of salt marshes are highly dependent on processes and changes taking place elsewhere in the tidal system and on the tidal activity as the driving force in the two-way exchanges between the salt marsh and the coastal water. The salt marshes in turn play an important role in the cycling of material within a tidal system.

Pomeroy (1970) pointed out that salt marshes are natural eutrophic systems where there is a large excess of all essential elements with the exception of nitrogen in some cases (Tyler, 1967; Pigott, 1969).

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Transformation, storage, inputs and outputs of nitrogen are therefore of special interest.

In the case of the Skallingen salt marsh, a large subsystem of tidal flats and channels are inserted between the marsh and the coastal water. The concentrations of inorganic nutrients in the tidal water, entering and leaving the marsh, may be considerably altered by exchange with the sediments of creeks and tidal flats and by mixing with different water masses in the tidal channel, before it reaches the coastal North Sea.

The present study concentrates on the distribu-

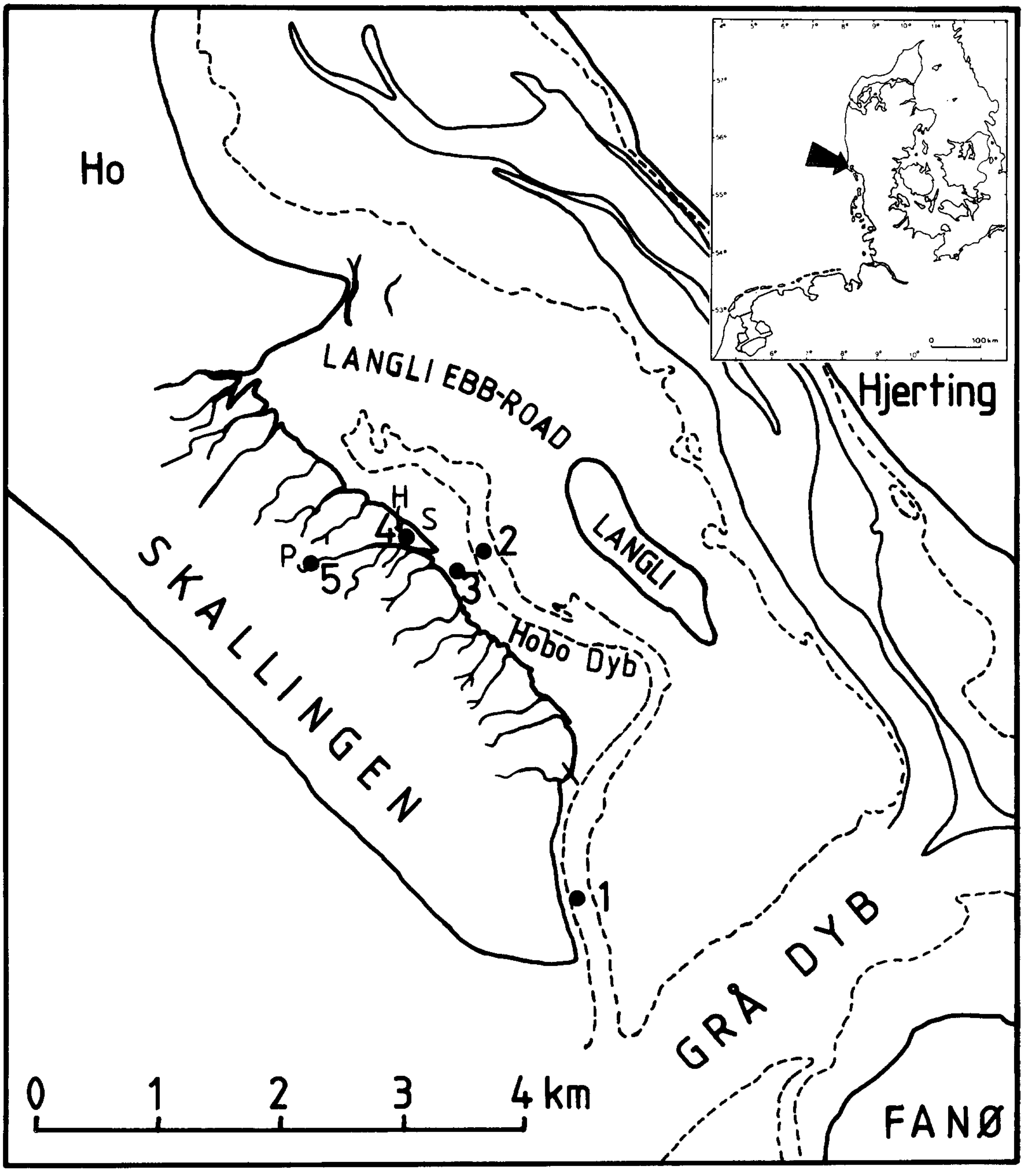


Fig. 1. Map showing the research area Hobo Dyb and Skallingen. Sampling stations are indicated with numbers from 1 to 5, and the letters H and P.

tion and exchange of inorganic nitrogen, ammonia and nitrate, between the salt-marsh sediments and the tidal water, entering and leaving the salt marsh and its creek system. Other papers are dealing with the nutrient dynamics of the tidal flats and mixing between different water masses (Henriksen *et al.*, in prep.) and the effect of nutrient supply from terrestrial sources relative to regeneration of nutrients within the Grådyb tidal area (Henriksen *et al.*, 1984).

