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Management of basiphilous dune slack communities in relation to carbonate accumulation and hydrological conditions

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Abstract. In dune slacks in The Netherlands, a decline of rare mesotrophic basiphilous plant species and their plant communities has been observed in combination with an increase of more productive systems with common, taller acidophilous plant species. This has been attributed to both natural and anthropogenic changes. In a humid climate with a precipitation surplus, as in The Netherlands, the calcium carbonate content of a calcareous soil increases with depth. However, soils in coastal dune slacks, may have a higher carbonate content in the topsoil horizon than in the underlying layers. Carbonates which buffer the pH can prolong the presence of mesotrophic basiphilous plant communities which are of high conservation value.

To explain the occurrence of calcareous surface horizons in dune slacks, hydrological and micromorphological analyses were carried out in three dune slacks. Two slacks are situated on the Wadden Sea islands in the northern part of The Netherlands; one on Schiermonnikoog and one on Texel. The third slack is situated in the dunes on the island of Goeree in the southwestern part of The Netherlands. In all three slacks, carbonate occurs as mollusc and gastropod fragments (silt- or sand-sized) and as micritic nodules in the topsoil layer, due to aeolian deposition and sedimentation by water. *In situ* carbonate accumulation (calcitans and calcareous crusts) due to CO_2 release in inundated and/or capillary rise of calcareous groundwater near, or at the soil surface. Accumulation of carbonate also occurs as a result of biological activity by algae in the topsoil of the Goeree site. In general, hydrological processes maintaining high levels of calcareous groundwater are a prerequisite for the maintenance of high carbonate levels in topsoils. Such levels are necessary for the conservation and management of basiphilous pioneer vegetation.

Keywords: Carbonate precipitation; Groundwater; Management; *Schoenus nigricans*; Micromorphology; Sod removal.

Nomenclature: For plants: van der Meijden et al. (1990), for plant communities: Schaminée (1995); for micromorphology: Brewer (1964).

Introduction

In dune slacks in The Netherlands, a decline of rare mesotrophic basiphilous plant species and their plant communities has been observed in combination with an increase of more productive systems with common acidophilous plant species. This has been attributed to both natural and anthropogenic changes during the last decades (Grootjans et al. 1988; 1991; Van Dijk & Grootjans 1993). Among the species most affected are *Dactylorhiza incarnata, Epipactis palustris, Littorella uniflora*, *Parnassia palustris* and *Schoenus nigricans.* These species have their optimum in the dune slack communities *Junco baltici-Schoenetum nigricantis*, *Samolo-Littorelletum* and *Parnassio-Juncetum atricapilli.* Consequently, these communities are threatened as well.

These endangered basiphilous plant species grow in young calcareous dune slacks (depressions in dune systems) which are regularly inundated during winter and spring (Bakker 1981), have nutrient-poor soils with a pH > 6 (Lammerts et al. 1995). The near-neutral to alkaline conditions of the topsoil can be sustained by dissolution of calcium carbonate (van Breemen et al. 1984; Rozema et al. 1985) or by neutralization of bicarbonate from groundwater. Periodical inundation with calcareous groundwater, mainly due to dissolving $CaCO_3$ from deeper soil horizons underlying the decalcified topsoil, sustains this bicarbonate input (Kenoyer & Anderson 1989; Cook et al. 1991). Inundation of calcareous groundwater in dune slacks has been described by Grootjans et al. (1996) as a flow-through mechanism: when the slack is inundated it receives exfiltrating groundwater along the up-gradient border and discharges its water along the down-gradient border (Born et al. 1979; Stuyfzand 1993).

Generally, the carbonate content in the topsoil is low and increases with depth in areas with a precipitation surplus (van Breemen & Protz 1988). However, in some coastal dune slacks in The Netherlands, the carbonate content of the topsoil was three times higher than in the underlying soil layer at 15-20 cm (Sival 1996). Sival (1996) suggested that this could be a result of *in situ* formation and accumulation of carbonates. The carbonate accumulation could be the result of CO_2 release in inundated and/or capillary rise of calcareous groundwater near or at the soil surface (Boyer & Wheeler 1989, Komor 1994). This is a common phenomenon in areas with an annual precipitation deficit, but it is rarely observed in dune slacks in humid climates with a precipitation surplus (Mücher 1990). *In situ* accumulation of carbonates may prolong the maintenance of basiphilous mesotrophic plant species. If conditions for *in situ* carbonate accumulation can be created or maintained, this could provide possibilities for the conservation and regeneration of these rare plant species and their plant communities.

The main objective of this study is to test whether high carbonate percentages in the topsoil are the result of *in situ* accumulation of carbonates. We identified the various forms in which carbonate occurs and the accumulation processes responsible for their formation. Then we specified the environmental conditions for the maintenance and restoration of basiphilous pioneer vegetation, to support conservation management.

Site description

Three dune slack systems were selected along the Dutch coast (Fig. 1) which have significantly more carbonate in the topsoil than in the underlying soil horizon:

(A) a beach plain on the Wadden Sea island of Schiermonnikoog in the north of The Netherlands (Fig. 2: site S1); (B) the Kammosvallei on Texel (Fig. 2: sites T1, T2 and T4); (C) Meinderswaalvallei on the former island of Goeree in the southwestern part of The Netherlands (Fig. 2: sites M1 and M2). For soil characteristics, see Table 1.

