LANDSCAPES AND SOILS OF NORTH SEA BARRIER ISLANDS: A COMPARATIVE ANALYSIS OF THE OLD WEST AND YOUNG EAST OF SPIEKEROOG ISLAND (GERMANY)

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With 3 figures and 1 table
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Summary: To get further insights into the development of landscape elements and soils of North Sea barrier islands; an old part in the West (formed between approx. 1650-1860) and a young part, largely unaffected by anthropogenic influences in the East (formed approx. 1960), of the island Spiekeroog were comparatively analyzed. Between the two parts beach soils (World Reference Base of Soil Resources (WRB), IWG WRB (2015): Eutric Fluvic Tiadalic and Eutric Endosalic Arenosols; German Soil Classification System (GSCS), Ad-hoc-AG Boden (2005): Nassstrand and Strand) did not differ, except for microbial mats, which were found only in the East. In the West, a dune complex comprising white, gray and brown dunes holds a soil chronosequence from unaltered sands (WRB: Eutric Protic Arenosol; GSCS: Lockersyrosem) to braunified and podzolized soils (WRB: Dystric Brunic Arenosol; GSCS: Braunerde). However, in the East, only a single white dune chain, with adjacent shallow dune mounds to the south, had formed. In both parts, dune slacks evinced remarkably rapid peat formation (WRB: Dystric Histic and Eutric Histic Gleysols; GSCS: Niedermoorgleye). Here, iron content of groundwaters determined the formation of redoximorphic features. Soils of the salt marshes (WRB: Eutric Fluvic and Eutric Gleysols; GSCS: Rohmarschen) showed the highest contents of soil organic carbon (SOC) in the West, where the thickest fine sediment layers were also found. Revealed shortcomings of the German soil classification system concerning the classification of 'Strand' and 'Rohmarsch' soils are discussed. It is suggested to exclude the obligatory carbonate ($CaCO_3$) content in the definition of the Strand soil and to introduce an additional horizon prefix to indicate carbonate contents between > 0 and < 2 %, in order to classify Rohmarsch soils, with primary carbonate contents < 2 %. Finally, an outlook on the future landscape -and soil development is provided, which is expected to be most profound in the young East.

Zusammenfassung: Um Einblicke in die Entwicklung von Landschaftselementen und Böden auf Nordseebarriereinseln zu vertiefen, wurden ein alter Teil im Westen (gebildet ca. 1650-1860) und ein junger, weitestgehend anthropogen unbeeinflusster Teil im Osten (gebildet ca. 1960) der Insel Spiekeroog vergleichend analysiert. Strandböden (World Reference Base of Soil Resources (WRB), IWG WRB (2015): Eutric Fluvic Tidalic und Eutric Endosalic Arenosols; Deutsche Bodensystematik (Ad-hoc-AG Boden (2005): Nassstrand und Strand) glichen sich mit der Ausnahme des Vorkommens mikrobieller Matten, das auf den Osten beschränkt war. Ein im Westen gelegener Komplex aus Weiß-, Grau- und Braundünen bildet eine Bodenchronosequenz aus pedogen unveränderten Sanden (WRB: Eutric Protic Arenosol; Deutsche Bodensystematik: Lockersyrosem) bis hin zu verbraunten und podsolierten Böden (WRB: Dystric Brunic Arenosol; Deutsche Bodensystematik: Braunerde). Im Osten kam es bisweilen lediglich zur Ausbildung einer einzigen Weißdünenkette und südwärts angrenzenden flachen Dünenhügeln. In beiden Teilen wurde eine bemerkenswert schnelle Torfbildung in Dünentälern festgestellt (WRB: Dystric Histic and Eutric Histic Gleysols; Deutsche Bodensystematik: Niedermoorgleye). In ihnen determiniert der Eisengehalt des Grundwassers die Ausbildung von redoximorphen Merkmalen. Böden der Salzmarschen (WRB: Eutric Fluvic und Eutric Gleysols; Deutsche Bodensystematik: Rohmarschen) wiesen die höchsten Gehalte an organischen Kohlenstoff (SOC) im Westen auf, dort lagen auch die höchsten Feinsedimentmächtigkeiten vor. Gefundene Schwächen der deutschen Bodensystematik bezüglich der Klassifizierung der Bodentypen Strand und Rohmarsch werden erörtert. Es wird vorgeschlagen, den obligatorischen Carbonatgehalt ($CaCO_3$) aus der Definition des Bodentyps Strand herauszunehmen, sowie ein zusätzliches Horizontpräfix für Gehalte zwischen > 0 und < 2 % einzuführen, um die Klassifizierung von Rohmarschen mit primären Gehalten < 2 % zu ermöglichen. Abschließend wird ein Ausblick auf die zukünftige Landschafts- und Bodenentwicklung gegeben, wobei prägnanteste Entwicklungen im jungen Osten erwartet werden.

Keywords: East Frisian Islands, landscape development, toposequence, soil geography, soil synopsis, soil formation

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1 Introduction

North Sea barrier islands extend from the island of Texel in the Netherlands via the East and West Frisian Islands in Germany to the island of Fanø in Denmark (Pott 1995). Like a rope of elongated pearls, they are located offshore the mainland, parallel to the coast and separate small parts of the Wadden Sea from the open sea. The barrier islands are very young Holocene formations, approximately 2000 years old (Streif 1990). They developed as a result of forces such as waves, water currents and wind. The required geo-hydro-morphological conditions for their formation are shallow coasts, sufficient sediment supply and adequate tidal amplitudes. According to Barckhausen (1969), the formation process starts with the accumulation of Holocene marine sediments on a Pleistocene substratum, such as cores and channels (Streif 1990; 2002), initially below mean high water level (mhwl), leading to periodically flooded shelves with tidal flats and subsequently formed partially dry beaches. Desiccated sediments at the dry beaches are subjected to ongoing deflation and sorting. Translocation and resedimentation of sandy sediments leads to the formation of pioneer dunes that evolve to dune chains higher than 20 meters above sea level (masl), which are separated by mostly near-groundwater slacks (Streif 1990; Pott 1995). Advanced developed dune landscapes comprise several dune chain generations, and thus hold soil chronosequences. With proceeding soil formation and plant succession, white dunes closest to the beach develop to gray dunes, which, in turn, eventually transform to brown dunes. The sea-averted backbarrier sites adjoining the dune chains are unaffected by wave action of the open sea. There, calm sedimentation conditions allow for the accumulation of fine-grained marine sediments and give rise to the development of salt marshes (e.g. Gierloff-Emden 1980). At the North Sea coast, salt marsh soils affected by daily, periodical floodings below mhwl show salinities of about 25 ‰ (electric conductivity, EC ≈ 39 mS cm^{-1}), while those above mhwl show salinities of about 8–14 ‰ (EC ≈ 12.5–22 mS cm^{-1}) (Giani et al. 1993).