Research area

Skallingen is a peninsula situated near Esbjerg, Denmark. The salt marsh has developed on an offshore sandflat on the northeastern side of the peninsula, since the beginning of this century (Jacobsen, 1952). The marsh has a well-developed creek system (Fig. 1).

The tidal amplitude is 130 cm with a salinity of 25–30‰. The area of the intertidal flats between Skallingen and Langli is 9 km^2 in total. The area of the tidal channel Hobo Dyb is 0.85 km^2 with a water volume at mean low tide of 2.1×10^6 m^3. The intertidal flats consist of well-sorted fine sand with D_{50} ranging from 165 μm to 216 μm (Jacobsen, 1972). Extensive mussel beds of *Mytilus edulis* occur along the edge of the tidal channel Hobo Dyb. The fine sand is here overlayered by silt and clay. In the salt marsh of Skallingen a layer of fine-textured sediment, deposited on top of the marine sand, consists of ca 60% silt, 25% clay and 5% sand (Hansen, 1951). The depth of the fine-textured sediment varies between a few mm and 20 cm.

Material and methods

Concentrations of NH_4^+, NO_2^- and NO_3^- ions were determined in the tidal water, the interstitial water of the tidal flats, the groundwater in the salt marsh and in the top sediment layer in the marsh.

Tidal water: during each sampling period, water samples were collected at intervals of one hour at 5 stations (Fig. 1), for one or two sequential tidal cycles. Samples were chilled with dry ice and brought to the field laboratory within three hours.

Groundwater was sampled four times in each tidal cycle at nine different depths through permanent sampling pipes (2.5 cm in diameter) containing sampling tubes for each sampling depth, equipped with small filter units to avoid sediment in the sampling tubes. The samples were treated as the tidal water samples.

Salt-marsh surface sediment was sampled from the marsh close to sampling stations 4 and 5 (Fig. 1) nine times a year. For each sampling date ten cores were taken with a core auger (3.0 cm) to a depth of 20 cm at sampling point H, and to 8 cm depth at sampling point P. Prior to extraction with 1 M KCl for analysis of NH_4^+, NO_2 and NO_3 the ten cores were lumped and mixed carefully.

Potential nitrification in sediment samples from sampling point H was measured as described by Henriksen *et al.* (1981). Twenty soil cores were sectioned into nine layers and corresponding layers lumped and thoroughly mixed before analysis. The amount of KCl-extractable NH_4^+ and NO_3 was measured at the same depths.

Fluxes of NH_4^+, NO_2 and NO_3 between sediment and water-bodies were measured using chambers, placed on the tidal flats during flooding. PVC rings (19 cm in diameter, 10 cm high) were pressed 5 cm into the sediment and anchored with four 50 cm piano wires. Before flooding polythene bags were fixed on top of the cylinders with rubber bands.

Wave action and currents ensured mixing of the water in the bags. The change in concentration of NH_4^+, NO_2^- and NO_3^- was measured during the flood period and the flux calculated. At each sampling station two dark and two light chambers were used.

Ammonia, nitrite and nitrate were measured on filtered samples with an autoanalysis system (Chemlab Instruments Ltd., Essex) using the automated methods of Solorzano (1969) and Armstrong *et al.* (1967).

Results

Tidal activity

From the data presented in Figure 2A it is clear that tidal frequency varied considerably throughout the year. At 40 cm above DZL (Danish zero level), which is the approximate lower limit for *Spartina anglica*, the tidal frequency was very much the same throughout the year, but reached a maximum in the summer. Between 40 and 80 cm above DZL (lower part of the vegetated marsh flats), there were marked differences in inundation frequency at different times of the year. In March, April and May only 15–19 tides per month reached a level of 80 cm above DZL. From May to September this increased to 35 tides per month – the highest frequency at that level. At the upper parts of the marsh, 100–120 cm above DZL, the low frequency period was prolonged into June and July, and the highest frequency was found in winter. This tidal seasonality at different levels of the marsh influences the connection and possible exchange of particulate and soluble matter between tidal water and the salt marsh.