A. Schiermonnikoog

This dune slack is part of a former primary beach plain, known as Strandvlakte. It was cut off from the sea by the construction of a sand dike in 1959. The influx of sea water was then reduced. Heavy storms in 1972 made a large gap in the dike. Sand from the dike was deposited on the former beach plain and a small dune slack was formed behind the deposited sand (Olff et al. 1993). The slack is inundated during winter and early spring (Fig. 2, site S1). Since 1972, sea-water enters the slack only at very high tides. Between May and September the water table drops, even to 1.0 m below the soil surface in very dry summers (Olff et al. 1993). Sea-water can penetrate via tidal creeks from the adjacent salt marsh which is connected to the Wadden Sea (Rozema 1976). The sandy soil profile of this site on Schiermonnikoog has a dark, organically enriched mineral surface horizon (A-horizon) and a mineral subsoil (C-horizon). For more detailed information see Sival (1996). The soil is classified as Fluviosol (Anon. 1981) or Udipsamment (Anon. 1975).

Fig. 1. The three dune slack systems selected: (A) beach plain on Schiermonnikoog; (B) Kammosvallei on Texel; (C) Meinderswaalvallei on Goeree.

B. Texel

The Kammosvallei is 1200m ^{2} in size and situated 3m above mean sea level at the edge of a former beach plain, separated from it by a low dune ridge. The slack is >200 yr old. Landward the slack high dunes (up to 25m) are found. Until the 1850s, the groundwater level rose because of accretion of the coast. Thereafter the groundwater levels dropped as a result of: (1) retreat of the coastline, (2) drainage by the Moksloot ditch (dug in 1880) and (3) increasing groundwater extraction since 1956 in the neighbourhood. In 1992, the extraction stopped and the discharge of the ditch was regulated by a weir which resulted again in rising groundwater levels. The sandy soil profiles of the three sites (Fig. 2, T1-T2, T4) include a dark-coloured, organically enriched mineral surface horizon (A-horizon) and a mineral subsoil (C-horizon). The soils are classified as Fluviosols (Anon. 1981) or Udipsamments (Anon. 1975).

C. Goeree

The third slack, the 'Meinderswaalvallei', 1.4 ha in size, forms part of the dune area Middelduinen on the former island of Goeree (van Delft 1995). It is a former

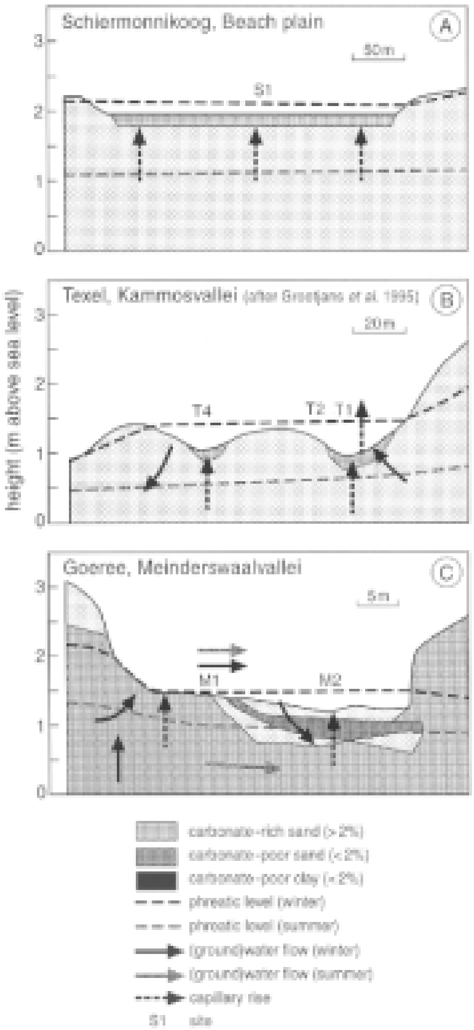

Fig. 2. Cross sections through the dune slacks A (S1), B (T1, T2, T4) and C (M1 & M2); see Fig. 1.

primary beach plain, which was cut off from the sea ca. 1000 yr ago through the formation of dune ridges. In the 17th century, the sea made a gap in these ridges and Seawater could invade the slack for a long time. The last inundation and subsequent deposition of clay took place about 150yr ago. The study sites are situated at a somewhat higher position in the southern part (Fig. 2, site M1) and in the northern lower part (M2) of the slack, respectively. Groundwater runs northward from a higher dune ridge through the slack to the sea. Of the soils described (Fig. 2, M1 and M2), sods were removed in 1988 resulting in bare soils. After 1988, carbonates could precipitate at the topsoil, forming a calcareous crust (Fig. 3; Table 1). There is some clay in the topsoil of site M1 (4%), and a clay layer occurs at 20 - 40 cm in the low northern site of the Goeree slack (Fig. 2, M2).

Methods

Vegetation

At all three slacks the vegetation was analysed by means of two phytosociological relevés in 2 m × 2 m plots, established near the soil profiles (Sival 1996) plant communities were described using the Londo scale of abundance (Londo 1974).