The described genesis of a North Sea barrier island finally results in a typical North-South toposequence comprising the following landscape elements: tidal flat – beach plains – dunes with slacks – salt marsh – tidal flat. Valid data on soils within these landscape elements at North Sea barrier islands are rare, fragmentary and partially contradictory. Furthermore, these data are inconclusive due to the application of different classification systems (Gerlach 1993; Gerlach et al. 1994; NLFB 1997; Sponagel et al. 1999; Giani and Buhmann 2004). This is particularly true for dune soils. According to NLFB (1997), white dunes comprise Lockersyroseme and brown dunes of Podsol-Ranker with initial formation of orterde. However, orterde formation is not recognizable in the photograph presented by NLFB (1997). Sponagel et al. (1999) report Podsol-Braunerden for the brown dunes, and Regosole for gray dunes after the classification of Ad-hoc-AG Boden (1994). Using the classification after Avery (1973), Gerlach et al. (1994) describe raw soils and sand rankers for yellow dunes (synonymous with white dunes), podzolic rankers for gray dunes, and podzolic brown soils, as well as slightly podzolic sandy rankers, for brown dunes. Giani and Buhmann (2004) found Calcaric Arenosols on white dunes and Dystric Arenosols on gray- and brown dunes, following the classification of FAO (1998). They found visible weak braunification and illuviation of humus in brown dune soils, the latter of which, however did not fulfill the criteria of a spodic horizon.

Due to the lack of clarity for present soils and to widen the data basis, the first objective of this study was to give a comprehensive synopsis on soils of North Sea barrier islands using a soil sequential approach, based on the described landscape toposequence as illustrated on Spiekeroog island. For greater comparability, we applied current classification systems namely the World Reference Base of Soil Resources (WRB, IWG WRB 2015) and the German Soil Classification System (Ad-hoc-AG Boden 2005). Since microbial mats at the surface of beach soils are commonly found on North Sea barrier islands (De Groot et al. 2017), but, no detailed description of such soil there exhibiting this feature exist, we included such soil in our study.

The predominance of sands, low elevation above sea level and frequently occurring storm tides strongly affect the geomorphological and position stability of North Sea barrier islands (Pott 1995). Land reclamation activities at the mainland resulted in changing hydrographical conditions at Spiekeroog, which induced profound sand sedimentation and the rapid formation of an island tail in the East (Streif 1990), locally referred to as 'Ostplate' (germ. Ost = East, germ. -plate = flat), which is a characteristic geomorphological feature of North Sea barrier islands (De Groot et al. 2017). Between 1650–1960, the Ostplate continuously extended eastwards, by which Spiekeroog consequently grew from a length of 6 km (Sindowski 1970) to its present extent of approx. 10 km. Initially, the Ostplate was a periodically flooded sand flat that started to develop into a dune island around the year 1940, with first dunes evinced in the 1960s (Röper et al. 2013), hence bearing soils approx. 80 years old. However, the pedological setting is still unknown today. An elongated white dune chain higher than 10 masl stretches from West to East. At its sea-averted site, it is partly adjoined by shallow primary dune slacks and small isolated dune mounds elevated approx. 2–3 masl. Through strict nature conservation requirements, great parts of Spiekeroog and the entire Ostplate remained largely unaffected by human activities. The consequent pristine condition of the Ostplate makes it an ideal study site to investigate initial soil formation in very young sediments and compare the development of landscape elements and soils with those of the older part of Spiekeroog in the West, which was the second objective of this study.

To get more insights into the study objectives, two soil sequences - one established at the older part in the West and the other at the recently formed Ostplate in the East - were comparatively analyzed. As a third objective, evident shortcomings of the German soil classification system (Ad-hoc-AG Boden 2005), are briefly discussed and remedial changes are suggested.

2 Study area

2.1 Geology and morphology

The East Frisian Island, Spiekeroog was the study area (Fig. 1). It is located 5 km from the mainland and is part of the Niedersächsisches Wattenmeer national park. The Otzumer inlet and the Harle inlet separate Spiekeroog from the neighboring islands Langeoog in the West and Wangerooge in the East. The older western part of the island is characterized by several generations of dune chains with heights up to approx. 24 masl, enclosing the island's village. The oldest dunes were found to be > 350 years old (Sindowski 1970), which, according to a geological timescale, are very young formations. The studied toposequence stretches from the beach plain, over the dune chains, to the salt marsh (P1–P8). In the east, young sediments of the island tail, Ostplate, bears soils approx. 80 years old (Röper et al. 2013). Here, the toposequence stretches from the beach plain to the salt marsh, crossing a single dune chain (up to heights of approx. 14 masl) and isolated shallow dune mounds (heights of up to approx. 3 masl) (P9–P15).