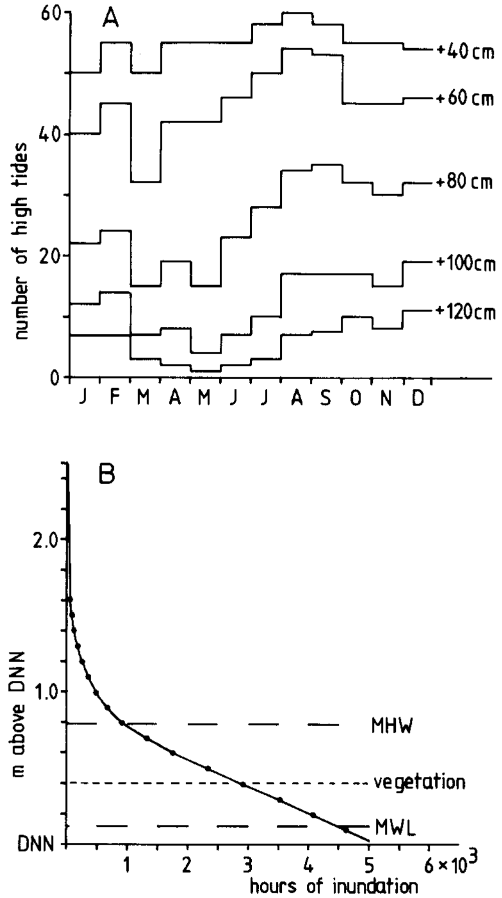


Fig. 2. Tidal frequency in the research area expressed as:
A: frequency of high tides reaching five different levels in the area on a monthly basis; calculated from tidal statistics (1945–1965) from the harbour of Esbjerg; B: hours of tidal inundation per year in relation to levels above DZL (Danish zero level); calculated from tidal statistics (1900–1962) from the harbour of Esbjerg and tidal recording at Skallingen in 1972 and 1981.

Large areas in the salt marsh lie between the neap and spring tide levels. These parts of the marsh were subject to periodicity in the tidal activity following the lunar spring tide/neap tide cycle, which in turn probably caused cyclic fluctuation in salinity.

The total inundation time per year (Fig. 2B) is very important because inundation means physical contact between tidal water and the salt marsh, tidal flats and the organisms living there. As expected, there was a sharp, almost linear decrease in hours of inundation from mean water level to mean high water level, but from MHW and upwards there was a curvilinear relationship. The lower limit of the salt-marsh vegetation was inundated only 30% of the time (Fig. 2). MHW level was inundated 13% of the time.

Ammonia and nitrate in the tidal water

The tidal system studied appeared to consist of three water parcels, which will be treated in detail elsewhere. At low tide water parcel one (WP1) was laying outside the main inlet Grådyb (Fig. 1). Water parcel two (WP2) was situated in the tidal channel Hobo Dyb and water parcel three (WP3) was in the creek from sampling point 2 through to sampling point 5. At high tide, the whole system was compressed so that WP1 reached into sampling point 3 and covered a large part of the Hobo Dyb area, and WP2 was laying on the upper parts of the tidal flats and in the creeks up to sampling point 5 in the central part of the marsh. WP3 was then in the innermost part of the main creek and in small side branches. The system with three water parcels was consistent throughout the year. The different water parcels could easily be identified due to their marked difference in concentrations of inorganic nutrients (especially nitrate).

The concentration of NO_3^- was low during the growing season compared with the concentration during autumn and winter, because most of it was assimilated by phytoplankton and phytobenthos (Fig. 3B). During autumn and winter, nitrogen of dead benthic micro-algae and phytoplankton, deposited on the tidal flats, was mineralized and released as ammonia, which in its turn was nitrified in the sediment and in the water column. This resulted in an accumulation of NO_3^- in WP2, compared to WP1 and WP3. Nitrate concentrations in the three water parcels appeared to be different during autumn and winter, where the tidal activity was high. This indicates, that the water parcels mix only very slowly. The estimated flushing time for WP2 in December was 10 days (Henriksen *et al.*, 1984).

The concentration of ammonia did not show the same clear seasonal pattern (Fig. 3A). There was no accumulation of NH_4^+ during the winter, possibly because it was nitrified. During the growing season, ammonia was recycled internally and nitrified only to a lesser degree. Haines *et al.* (1977) calculated the net regeneration of ammonia as 2.5 times during a tidal cycle. The ammonia pool was depleted during the second growing season, probably due to the