Hydrology

In the slacks A and B, at each site three piezometers were installed, each equipped with filters of 0.10m length at 0.35 m, 0.65 m and 1.65 m depth below the soil surface. In slack C, two piezometers (filter length 0.10m) were placed at depths of 1.2m and 1.9m (Jansen 1996).

The filters on Schiermonnikoog and Texel were sampled in July 1991. Temperature, electric conductiv-

Table 1. Soil characteristics of dune slacks on Schiermonnikoog (S1), on Texel (T1, T2 and T4; Sival 1996) and on Goeree (M1 and M2; van Delft 1995); - = no data. Soil horizon according to de Bakker & Schelling (1989).

Site	Soil horizon	Horizon depth (cm)	Sample depth (cm)	pH(H_2O)	pH(KCl)	$CaCO_3$ (%)	Organic matter (%)	Clay (< 2 µm) (%)
Schiermonnikoog; Beach plain								
S1	1A	0 - 3	0-3	7.1	6.8	3.4	4.0	7.4
	1C	> 3	15 - 20	7.2	6.9	1.9	0.4	-
Texel; Kammosvallei								
T1	1A	0-12	0 -12	7.8	7.3	16.6	6.8	4.2
	1C	> 12	15-20	7.6	7.2	1.5	1.5	-
T2	1A	0-14	0-14	7.1	6.5	2.2	6.0	1.5
	1C	> 14	15-20	8.0	7.2	0.1	0.5	-
T4	1A	0-15	0-15	7.8	7.3	10.5	8.6	4.7
	1C	> 15	15-20	8.0	7.3	0.2	0.5	-
Goeree; Meinderswaalvallei								
M1	1Ck	0.0- 0.1	0-0.1	7.9	-	17.3	4.0	4.0
	2AC	0.1-2	-	-	-	-	-	-
	2Cg1g	> 2	-	-	-	-	-	-
M2	2ACg	0-13	2-13	7.0	7.1	0.3	-	-
	2Cr	13-14.5	-	-	-	-	-	-
	3Ahb	14.5-27	14.5-25	6.3	5.7	0.2	8.3	27.9

Fig. 3. The calcareous crust at the soil surface (arrows) at site M1 in the Meinderswaalvallei on Goeree.

ity (EC_{25}) and pH were measured in the field immediately after sampling.

The concentration of bicarbonate (titration with 1M HCl up to a pH of 4.5) was measured within 24 h after sampling. The samples were stored in the dark at 4 °C prior to analysis. To prevent precipitation of the cations, a 50 ml subsample was adjusted to pH 2 using 2.5 ml 4% HCl.

- Ca, Mg, K and Na were analysed without any preparation (AAS).
- Cl^- was analysed by measuring the ferric-thiocyanate colour at 490nm.; - SO_4^{2-} was analysed by measuring the methylthymolblue colour at 460 nm (Skalar).
- The charge balance and EC_{25} were calculated to check the reliability of the analyses. Accurate analyses had less than 5% deviation of the charge balance from electroneutrality.
- The saturation index for calcite (SI-$CaCO_3$) was calculated using the chemical model WATEQX-A (van Gaans 1989). Groundwater with a SI-$CaCO_3$ lower than $-$ 1.0 is considered undersaturated (aggressive), a SI-$CaCO_3$ value between -1 and 0.3 indicates that the groundwater is in equilibrium with calcite, and when the $SI > 0.3$, the water is considered to be supersaturated with calcite (Stuyfzand 1993).
- On Schiermonnikoog and Texel, groundwater levels were measured every 14th and 28th day of the month from May 1991 to December 1991. On Goeree, groundwater levels were measured every 14th and 28th day of each month in 1992 and 1993.
- Clay percentages of the topsoil horizons were measured by the sedimentation method of Robinson (Black 1965).

Soil: micromorphological analyses

At each site, two, occasionally three, undisturbed vertical samples were taken from the topsoil horizon. Thin sections (4.5 cm high, 7.5 cm wide, and 20 µm thick) were prepared according to the method of FitzPatrick (1970). They were studied under a Leitz polarizing microscope. Micromorphological description was done according to the concepts proposed by Brewer (1964).

Results

Vegetation

Slack A on Schiermonnikoog is sparsely vegetated with salt marsh species *Juncus gerardi, Glaux maritima* and *Salicornia europaea*.

In slack B on Texel, the vegetation is dominated on all three sites by the mesotrophic basiphilous plant species such as *Schoenus nigricans* and *Juncus subnodulosus*. A small number of rare plant species occur, notably *Dactylorhiza incarnata, Epipactis palustris* and *Parnassia palustris*; they are also characteristic of alkaline conditions.

In the lower northern part of the 'Meinderswaalvallei' on Goeree (Fig. 2: site M2) the vegetation is dominated by species such as *Phragmites australis* and *Juncus subnodulosus*. In the higher southern part (site M1), mesotrophic basiphilous plant species occur including *Schoenus nigricans*, *Anagallis tenella*, *Centaurium erythraea*, *Centaurium littorale* and *Radiola linoides*.