2.2 Vegetation

Except for inhabited and small afforested areas, large parts of Spiekeroog are not used, and thus comprise natural vegetation. Beach grass (*Ammophila arenaria*) is characteristic for the white dunes. Gray dunes are covered with dominantly sand sedge (*Carex arenaria*), gray hairgrass (*Corynephorus canescens*), seabuckthorn (*Hippophaë rhamnoides*) and beach rose (*Rosa rugosa*). Brown dunes are covered mostly with crowberry *(Empetrum nigrum*) and common polypody (*Polypodium vulgare*) at the north slopes and gray hairgrass accompanied by lichen and moss species at the south slopes. Groundwater-near slacks of the western part of Spiekeroog are typically covered with small stocks of moor birches (*Betula pubescens*) representing late stages of vegetation succession. The younger dune slacks at the Ostplate harbour species, such as sedges (*Carex L.*), common silverweed (*Potentilla anserina*) and common reed (*Phragmites australis*), typical for dune slacks of North Sea barrier islands with active vegetation succession (Petersen 2000). The beaches are mostly without any vegetation except for sparse occurrences of salt tolerant pioneer species, such as seaside sandplant (*Honckenya peploides*). High salt marshes are covered with dominantly grasses, e.g. longbract sedge (*Carex extensa*), red fescue (*Festuca rubra agg.*) and sea couch (*Elymus athericus*). Low salt marshes harbour dominantly halophytes e.g. sea lavender (*Limonium vulgare*), glasswort (*Salicornia europaea*) and sea meadow grass (*Puccinellia maritima*) (Pott 1995; Petersen and Pott 2005).

2.3 Climate and hydrology

The climate is temperate oceanic (Köppen-Geiger Cfb type) (Kottek et al., 2006). The average annual air temperature is 8.8 °C. The warmest months are July and August (18 °C) and the coldest January and February (2 °C). The average annual precipitation is 795 mm with a maximum in August (80 mm) (Climate-data 2018). The mhwl at Spiekeroog is 1.38 masl (Röper et al. 2013) and the mean high water spring level (mhwsl) is 1.54 masl (WSV 2016).

3 Methods and material

Fifteen (15) soil profiles were dug along two toposequences: one in the year 1995 at the older part in the West (Toposequence West), and the other be-

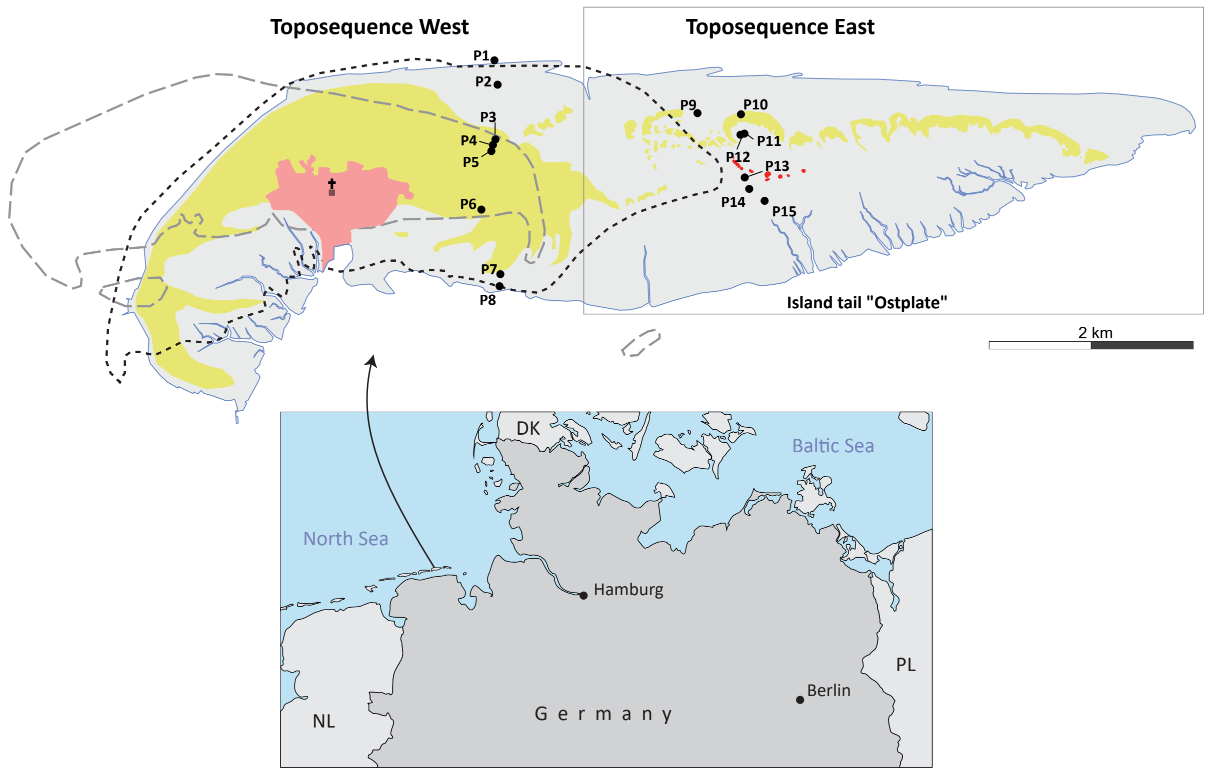

Fig. 1: The study area, Spiekeroog. The outline of the island is defined by the mean high water level (mhwl, 1.38 masl) of 2011; the yellow areas mark the extent of dunes in 2011 (Röper et al. 2013). The pink area represents the inhabited area of Spiekeroog. The dashed lines indicate geographical positions of the island at 1650 (grey line) and 1860 (black line) (Sindowski 1970). The island tail, Ostplate is marked by the grey frame. The red areas show isolated dune mounds (heights of up to approx. 3 masl) protruding from the salt marsh, derived from a digital elevation model (NLWKN 2008) and confirmed by field surveys in 2017. Black dots mark the location of investigated soil profiles (P), numbered consecutively along the toposequences West and East, respectively.