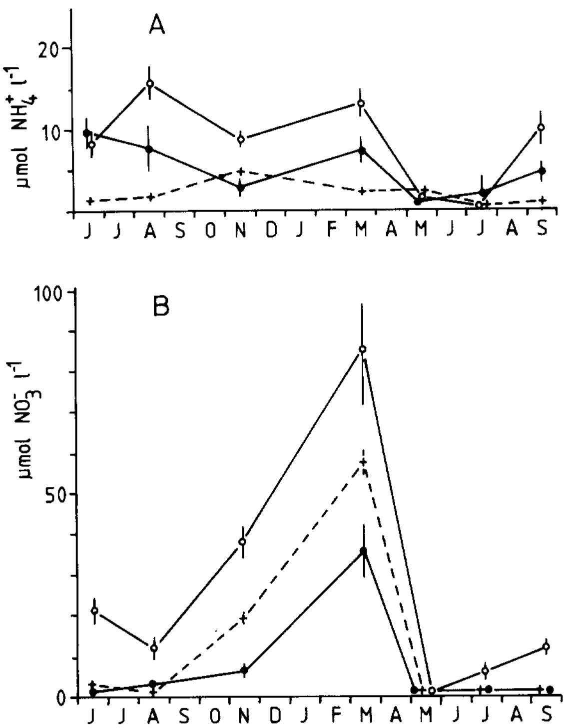


Fig. 3. Concentration of NH_4^+ (A) and NO_3 (B) in tidal water over the year in the three different water parcels. (+- - -+) water parcel 1; (O——O) water parcel 2; (●——●) water parcel 3. Bars indicate standard error within the water parcels.

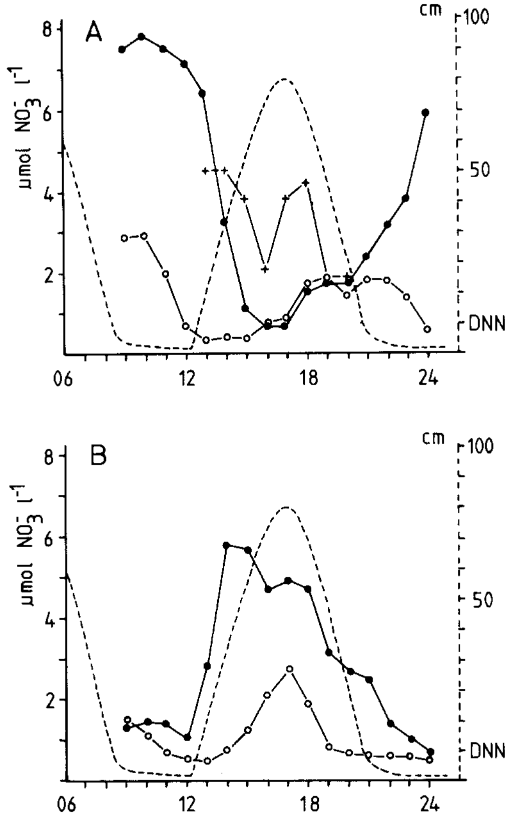


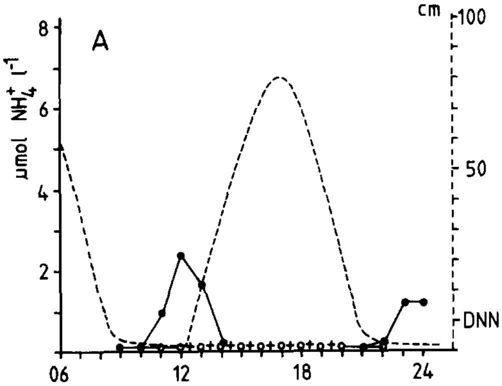
Fig. 4. Concentration of NO_3 in the tidal water over one tidal cycle in July 1982; (- - - - -) indicates the water level at sampling point 4. A: (O——O) sampling point 1; (●——●) sampling point 2; (+——+) sampling point 3; B: (●——●) sampling point 4; (O——O) sampling point 5.

high primary production. WP1 had the lowest ammonia content due to high phytoplankton production (Rasmussen *et al.*, unpubl. results). WP2 had the highest concentration of NH_4^+ throughout the year except for mid summer, where the highest NH_4^+ concentrations were measured in WP3. Large amounts of ammonia are known to be excreted from mussel beds (Henriksen *et al.*, 1982) and the extensive mussel beds in close connection with WP2 were enriching this part of the tidal system with ammonia. The other parts of the tidal flats appeared to have a net flux of ammonia towards the sediment from June to September and a net flux out of the sediment in the rest of the year.

Nitrogen within a tidal cycle

The variation in concentration of nitrate during a tidal cycle at the five different sampling stations was dramatic. Figure 4 shows this for a tidal cycle on 6 July 1982, from low tide to low tide. The tide was measured at sampling point 4 and therefore it is not a sinus curve. The fast rise in water level in the beginning of high tide and tailing at the end of high tide indicates a barrier in front of the marsh. During the ebb tide the water moved out of the system into Grådyb. Water from WP2 – rich in nitrate – passed sampling points 1 and 2. The water passing points 4 and 5 at ebb tide belonged to WP3 which was poor in nitrate. Sampling point 3 situated on the tidal flat, was dry during ebb tide. During high tide, water moved into the system from Grådyb. Water from WP1 with a low nitrate concentration passed sampling points 1 and 2, reaching sampling point 3 on the tidal flats at 17.00 hours. Water from WP2, rich in nitrate, flooded station 3 on the tidal flat, passed sampling point 4 and reached sampling point 5 in the innermost part of the creek.