Hydrological conditions

On Schiermonnikoog, the groundwater had SI-$CaCO_3$ values (saturation index) between 0.4 and 0.7 till a depth of 1.65 m., indicating that it was supersaturated for calcite (Stuyfzand 1993; Table 2). The mean groundwater level was 0.5-0.6 m below soil surface in July 1991.

At site T1 on Texel, in July 1991, groundwater at 0.35

m depth was supersaturated for calcite ($SI\text{-}CaCO_3 = 0.4$; Table 2). Of all sites (T1, T2, T4) the deeper groundwater had $SI\text{-}CaCO_3$ values between – 0.1 and 0.6, indicating that it was in equilibrium with or supersaturated for calcite. Mean groundwater levels were 0.45 m below the soil surface.

On Goeree, the mean summer groundwater level was 0.35 m below the soil surface, permitting a constant capillary flux (Bakker 1981). The $SI\text{-}CaCO_3$ values were 0.5 at 1.2 m and 1.9 m depth, indicating that the groundwater was supersaturated for calcite.

Table 2. pH, Ca^{2+}, HCO_3^- and $SI\text{-}CaCO_3$ (saturation index) for calcite in groundwater at different depths and the mean groundwater level in July 1991 at site S1 and sites T1, T2 and T4; Sival pers. obs.) and in July 1992 at sites M1 and M2. GW = Mean groundwater level (m below surface).

Site	Depth (m)	pH	Ca^{2+} (meq/l)	HCO_3^- (meq/l)	$SI\text{-}CaCO_3$	GW
S1	0.35	7.4	17.1	9.9	0.7	0.35
	0.65	7.3	14.9	9.4	0.5	
	1.65	7.2	16.0	9.3	0.4	
T1	0.35	7.2	6.0	7.1	0.4	0.35
	0.65	7.2	3.5	3.6	-0.1	
	1.65	7.5	4.5	3.7	0.3	
T2	0.65	7.3	5.0	3.4	0.1	0.45
	1.65	7.8	4.2	4.4	0.4	
T4	0.65	7.6	5.0	4.6	0.5	0.45
	1.65	7.7	5.3	3.6	0.6	
M1	1.90	7.3	6.6	5.0	0.5	0.35
M2	1.20	7.3	5.2	5.4	0.5	0.35
	1.90	7.0	8.7	8.0	0.5	

Soil micromorphology

The topsoil of the slack on Schiermonnikoog is mainly composed of fine and medium sand, mainly quartz (Fig. 4-IA), with thin (1-5 mm) horizontal clayey layers (Fig. 4-IB), suggesting a marine deposit. The topsoils of the 'Kammosvallei' on Texel (Fig. 2: sites T1, T2 and T4) were mainly composed of a rather compact, calcareous, clayey, humic, fine and medium sand (Fig. 4-IIC). Both sites on Goeree, at foot-slope position (Fig. 2, M1) and in the lower part of the slack (M2), showed a well sorted fine and medium grained sand deposit with a calcareous crust on top (Fig. 4-IIID).

Several carbonate forms are observed in all topsoils with the exception of site 2 on Goeree (Table 3). Here, only one type occurs, calcareous nodules. Carbonate forms, such as (1) sand-sized carbonates, molluscs and gastropods fragments (often locally weathered and partly in solution; Fig. 5-Ia) and (2) sharply bounded silt-sized carbonates (Fig. 5-Ib), are deposited by wind and water (Table 4). In addition, microcrystalline carbonates (called micrite) occur in various forms, such as diffusely bound micritic nodules or as coatings in vughs and channels (i.e. vugh and channel calcitans respectively), or as coatings around sand-sized grains (i.e. free and embedded grain calcitans), or as calcareous crusts. The soil space is present in the soil due to the formation of the mineral grains (vugh) or biological activity (channel). The morphology of the micrite forms indicates that these features were formed by precipitation of carbonates *in situ* (Table 4).

Diffusely bounded calcareous nodules, for example, become rounded with sharp boundaries during redeposition. In Table 3, group 1 mainly represents redeposited carbonates and group 2 mainly represents carbonate formations *in situ*, after sedimentation. On Schiermonnikoog, mollusc and gastropod fragments were more abundant on Texel and Goeree. Micrite and silt-sized carbonates were more abundant on Schiermonnikoog and Texel than on Goeree.

At all locations, the sand skeleton grains consisted, besides quartz, of carbonate grains (Fig.5-IIc) and micrite grains (Fig. 5-IIId). These micrite grains had the same size and rounded shape, and they were also sharply bounded, just as the quartz, indicating a deposition simultaneous with the bulk of the sediment. On Schiermonnikoog, the thin organic-rich, calcareous clayey laminae commonly contained micrite and very fine silt-sized carbonates (<15 µm; Fig. 5-Ib), both probably deposited together with the clay. The clay with micrite was locally reworked by biological activity into calcareous matric fecal pellets. In the sand laminae, and especially in the clayey laminae, neoformations of carbonates occurred as irregular micritic nodules, up to 500 µm ∅ (Fig.5-IIId), and as micritic coatings (calcitans) in vughs and channels (Fig. 5-IV). Clayey laminae commonly contained micrite and very fine silt-sized carbonates (<15 µm; Fig. 5-Ib), both probably deposited simultaneously with the clay. The micrite containing clay was locally biologically reworked into calcareous matric

Table 3. Presence of the various types of carbonates in the thin sections in the topsoil of the three dune slacks; S = Schiermonnikoog; T = Texel; M = Goeree. Group 1: carbonates present in the sediment; group 2: neoformations. (– = absent; + = rare; ++ = few; +++ = common).