tween 2015 and 2017 at the recently formed Ostplate in the East (Toposequence East) (Fig. 1). After preliminary drilling, in order to find representative sites, the profiles were established in different landscape elements: wet beach (only in Toposequence West), dry beach, dunes, dune slacks, high and low salt marshes. The soils were classified according to the World Reference Base for Soil Resources (WRB, IWG WRB 2015) and the German Soil Classification System (GSCS) (Ad-hoc-AG Boden 2005). Mixed samples were taken from each horizon. Ground surface heights were derived from a digital elevation model (NLWKN 2008). Electric conductivity (EC) of groundwater was measured in-situ, using a portable conductivity meter. Textural classes after FAO (2006) and Ad-hoc-AG Boden (2005) were derived from results of sieve and sedimentation analysis after Köhn (1928) and Atterberg (1912), or via field estimation, following Ad-hoc-AG Boden (2005). On fine earth (< 2 mm) and oven-dried (105 °C) samples, soil organic carbon (SOC) were determined using a CN-Analyzer. On air-dried fine earth samples, the pH ($CaCl_2$) was measured electrometrically in 0.01 M $CaCl_2$ solution, using a soil-solution-ratio of 1:2.5. Base saturation (BS) was derived from pH ($CaCl_2$) according to Ad-hoc-AG Boden (2005). Calcium carbonate ($CaCO_3$) were either gasometrically measured on air-dried fine earth samples or determined semi-quantitatively in-situ, using 10 % hydrochloric acid (HCl) following Ad-hoc-AG Boden (2005).

4 Results

4.1 Sequential synopsis of soils

4.1.1 Toposequence West

Beach plain

Soils below mhwl are represented by Profile 1 (1.0 masl) (Tab. 1 and Fig. 2). These soils are inundated during periodic tides twice a day, and are thus affected by saline seawater. Consequently, the con-

Tab. 1: Soil morphology, vegetation, surface heights and selected physiochemical properties

Profile	Landscape element	Dominant vegetation	Surface (masl)	Horizon a	Horizon b	Depth (cm)	Textural class a	Textural class b	Colour (moist)	SOC (g kg-1)	pH ($CaCl_2$)	$CaCO_3$ (g kg-1)	BS[e] (%)
	Toposequence West												
1	Beach plain	none	1.0	W	tmzFw	-30	S	mSfs	10YR 6/2	n.d.	6.3	5-<20	80-100
				Wr	tmzFr	-40	S	mSfs	10YR 6/2	n.d.	-	5-<20	-
2	Beach plain	none	1.8	C1	tmAi/tmlC	-55	S	mSfs	10YR 6.2	n.d.	6.8	>0-<5	80-100
				C2	tmzGw	-80	S	mSfs	10YR 6.4	n.d.	-	>0-<5	80-100
				Cr	tmzGr	-100	S	mSfs	10YR 6.5	n.d.	-	>0-<5	80-100
3	White dune	Beach grass	8.0	A	Ai	-0.5	S	fSms	-	-	6.8	3	80-100
				C	ilC	87	S	fSms	2.5Y 6/2	1.2	6.8	3	80-100
4	Gray dune	Sand sedge, mosses	8.0	Ah	Ah>	-6	S	fSms	10YR 3/2	7.3	5.4	0	50-<80
				C	ilCv	-100	S	fSms	10YR 4/3	1.9	5.4	0	50-<80
5	Brown dune	Crowberry	8.0	O	L/Of/Oh	+5	-		-	-	-	-	-
				AE	Aeh	-4	S	fSms	10YR 6/2	4.6	3.5	0	5-<20
				Bw	Bv	-25	S	fSms	7.5YR 5/4	3.0	3.8	0	20-<50
				C	ilCv	-90	S	fSms	10YR 8/3	-	4.2	0	20-<50
6	Dune slack	Moor birch	2.0	O	L	+4	-	-	-	-	-	-	-
				H	nHw	-17	-	-	5YR 2.5/1	347.0	3.0	0	<5
				2Cl	II Gro	-55	S	fSms	10YR 6/2	1.2	3.8	0	20-<50
				2Cr	II Gr	-65	S	fSms	2.5Y 7/1	-	4.0	0	20-<50
7	High salt marsh	Red fescue	2.0	Alh	tmzGo-Aa	-14	SL	Sl4	10YR 2/2	152.0	6.1	0	80-100
				2Cl1	II tmzGo	-17	S	mSfs	10YR 4/2	9.7	5.9	>0-<5	50-<80
				2Cl2	II tmzGro	-40	S	mSfs	10YR 5/2	-	6.0	>0-<5	80-100
				2Cl3	II tmzGor	-60	S	mSfs	5Y 5/2	-	-	0	-
				2Cr	II tmzGr	-80	S	mSfs	5Y 5/1	-	-	0	-
8	Low salt marsh	Sea lavender	1.6	Alh	tmzeGo-Ah	-13	CL	Lt2	5Y 4/3	45.6	7.1	42	80-100
				2Cl	II tmzeGo	-33	SiCL	Tu3	5Y 4/2	22.0	7.2	33	80-100
				3Cr	III tmzGr	-55	SCL	Lts	5Y 4/2	-	7.2	5-<20	80-100
	Toposequence East												
9	Beach plain	Few glasswort	2.0	A	tmeAi	-3	S[c]	Ss[c]	-	1.7[d]	7.8[d]	27[d]	80-100[d]
				Cr	tmzGr	-100	S[c]	Ss[c]	10YR 6/2	-	-	-	-
10	White dune	Beach grass	8.0	A	Ai	-0.5	S[c]	Ss[c]	-	-	-	-	80-100
				C	ilC	-56	S[c]	Ss[c]	2.5Y 6/2	2.2	6.9	4	80-100
11	Shallow dune	Sea couch	2.5	Ah	Ah	-8	S[c]	Ss[c]	10YR 2/1	49.3	6.5	2	80-100
				Cl	Go	-23	S[c]	Ss[c]	10YR 6/2	0.7	6.5	2	80-100
				Cr	Gr	-100	S[c]	Ss[c]	10YR 7/2	-	6.5	2	80-100
12	Dune slack	Common silverweed	1.9	H	nHw	-16	-		10YR 2/1	208.5	5.5	0	50-<80
				2Cr	II Gr	-100	S[c]	Ss[c]	Gley1 4/N	-	-	0	-
13	Isolated dune mound	Sea couch	2.4	Ah	Ah	-8	S[c]	Ss[c]	10YR 3/1	12.0	6.8	2	80-100
				Cl	Go	-48	S[c]	Ss[c]	10YR 6/2	-	7.3	2	80-100
				Cr	Gr	-100	S[c]	Ss[c]	10YR 6/2	-	7.5	2	80-100
14	High salt marsh	Sea couch	1.9	Alh	tmzeGo-Ah	-5	SiC	Tu2	10YR 2/1	75.7	7.9	46	80-100
				Cl	tmzGor	-17	SiC	Tu2	10YR 3/1	34.2	7.7	10	80-100
				2Cl	II tmzGor	-27	S	mSfs	10YR 5/2	-	7.5	2	80-100
				2Cr	II tmzGr	-60	S	mSfs	-	0.7	-	-	-
15	Low salt marsh	Sea meadow grass	1.6	Alh	tmzGo-Ah	-11	L	Ls4	10YR 3/1	62.5	7.2	5	80-100
				2Cl1	II tmzGro	-26	S	mSfs	10YR 5/2	1.1	7.5	2	80-100
				2Cl2	II tmzGor	-62	S	mSfs	10YR 4/2	1.1	8.0	6	80-100
				2Cr	II tmzGr	-70	S	mSfs	10YR 5/2	0.7	8.5	5	80-100