Figure 5 shows the variation in ammonia concen-



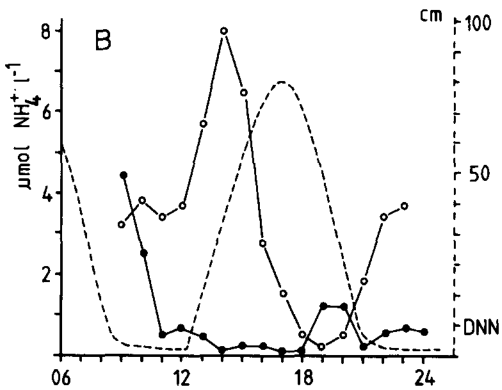


Fig. 5. Concentration of NH_4^+ in the tidal water over one tidal cycle in July 1982; (-----) indicates the water level at sampling point 4. A: (O——O) sampling point 1; (●——●) sampling point 2; (+——+) sampling point 3; B: (●——●) sampling point 4; (O——O) sampling point 5.

tration of the different sampling points during the same tidal cycle. During ebb tide water from WP3 containing some ammonia passed sampling points 4 and 2. The rising water caused water from WP3 to be pushed back into the creek, creating a sharp increase in ammonia content at sampling point 5 at the beginning of high tide. Later during high tide WP2 water, low in ammonia, reached sampling point 5. The sharp increase in ammonia content at the end of ebb tide was unexpected, because we know that the flux of NH_4^+ during daytime was towards the sediment resulting in a decrease in ammonia in the water body. In our opinion this peak of ammonia points to a flow of groundwater with high concentrations of ammonia from the marsh into the creek during ebb tide The nitrogen content in the groundwater in different parts of the marsh seems to support this view.

Nitrogen in the groundwater

At the front of the salt marsh the vegetation consists of an almost pure stand of *Spartina anglica* established on the sandflat. The *Spartina* in this area (S in Fig. 1) was growing in sand with no mud deposited on the top down to ca 40 cm above DZL. Below that level only occasionally individuals of *Zostera* could be found. The nitrate content was extremely low at all three sampling spots right from the surface down to 110 cm depth, indicating nearly total depletion and/or low nitrification. The *Spartina anglica* vegetation greatly influenced the groundwater content of ammonia (Fig. 6). In the

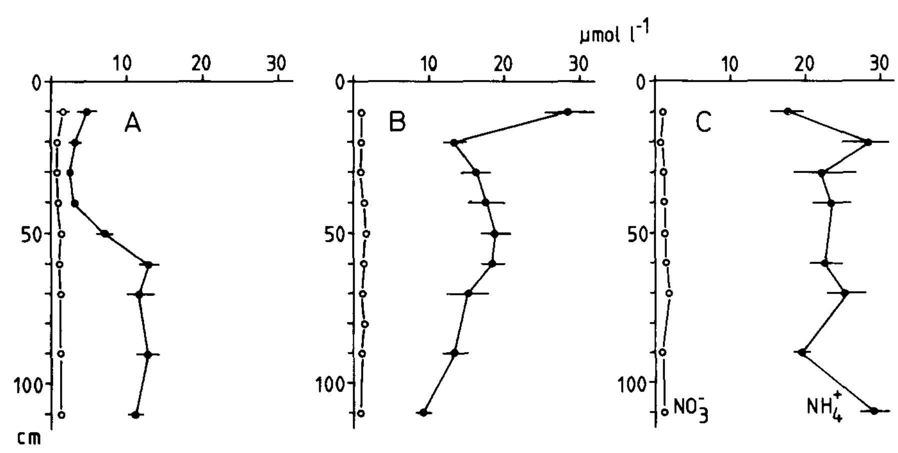


Fig. 6. Concentrations of NH_4^+ and NO_3 in the groundwater at different depths at sampling point S in August 1982; A: within dense *Spartina* vegetation; B: non vegetated area surrounded by *Spartina* vegetation; C: non-vegetated tidal flat with *Arenicola marina*. Bars indicate standard error within the different depths.