Site	S1	T1	T2	T4	M1	M2
Group 1						
Sand-sized carbonates	+	+	+	+	+	-
Mollusc fragments	++	+	+	+	+	–
Gastropods fragments	++	+	+	+	–	–
Micrite and silt-sized carbonates	++	++	++	++	+	–
Group 2						
Calcareous nodules	++	+	++	+	+	+
Calcitans (vugh & channel)	+++	+	+	+	-	–
Free grain calcitans	+++	+	+	+	+	–
Embedded grain calcitans	+++	+	+	+	–	–
Calcareous crust	–	–	–	–	++	–

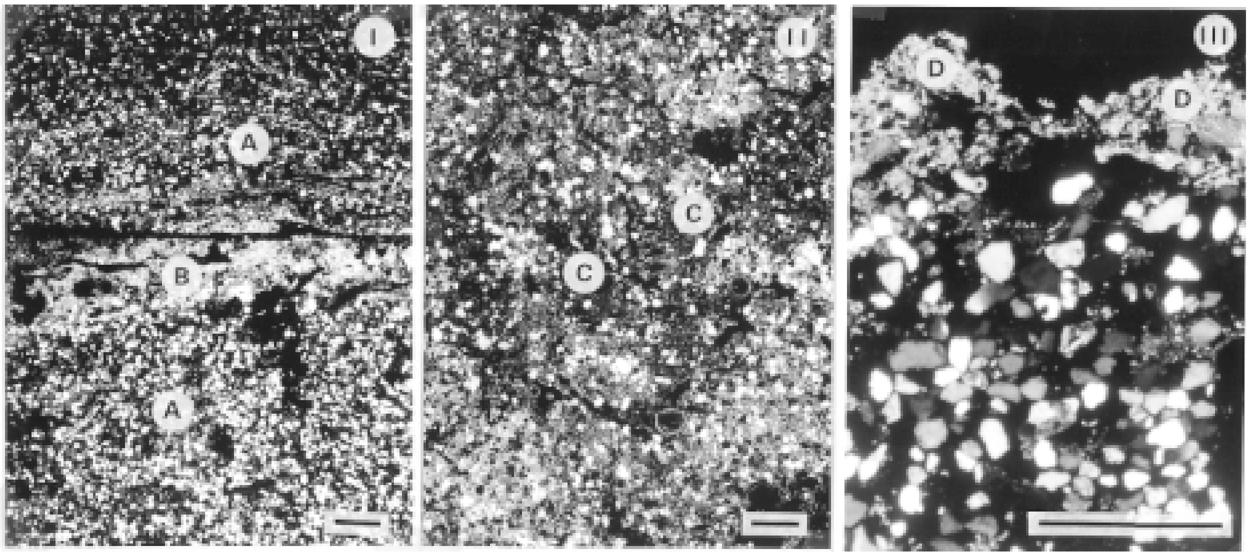

Fig. 4. Thin sections with crossed polarized light of the topsoil horizon from soil surface (top of the picture); scale bar = 1.2 mm. **I.** Fine and medium sand, mainly quartz (A), with intercalated few thin (1-5 mm) horizontal clayey laminae (B) matrix of the soil at site S1 on Schiermonnikoog. **II.** Massive, calcareous, clayey, humic, fine and medium sand deposit (C) of the soil on Texel. **III.** Calcareous crust (D) on the topsoil horizon and the irregular micrite carbonate nodules on the dune slack soil of Goeree.