[a] according to FAO (2006); [b] according to Ad-hoc-AG Boden (2005); [c] according to field estimations after Ad-hoc-AG Boden (2005); [d] value of a mixed sample taken from 0–10 cm soil depth; [e] derived from pH-values according to Ad-hoc-AG Boden (2005); n.d.: not detectable.

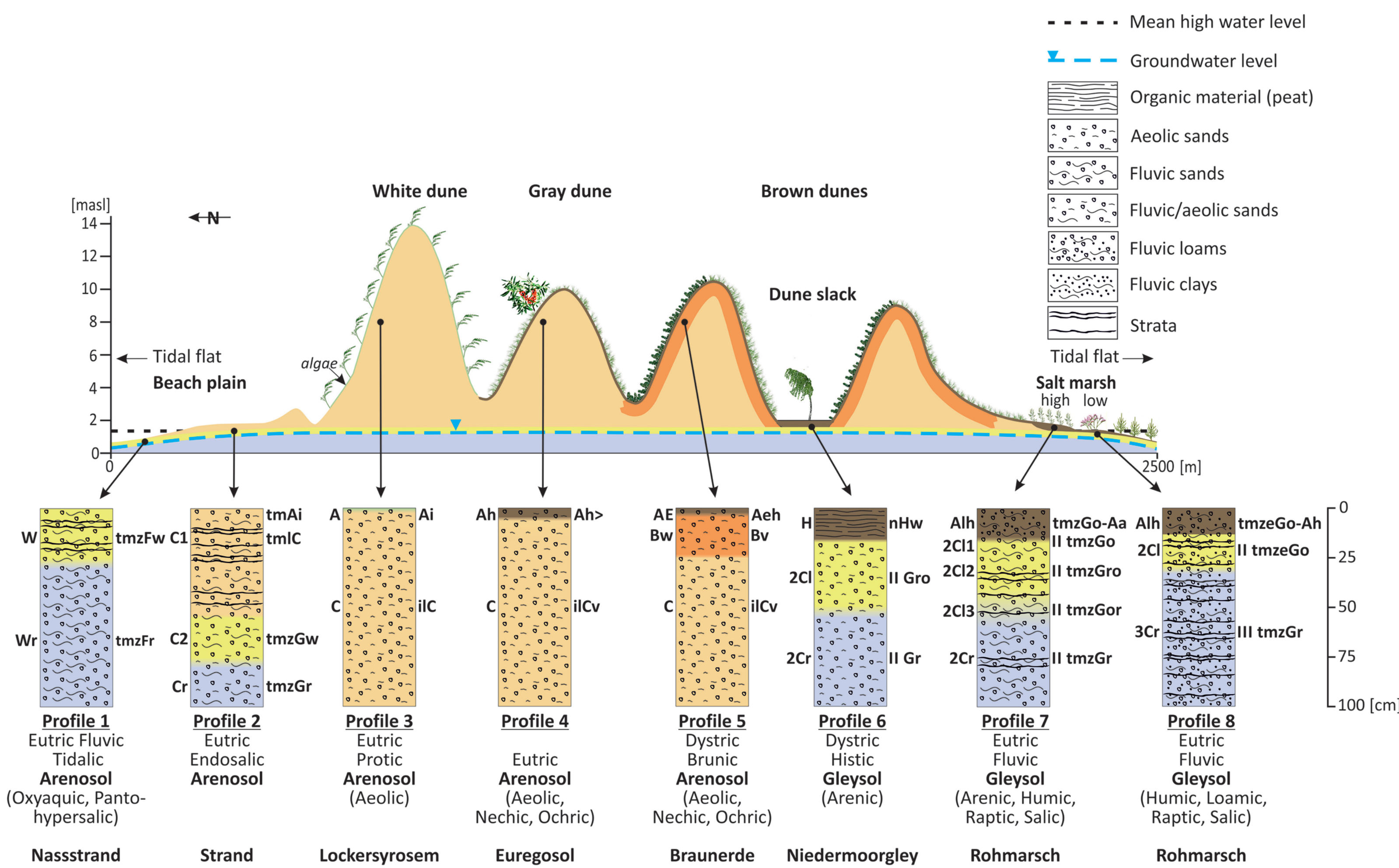

Fig. 2: Toposequence West. Conceptual sketch from the beach plain to the salt marsh in the West of Spiekeroog (top) and morphologies of studied soils (middle) with soil names according to WRB (IWG WRB 2015) and the German Soil Classification System (GSCS) (Ad-hoc-AG Boden 2005) (bottom).

stant supply of oxygen rich water and periodic aeration during low tide, resulted in continuous oxic conditions in the upper part of the soil, whereas in the subsoil (below 30 cm), reductive conditions prevailed. The sandy soil was interfused by thin (ca. 1-3 mm) strata of black heavy minerals and was free of vegetation and humus. It evinced weak acidic reactions (pH 6.3) and low carbonate contents (5–< 20 g kg^{-1}), although its matrix was interfused with shells and shell fragments.