Spartina vegetated areas (A and B) situated ca 50 cm above DZL the overall concentration of ammonia was lower than in non-vegetated areas. Dense vegetation of *Spartina* (A) was able to reduce the concentration of ammonium within the zone of the main distribution of the roots, to a depth of 60 cm. The depletion was very local, because in an open spot (about 3 × 3 m) within the *Spartina* vegetation the concentration of ammonia increased towards the surface (Fig. 6B). This indicates a very limited horizontal groundwater transport of nutrients. The high concentrations in the surface possibly reflect a high ammonification rate and limited assimilation, because benthic vegetation was sparse.

The non-vegetated area (C) (situated 10 cm above DZL) had a higher concentration of ammonia below a depth of 20 cm than the profiles in Figure 6A and B. The decrease in the uppermost part of the profile indicates either export to the tidal water or assimilation by the benthic vegetation or both. The sediment was subject to bioturbation to a depth of about 20 cm during the summer period by a dense population of *Arenicola marina*.

Concentrations of NH_4^+ and NO_3^- in the groundwater under *Puccinellia maritima* at sampling point (P) in the inner part of the marsh (Fig. 1) are shown in Figure 7. As in the *Spartina* area, the concentration of nitrate was rather low as compared with the ammonia concentration, but higher than the nitrate concentration in the *Spartina* marsh. The concentration of NH_4^+ was 20 μmol/l just below the surface layer of fine sediment. Between 10 and 30 cm there was a dramatic increase in ammonia to 78 μmol/l. From 30 to 110 cm the concentration decreased again to 30 μmol/l. The low concentration of NH_4^+ in the upper part of the profile probably reflects nitrification and plant uptake of nitrogen. Decreasing NH_4^+ concentrations with depth could mean that nitrogen was leached out from the fine surface sediment – where the amount of NH_4^+ was an order of magnitude higher than in the groundwater (Fig. 8A) – and into the groundwater.

The groundwater in the *Halimione portulacoides* vegetated area (H in Fig. 1) was very different from what we found in the *Spartina* and *Puccinellia* areas. Ammonia was only present as traces, whereas the nitrate concentration was very high. As shown in Figure 7B the concentration of nitrate decreased with increasing distance from the creek, but 16 m from the creek nitrate content was comparable to the *Puccinellia* area (Fig. 7A).

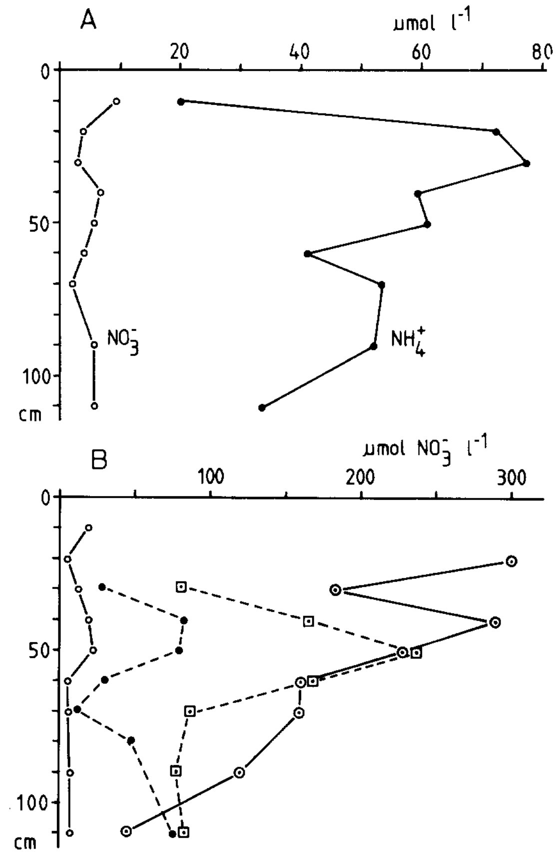


Fig. 7. Concentrations of NH_4^+ and NO_3 in the groundwater at different depths in July 1982; A: from the Puccinellia sampling plot P in the inner marsh; B: from the *Halimione* sampling plot H in the outer part of the marsh; (⊙——⊙) one m from the creek; (⊡- - -⊡) four m from the creek; (●- - - -●) eight m from the creek; (O——O) sixteen m from the creek.

The shape of the curves indicates leaching of nitrogen from the fine textured surface sediment. The concentration was between 25 and 40 times greater than in the tidal water from WP2, creating an enormous gradient between groundwater and tidal water.