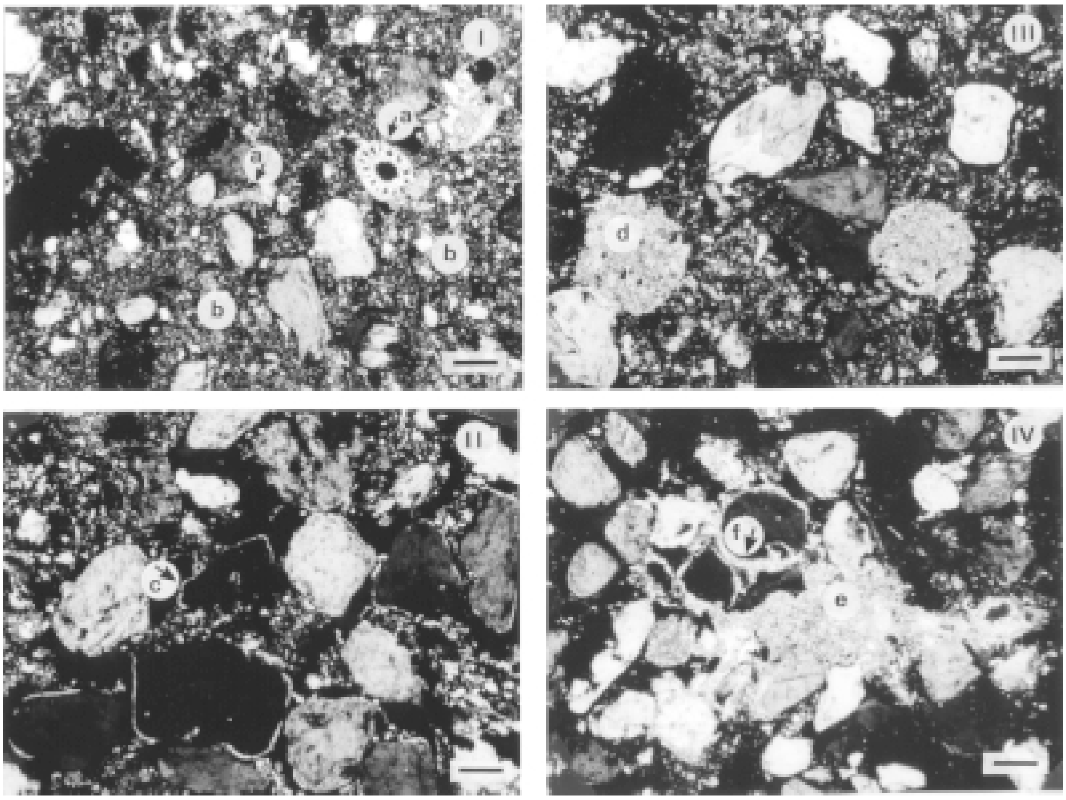

Fig. 5. Photographs of carbonate forms, crossed polarized light; scale bar = 110 μm. **I.** Mollusc and gastropod fragments (a), common micrite and fine silt-sized carbonates (b); **II.** Calcareous sand grains on Texel (c); **III.** Carbonate nodules (d); **IV.** Free grain calcitans (e) and embedded grain calcitans (f).

fecal pellets. In the sand laminae, and especially in the argillaceous laminae, neoformations of carbonates occurred as irregular micritic carbonate nodules, up to 500 µm ∅ (Fig. 5-IIId), and as micritic coatings (calcitans) in vughs and channels (Fig. 5 IV). In addition, the sand matrix contained discontinuous coating of carbonate around sand grains, surrounded by voids (i.e. free grain calcitans; Fig. 5-IVe) and around sand grains embedded in the matrix (i.e. embedded grain calcitans; Fig. 5-IVf). These calcitans were in most cases less than 30 µm thick. All these carbonate features were formed *in situ*, after sedimentation.

In situ formations of carbonates are also found in the soils on Texel and Goeree. On Texel, a few channel and vugh calcitans (< 100 µm thick) were observed. The two sites on Goeree, M1 at foot-slope position and M2 in the lower part of the slack (Fig. 4-III), showed an *in situ* carbonate development which was quite different from that on the other islands. At site M1, the carbonate grains increased from 1% by volume in the upper part to about 4% by volume at 7cm depth. In addition, at site M1 a discontinuous calcareous crust had developed on and in the soil surface (1-2.5 mm thick, with enclosed fine organic material). The crust was composed of irregular micrite nodules, 160-800 µm ∅, with sand grains enclosed. In buried positions (2, 3, 4, 5 and 6cm) five additional discontinuous calcareous crusts occurred parallel to the soil surface. They were less developed (0.2-0.6 mm thick) than the crust on top of the soil profile, but contained also fine organic material. This resulted in a weak banded fabric. The buried calcareous crusts contained, besides micritic nodules, also neoformations of large carbonate crystals (∅ 16-60 µm) occurring in clusters (∅ 0.2-0.5mm) in some packing voids. Site M2 on Goeree (Fig.2), showed in thin section also mainly fine and medium sand-sized quartz grains, but without carbonate grains. A weak humic A-horizon, less than 1cm thick, was developed in the soil profile. This A-horizon contained a discontinuous calcareous crust consisting of irregular micrite nodules (∅ 50-300 µm) mixed with organic material (algae, litter and roots). The crust was 1.2-3.2 mm thick, locally less (0.1-1.2 mm). At more than 3.2 mm depth no carbonates could be observed.

Table 4. Conditions for the development of different carbonate forms in dune slack soils; sed. = sedimentation; mov. = movement; seep. = seepage; prec. = precipitation: calc. gw. = calcareous groundwater

Carbonate forms	Process/mechanisms	Conditions
Sand-sized fragments	Wind and water sed.	Wind and water mov.
Mollusc fragments	Wind and water sed.; in situ formation	Wind and water mov.
Gastropod fragments	Wind and water sed.; in situ formation	Wind and water mov.
Micrite and silt-sized carbonates	Wind and water sed.	Wind and water mov.
Calcareous nodules (diffusely bounded and irregular)	In situ prec.	Upward water mov.; seep. of calc. gw
Vugh & channel calcitans	In situ prec.	Upward water mov; seep. of calc. gw.
Free grain calcitans	In situ prec.	Upward water mov.; seep. of calc. gw.
Embedded graincalcitans	In situ prec.	Upward water mov.; seep. of calc. gw.
Calcareous crust	in situ prec.	Upward water mov.; seep. of calc. gw.