Similar properties were found for Profile 2 (1.8 masl) (Fig. 2). However, its position above mhwl resulted in the formation of a temporally groundwater affected C horizon (C2) beginning at 55 cm depth. (Tab. 1). The higher elevated soil surface is subject to desiccation and deflation. Wind-sorting resulted in typical black bands (ca. 1-3 mm thick) of redeposited heavy minerals within the solum. The soils of Profile 1 and 2 were classified as Arenosols (WRB) with different qualifiers and as Nassstrand (*engl.* wet beach) and Strand (*engl.* beach) (GSCS), respectively.

Dunes

Soils of white dunes adjoining the beach plain, covered with beach grass (*Ammophila arenaria*), are represented in Profile 3 (Fig. 2). The profile was comprised of weak calcareous (3 g kg^{-1} $CaCO_3$) sands, showed neutral reaction (pH 6.8) and high base saturation (80-100 % BS) (Tab. 1). No pedogenetic features were found, except for a 0.5 cm thick crust of mineral grains cohered by light greenish algae at the surface. The soil was classified as Arenosol (WRB) and Lockersyrosem (GSCS). North of the white dunes, shallow pioneer dunes formed.

Profile 4, covered with dominantly sand sedge (*Carex arenaria*), represents soils of gray dunes, which have developed from previous white dunes (Fig. 2). The topsoil was enriched with humus (7.3 g kg^{-1} SOC). The entire solum was decalcified, showed weak acidic reactions (pH 5.4) and lower base saturation (50–< 80 % BS) than the white dune soil (Tab. 1). The soil was classified as Arenosol (WRB) and Euregosol (GSCS).

Soils of the brown dunes were exemplified by Profile 5 (Fig. 2). It was covered with dominantly crowberry (*Empetrum nigrum*), which built up a 5 cm thick layer of litter on top of the mineral surface. The solum showed very acidic reactions (pH 3.5–4.2) and low base saturation (up to 5–< 20 % BS) (Tab. 1). The mineral topsoil was initially podzolized (AE; Aeh horizon) and the subsoil evinced braunification (Bw; Bv horizon). The soil was classified as Arenosol (WRB) and Braunerde (GSCS).

Dune slacks

In a dune slack surrounded by acidic brown dunes (Seibert et al. 2018), that have formed between 1650 and 1750 (Sindowski 1970), Profile 6 was established (Fig. 2). The slack was covered by a small stock of moor birches (*Betula pubescens*) and was affected by mostly high groundwater levels. The groundwater was fresh, originating from a fresh groundwater lens developed below the dune complex (Röper et al. 2013). A 17 cm thick layer of slightly decomposed peat (347 g kg^{-1} SOC) superimposed a sandy subsoil. The latter showed gleyic features (iron oxide mottles) in the upper part and reductive properties in the lower part (Tab. 1). The profile was free of carbonates and exhibited acidic conditions (pH 3–4). It was classified as Gleysol (WRB) and Niedermoorgley (GSCS).

Salt marshes

The high salt marsh covered with red fescue (*Festuca rubra agg.*) was the location of Profile 7 (2.0 masl) (Fig. 2). Similar to other soils at this location, sands were superimposed by a fine grained (SL) layer of marine carbonate-free deposits, that was interposed by loamy layers (approx. 0.5–1 cm thick), indicating fluvic stratification. Within the fine grained layer, a 14 cm humus enriched horizon (152 g kg-1 SOC) had formed. It was free of carbonates and showed slightly acidic conditions (pH 6.1) (Tab. 1). Below, four horizons followed, which exhibited gleyic features and reductive conditions to different extents. The soil was classified as Gleysol (WRB) and Rohmarsh (GSCS).

Profile 8 was located at the low salt marsh (1.6 masl) and covered with sea lavender (*Limonium vulgare*) (Fig. 2). Two layers of fine grained (CL over SiCL), calcareous (42 and 33 g kg^{-1} $CaCO_3$) marine deposits, superimposed fluvic stratified sandy clay loam (Tab. 1). The profile showed humus enrichment (45.6 g kg^{-1} SOC), up to a similar depth (13 cm) as in Profile 7, and neutral reactions (pH 7.1–7.2). The two subsoil horizons showed gleyic and reductive properties, respectively. The soil was classified as Gleysol (WRB) and Rohmarsch (GSCS).

4.1.2 Toposequence East

Beach plain

Similar pedological conditions occur here, as in the West sequence (data not shown). However, restricted isolated areas of the dry beach showed stratification of differently colored microbial mats (grayish green over yellowish red) developed within the