Available (KCl-extractable) ammonia and nitrate (only very small amounts of nitrite were detected) in the fine-textured surface sediment were measured at sampling points P and H (Fig. 1) on eight occasions throughout the year – results are shown in Figure 8A and B. At both sampling stations the available nitrate remaining in the soil was extremely low throughout the year and showed practically no variation. Available ammonia increased during the growing season as a result of a higher ammonification rate, but even at the highest

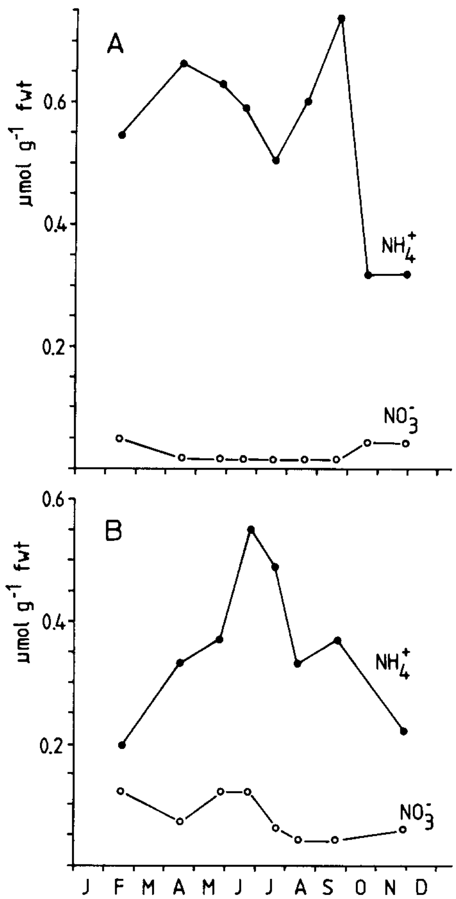


Fig. 8. KCl-extractable NH_4^+ and NO_3 concentrations in the topsoil over the year; A: the *Puccinellia* sampling point P; B: the *Halimione* sampling point H.

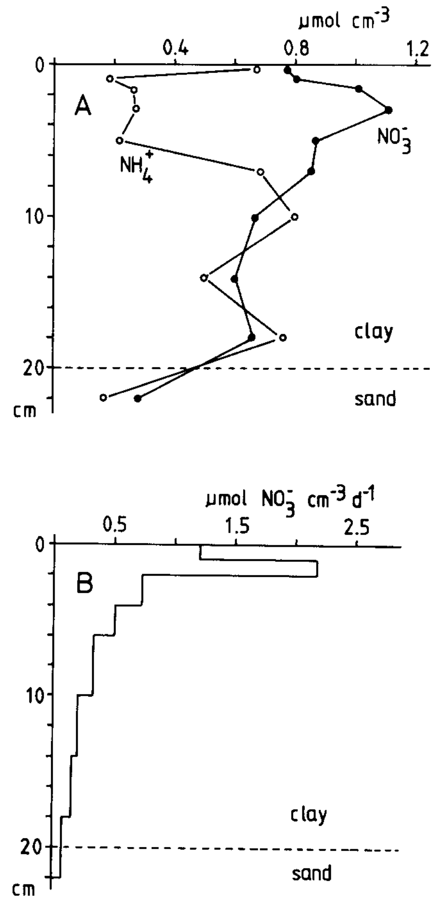


Fig. 9. KCl-extractable NH_4^+ and NO_3 and (A) and the potential nitrification rate (B) in the topsoil of the *Halimione* plot H in July 1982.

concentrations measured, 0.75 μmol/g, soil nitrogen was probably limiting the growth. 0.75 μmol/l $\sim$ 1 mmol NH_4^+ /l nutrient solution if nothing was adhered to the sediment colloids. The lower ammonium concentration in the *Halimione* plot (Fig. 8B) and higher nitrate content indicates higher nitrification rates as compared with the *Puccinellia* plot.

Ammonia, nitrate and potential nitrification in the surface sediment

The nitrogen content in the top sediment layer at sampling point H is illustrated in Figure 9A. The fine-textured surface sediment was 20 cm thick in this area and was well oxidized throughout the year. Redox potential varied between +250 and + 400 mv. Concentrations of ammonia and nitrate were about equal and fluctuated between 0.5 and 0.8 μmol/cm^3 from -7 cm to the bottom of the clay layer, whereas the concentration in the uppermost part of the sand layer was only about 0.2 μmol/cm^3. In the upper part of the profile the two curves seem to mirror each other - low NH_4^+ concentrations correspond with high NO_3^- concentrations. These results could be explained by a high nitrification rate in the upper five to seven cm of the sediment. The data presented in Figure 9B support this view, because the potential nitrification rate was high in the upper part of the sediment and in accordance with the measured ammonia and nitrate concentrations. Deeper in the sediment potential nitrification decreased to very low values at the bottom of the profile. From data not presented here it is known that potential nitrification rates do not vary much, whereas the extractable inorganic NH_4^+ and NO_3^- do vary considerably during the year (Fig. 8A).

The production and the pool of inorganic nitrogen (NH_4^+, NO_2 and NO_3^-) in the surface sediment were large and suggest that these compounds were being leached to the groundwater through downwards movement of interstitial water in the sediment column. We know from preliminary results (Theilgaard *et al.*, unpubl. results), that the nitrogen fixation rate in the outer part of the marsh was low and therefore of little importance for the nitrogen budget of the area. Other preliminary results indicate that denitrification possibly was of some importance in the outer marsh. The potential denitrification rate was quite high in the upper two cm of the profile, but decreased with depth just as potential nitrification.