Discussion

Origin of the carbonates

In all slacks, part of the carbonate is of biotic origin, consisting of whole and fragmented molluscs and gastropods. The mollusc fragments clearly result from sedimentation by wind or water (Mücher 1990). Because the smallest soil particles are blown away, larger fragments of shells and molluscs remain on the topsoil of a dune slack, forming a ‘desert pavement’ (Stuyfzand 1993). Gastropod fragments may also be either sediments or derived from remnants of the local soil fauna (Bullock et al. 1985). Micrite carbonates in the sand fraction of slacks behind dunes, such as on Schiermonnikoog, may result from aeolian processes. The finest sand fraction, with a higher carbonate content (Eisma 1968), is transported further away from the beach (Arens 1994). Since 1972, this slack became vegetated, which also favoured deposition of the finest fraction. Here, silt-sized carbonate crystals are present in the clay layers; they have likely been deposited together with clay during flooding by the Wadden Sea (Rozema 1976). A site T, the organic matter contains a large amount of micrite and very fine silt-sized carbonates. Indications for sedimentation such as on Schiermonnikoog have not been observed. However, the clay component suggests a deposition of clay together with micrite and very fine carbonates (∅ < 15 µm) in a calm sedimentary environment during flooding by the sea. The micrite grains, rounded and of the same size as the quartz sand grains, are inherited from the parent material (Mermut & St. Arnaud 1981; Assendorp & Mücher 1990). They were formed elsewhere and have been rounded off by abrasion during transport.

The *in situ* carbonate forms (free and embedded micritic grain cutans), found in the topsoil layer at Schiermonnikoog and Texel, and in the calcareous crust of the topsoil on Goeree have also been observed in other, coarser textured soils (Mermut & St. Arnaud 1981). The specific hydrological conditions of our slacks probably favoured the accumulation of these carbonate forms in the topsoil layer. On Schiermonnikoog and Texel, groundwater levels < 0.6 m below the surface in summer (Bakker 1981), *and* calcareous groundwater with a saturation index of $CaCO_3$ between –1 and + 0.3 (Stuyfzand 1993) were present in summer. The combination of both these hydrological conditions can create opportunities for capillary rise of calcareous groundwater and subsequent carbonate precipitation due to loss of CO_2 at the soil surface. On Texel and Goeree, CO_2 loss from carbonate-saturated groundwater occurs at the soil surface, during inundation of the soil in winter and early spring, when it is discharged from the surrounding dune ridges. This can stimulate carbonate precipitation. The higher dune ridges contain carbonates which, once dissolved, are transported by near-surface and subsurface flow to the lower sites of the slack.

On Goeree, at the higher part of the slack (M1), the precipitation of carbonates resulted in a calcareous crust and is limited to the soil-air interface. An explanation for this phenomenon, apart from the CO_2 loss at the bare soil surface may be an increased evapotranspiration. Due to sod removal, the topsoil lacks an organic layer (as at T) which reduces the transpiration. CO_2 uptake by algae can also stimulate carbonate precipitation at the soil surface. In a buried position, at M1, there are five calcareous crusts, resulting in a weakly developed banded fabric. This fabric, in combination with poor sorting of the mineral grains in the individual laminae, suggests deposition by near-surface flow during rain (Mücher 1986). The buried calcareous crusts and the organic material reflect fossil, weakly developed soil surfaces. The carbonate sources of *in situ* formed carbonates can be deposited carbonates, calcareous run-off water and calcareous groundwater.

In the lower part of slack M2, a calcareous crust occurs in the weakly developed humic A-horizon, although carbonate grains are absent in the soil material. The only carbonate source here could be calcareous water from overland flow and subsurface flow. This crust may have been produced by precipitation of the carbonates after evaporation of the water in the topsoil.

Precipitation of carbonates in a humid climate; a paradox?

In a humid climate with a precipitation surplus, as in The Netherlands, the infiltration of water and consequently the leaching of minerals is the rule, but there are circumstances where the opposite occurs. During winter and early spring, when the slack is inundated, it receives exfiltrating groundwater along the up-gradient border and infiltrating water along the down-gradient border (Stuyfzand 1993). If this exfiltrating groundwater is (over)saturated with calcite, CO_2 loss will cause precipitation of carbonates (Krauskopf, 1982; Boyer & Wheeler 1989; Komor 1994). Capillary rise of calcareous groundwater can also increase the carbonate content at the soil surface, especially during summer, which can be accelerated by evapotranspiration. We have estimated a maximum amount of precipitated carbonates in a 1-cm soil layer with an area of 1 m^2. In this estimate we assume that (1) the upward flux due to capillary rise and seepage equals the potential evapotranspiration (E_p) and (2) potential evapotranspiration equals evaporation and (3) there is no addition of rainwater:

$$CaCO_3\ (\%/yr) = ([Ca]_{gw} \cdot E_p) \cdot r_f \cdot 10^{-2}/\rho_d \qquad (1)$$