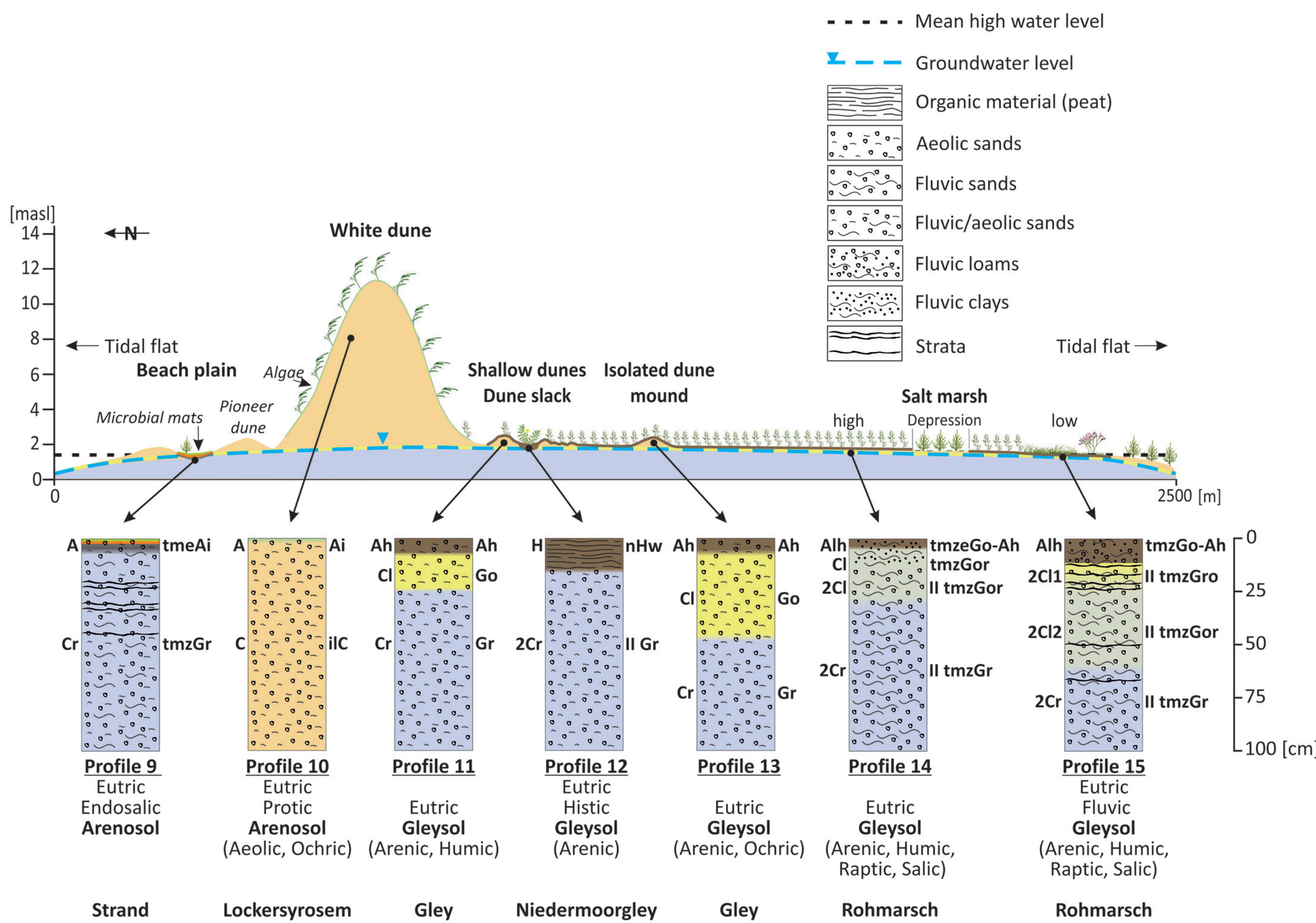

Fig. 3: Toposequence East. Conceptual sketch from the beach plain to the salt marsh in the East (Ostplate) of Spiekeroog (top) and morphologies of studied soils (middle) with soil names according to WRB (IWG WRB 2015) and the German Soil Classification System (GSCS) (Ad-hoc-AG Boden 2005) (bottom).

top 3 cm, as shown in Profile 9 (Fig. 3). The upper 10 cm of the profile were slightly enriched with SOC (1.7 g kg^{-1} SOC) and carbonates (27 g kg^{-1} $CaCO_3$) and showed weak alkalic reactions (pH 7.8). Below the microbial mats, a reductive horizon followed (Tab. 1). A few species of glasswort (*Salicornia europaea*) were present. The soil was classified as Arenosol (WRB) and Strand (GSCS).

Dunes

Like in the West, the white dune soil (Profile 10, Fig. 3) was covered with beach grass *(Ammophila arenaria*) and comprised weak calcareous (4 g kg^{-1} $CaCO_3$) neutral (pH 6.9) sands (Tab. 1). Similarly to the West, it lacked pedogenetic features and exhibited a 0.5 cm thick crust of sand grains adhered by greenish algae at the surface. The soil was classified as Arenosol (WRB) and Lockersyrosem (GSCS). Shallow pioneer dunes formed north of the white dune chain.

Contrary to the West, towards the southerly hinterland, the chain is not adjoined by further evolved dune chains. Instead, an irregular pattern of groundwater-affected shallow dunes separated by pond-like slacks formed within a previous tidal creek system (NLWKN 2008), marking the transition to the salt marshes (Fig. 3). There, the water sources (storm tide water and precipitation) varied temporally resulting in groundwater salinities spanning from 5 to 20 g l^{-1} (Holt et al. 2017), indicating brackish to saline conditions. At one of those shallow dunes (2.5 masl), Profile 11 was established (Fig. 3). It was covered with sea couch (*Elymus athericus*) and in the topsoil a humus enriched horizon (49.3 g kg^{-1} SOC) had formed (Tab. 1). The subsoil evinced oxic conditions in the upper part and reductive properties in the lower part. However, no iron oxide mottles were visible. Low carbonate contents (2 g kg^{-1} $CaCO_3$) and weak acidic conditions (pH 6.5) were found throughout the whole profile. The soil was classified as Gleysol (WRB) and Gley (GSCS).

Profile 13 was located on a shallow dune (2.4 masl), which was covered with sea couch (*Elymus athericus*) (Fig. 3). It forms part of a crescent-shaped arch, comprising several shallow, separately arranged dune mounds stretching through the salt marsh from West to East (Fig. 1). The soil's morphology was similar to that in Profile 11. However, the pH (6.8–7.5) was slightly higher and the SOC content (12 g kg^{-1} SOC) was about 4 times lower (Tab. 1). The subsoil was affected by brackish groundwater (5.5 mS cm^{-1} EC). The soil was classified as Gleysol (WRB) and Gley (GSCS).

Dune slacks

In one of the pond-like dune slacks (1.9 masl) at the south of the white dune chain, Profile 12 was established (Fig. 3). It was covered with common silverweed (*Potentilla anserina*). Above sands, a 16 cm thick peat layer (208.5 g kg^{-1} SOC) had formed, which mainly consisted of undecomposed fine, dead roots and showed acidic reactions (pH 5.5) (Tab. 1). The entire solum was free of carbonates and water saturation favored reductive conditions throughout. The soil was classified as Gleysol (WRB) and Niedermoorgley (GSCS).