Discussion

There is a net influx and accumulation of sediment in the marsh of about 2 mm/yr (Jacobsen, 1952). Sediment accumulation and the whole development of the marsh clearly depend on the tidal regime, which sets limits to the size and level of the marsh. Most of the salt-marsh areas at Skallingen have developed beyond mean high water level, which results in limited physical contact between those marsh areas and the tidal water. Water level was below the marsh edge for more than 90% of the time. Approximately 410 high tides out of 709 never reached the edge of the marsh. In those cases the tidal water moved into the creek system and then out again; the only contact was along the creek bank. Furthermore most of the tidal activity affecting the marsh occurred during autumn and winter outside the growing season. But the lunar cycle and varying weather make it probable that the marsh will be flooded every fortnight during the growing season. These floodings in the growing season appeared to have a very great and prolonged influence on the marsh by providing water and either diluting or increasing the salinity.

The time available for seeping of marine groundwater from the marsh to the creeks depended on the groundwater level in relation to the tidal level. Marine groundwater level was never below 20 cm above DZL (Jensen, 1973). Even at that low level there would be seepage towards the creeks. In most cases the marine groundwater level was between 40 and 60 cm above DZL, which leaves between 70 and 80% of the time for marine groundwater movement out of the marsh. For the remaining 20–30% of the time, tidal water was at the same level as the groundwater or above it, and flowed into the pool of marine groundwater. Tidal water percolated into the marsh at a rate of 15 to 25 mm/hr when the marsh was flooded with 10 cm of water (Jensen, unpubl. results). The seasonal change in tidal activity may signify an overall seasonal cycling in the groundwater level, with low levels during spring time and high groundwater levels during autumn and winter. At present we are not able to quantify the seepage of marine groundwater from the marsh, but with a length of the contact surface between the marsh and the creeks of ca 40 km/km² a substantial volume of water may be involved.

The low concentrations of nitrate in the groundwater both in the *Spartina* vegetation and on the tidal flat indicate that low nitrification rather than assimilation was the cause. Otherwise, differences between vegetated and non-vegetated areas would be expected.

The data presented, showed an important difference in nitrogen content of groundwater from different parts of the salt marsh. The surface sediment contains between 200 and 250 μmol N/cm³, whereas the sandy sediment in the *Spartina* area contains 30–35 μmol N/cm³ (Jensen, 1973; Henriksen & Jensen, 1979), so the nitrogen pool in the fine-textured sediment was about seven times larger than in the sandy sediment. This was probably the source for the marked difference in nitrogen content in the groundwater. It was shown (Henriksen & Jensen, 1979) that the nitrogen mineralization was 11 g/m² from September 1974 to September 1975 with maximum rates of 1.4 to 2.6 g N/m²/month during the growing season.

Nitrogen mineralization takes place throughout the surface sediment profile, but the potential for nitrification was shown to be highest in the upper part of the profile, possibly reflecting the distribution of organic material, which was easily mineralized. Benthic algae growing on the sediment surface, fresh sediment with dead plankton organisms, litter from higher plants and dead fine roots, are the main organic material. When the nitrogen was mineralized, it was susceptible to leaching if it was not assimilated by bacteria or higher plants. The exchange capacity of seawater inundating the marsh ensures that ammonia and nitrate percolate downwards.

Concentrations of dissolved inorganic NO_3^- and NH_4^+ were higher in WP2 compared to WP3 throughout the year, except for mid summer where NH_4^+ concentration was higher in WP3. It appears from the present data, that soluble inorganic nitrogen (NH_4^+, and NO_3^-) was exported from the marsh to WP3 at low tide due to enriched marine groundwater seeping out into the creek system. However, only in mid summer, there was a small export of ammonia from WP3 to WP2. During the rest of the year, there was an import of NH_4^+ and NO_3^- from WP2 to WP3. This import was small during the growing season and high during the winter time, following the gradient in concentration of inorganic nitrogen between the two water parcels (Fig. 3 A and B). The inorganic nitrogen, exported from salt marsh to tidal water is, therefore, almost entirely recycled within the salt marsh/creek system and has no contact with the coastal water. This is due to the intervening subsystem of tidal flats and channel water, inserted between the salt marsh and the coastal water. The tidal flat/channel system acts as a trap for phytoplankton and suspended organic matter from the coastal water and is in turn a source of inorganic nutrients by mineralization in sediment and water column. During winter time, inorganic nitrogen, mainly in the form of nitrate, is exported from the channel water (WP2) to the coastal water (WP1).

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