where E_p is the potential evapotranspiration; $[Ca]_{gw}$ the Ca^{2+} concentration of the groundwater; r_f, the recalculation factor which converts Ca^{2+} into $CaCO_3 = 2.5$; ρ_d the bulk density. In the case of the soil on Goeree, $E_p = 550$ mm/yr (Anon. 1992, 1995); $[Ca]_{gw} = 140$ mg/l (Anon. 1994); $r_f = 2.5$ and $\rho_d = 1500$ kg/m^3 (Sival 1996). The estimated percentage carbonate precipitated in the top cm of the soil is:

$$140 \cdot 550 \cdot 2.5 \cdot 10^{-2} / 1500 = 1.3\ \%\ CaCO_3/yr \qquad (2)$$

Accumulation of carbonates is possible under circumstances as described above. The net effect of precipitation and dissolution of carbonates depends on year-to-year rainfall/evapotranspiration differences. In winter and spring the northern, lower part of the slack (M2) is inundated by rain water which infiltrates into the soil. Although the somewhat higher southern part of the slack (M1) is not inundated, the soil was entirely saturated with water in winter and spring. Rain water which did not infiltrate runs off to the lower part, increasing the amount of infiltrating water there. The stagnant water in the lower part forces seepage water in the southern part to discharge at the surface. Data from The Netherlands Meteorological Survey (Anon. 1992, 1995) were used to calculate the cumulative precipitation and evapotranspiration. In 1992, the carbonate crust in the dune slack on Goeree was better developed than in 1995. This can be attributed to a lower precipitation excess in 1992 compared to 1995 (Fig. 6). Evapotranspiration in a 14-month period prior to the sampling was comparable in both years, but in 1994-1995 precipitation was higher than in 1991-1992. Precipitation and dissolution of carbonates seem to alternate depending on the amount of rainfall in subsequent years.

Some considerations for conservation management

Sod removal is an important practice in dune slacks on the Wadden Sea islands (Heykema1965) and in other dune areas along the mainland coast (Jungerius et al. 1995), to maintain nutrient poor conditions by reducing the organic matter accumulation. To maintain alka-

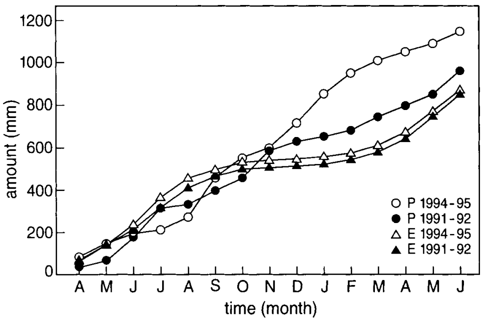

Fig. 6. Evapotranspiration (E; mm) and precipitation (P; mm) patterns in 1991-1992 and 1994-1995 on Goeree (Data used from Anon. 1992, 1995).

line conditions, hydrological measures may be necessary. In particular, addition of carbonates in the topsoil prolongs the growth of basiphilous plant species. Sival (1996) described how a basiphilous plant community in the initially brackish calcareous beach plain persisted for ca. 20-25 yr. This is almost twice as long as in a decalcified slack (Westhoff & van Oosten 1991). But after this period, the increased pool of organic matter and nutrients in the topsoil facilitated fast growing species which replaced the basiphilous plant species *Schoenus nigricans* and many associated rare species.

In the infiltration slack on Schiermonnikoog, the addition of carbonate is a result of capillary rise of oversaturated groundwater during summer. This results in carbonates percentage of the calcareous topsoil which is twice as high as in the underlying soil. Carbonates in the soil are probably in equilibrium with calcium and bicarbonate in the groundwater. Permanent supply is guaranteed because the groundwater level does not drop below the critical depth for capillary rise – ca. 0.6 m (Bakker 1981).

The *in situ* carbonates in the topsoil on Texel and Goeree, however, are the result of other hydrological mechanisms. The dune ridge adjacent to the slack causes exfiltration of calcareous groundwater. Thus, in winter and early spring, when the slack is inundated, oversaturated groundwater can reach the topsoil layer and carbonates can precipitate due to aeration and probably also due to the activity of cyanobacteria and algae (Chafetz 1994; Riege & Villbrandt 1994). Cyanobacteria and algae are also common in dune blowouts and can stabilize bare sand surfaces (Pluis & van Boxel 1993). This may stimulate the formation of a carbonate crust as in the dune slack soil on Goeree. During summer, with low groundwater levels, the carbonate precipitation continues, because CO_2-losses from capillary rise of calcareous groundwater also continues (Bakker 1981). During vegetation development and subsequent root accumulation, the amount of CO_2 will increase due to root respiration and stimulate the dissolution of carbonates in the topsoil. Finally, all the carbonates are dissolved causing acidification of the topsoil layer. In this situation, sod removal can increase the possibilities for carbonate precipitation and thus prolong the presence of mesotrophic basiphilous plant species.

In conclusion, besides sod removal hydrological interventions to increase the groundwater level, may also be necessary to favour conditions for carbonate precipitation, which in turn, can prevent further acidification of dune slack soils. During winter and early spring, flooding conditions can sustain exfiltration of calcareous groundwater and during summer the groundwater levels must not drop below the critical depth for capillary rise.

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