Salt marshes

Profile 14 was located in the high salt marsh (1.9 masl) and covered with sea couch (*Elymus athericus*) (Fig. 3). Representatively for other soils at this location; it exhibited a two-layered stratification with a 17 cm thick layer of very fine (SiC) calcareous (46 g kg^{-1} $CaCO_3$) marine deposits superimposing sands (2 g kg^{-1} $CaCO_3$) (Tab. 1). At the first 5 cm of the fine-grained layer, a horizon enriched in humus (75.7 g kg^{-1} SOC) had formed. The soil showed slightly alkalic reactions (pH 7.5–7.9) and oximorphic features (iron oxide mottles) in the upper part, and reductive conditions in the lower part. The soil was classified as Gleysol (WRB) and Rohmarsch (GSCS).

Profile 15 was located in the low salt marsh (1.6 mbsl) and covered with sea meadow grass (*Puccinellia maritima*) (Fig. 3). The soil was comprised of a fine-grained (L) layer superimposing sands. Both sediments contained carbonates (2–6 g kg^{-1} $CaCO_3$). Within the fine-grained layers, an 11 cm thick humus-enriched horizon (62.5 g kg^{-1} SOC) had formed. The pH (7.2–8.5) indicated neutral to slightly alkalic reactions. The soil was classified as Gleysol (WRB) and Rohmarsch (GSCS).

5 Discussion

5.1 Landscape and soil formation - West vs. East

Beach plains

Below mhwl the same soils occur in West and East (Ostplate). Hence, the same pedological conditions prevail. The main process affecting soil properties at both sites is consistent intense currents and wave action, which induce a constant redistribution and development of similar soils.

Similar soils are also found above mhwl, with respect to deflation and resedimentation, in the West and East. However, the occurrence of microbial mats (Profile 9) is restricted to isolated areas in the East. The versicolored layering of the mats is a typical feature of the 'Farbstreifensandwatt' reported by Schulz (1936). Microbial mats develop as vertically stratified colored layers that can be ascribed to the pigments of the participating communities of microorganisms, which results from physico-chemical gradients within the mat and the physiology of the contributing microflora. Their development depends mainly on grain size of the sediment, light penetration, capillary water rise and the absence of destructive forces (Stal 1985). In contrast to other beach soils, the microbial mat soil showed increased carbonate contents and pH. These findings are in line with carbonization as an initial pedogenetic process in biocrusts, that may form 100–200 µm large concretions or thin layers (Kremer et al. 2008). More moist conditions, which were reflected by a reductive horizon beginning at the surface below the mats, are probably related to fresh groundwater outflow from the flanking white dunes (Fig. 1 and 3) (De Groot et al. 2017). As anthropogenic actions may also be destructive, and is more evident in the West; it is assumed that the near-natural conditions are crucial for the formation and maintenance of microbial mats at the Ostplate.

Dunes

The beaches provide the sands for the formation of the the white dunes. Due to sorting of the windblown sands, only a small share of shell fragments were deposited, which resulted in low primary carbonate contents of the dunes, which occurs in both the West and East. Active sand movement prevented progression of soil formation. The only alteration of the dune sands was evidenced by algae imposing the first mm at the surface. Repeated over-sedimentation and subsequent decomposition of the nitrogen-fixing algae (Schulz et al. 2016) imposed sands, possibly increased nitrogen plant availability in the primary nitrogen-poor sediments (Gerlach et al. 1994).

In the West, the white, gray and brown dunes form a chronosequence, which enables to study soil formation of approx. maximal 160 years (Sindowski 1970). Contrary to the white dunes, the gray dunes are protected from sand movement. This allows for intensive vegetation growth and high plant biodiversity (Isermann 2011) and resulted in the initiation of soil formation. The latter was evinced by humus enrichment in the topsoil and leaching of carbonates throughout. The high proportion of quartz resulted in the sediments having a very low acid buffer capacity. Consequently, decalcification and acidification proceeded rapidly and affected the entire solum of the gray and brown dune soils (Profile 4, 5). Within only a few decades, pH values of 3.5 were reached in the brown dunes. The rapid decalcification is in line with other findings from dune soils of Spiekeroog (Gerlach et al. 1994; Giani and Buhmann 2004) and other coastal sites with dune sediments low in primary carbonate content (Wilson 1960; Stuyfzand 1993; Grootjans et al. 1996). According to Seibert et al. (2018), the decalcification front in brown dune soils of Spiekeroog reaches up to > 2 m below the ground surface. The brown dune soil (Profile 5) developed in a dune that formed between 1860 and 1960 (Sindowski 1970). The early occurrence of podzolization and the lack of visible illuvial horizons within approx. maximal 160 years of soil formation are in agreement with findings reported by Stützer et al. (1998), in which podzolization in a coastal dune site similar in soil parent material and climatic conditions was investigated.

No dune chronosequence has yet been established at the Ostplate. There, only a single white dune chain and shallow isolated dune mounds at the southern hinterland have formed. This geomorphological setting is due to the very young age of the Ostplate, with initial dunes formed in the 1960s and the closure of the white dune chain in the 1990s (Röper et al. 2013). From then on, aeolian sand movement southwards of the chain was almost completely prevented. Consequently, the isolated small dune mounds were cut off from aeolian sand supply and therefore stopped growing further. Their surfaces were stabilized by dense vegetation cover of salt marsh grasses and humic topsoil horizons had formed in contrast to the the white dunes soils. Due to low surface elevation, the dune mounds are influenced by brackish groundwater (Profile 13) and are affected by sedimentation during storm tides. The latter is often evinced by sandy layers, several cm thick, superimposing A horizons, after storm tide events (not shown).

Dune slacks

The slack in the West (Profile 6) is enclosed by acidic brown dunes. Disconnected from the sea, it lacks any alkalic input however; it is influenced by fresh groundwater. Inflow of acidic soil solution from the enclosing brown dunes is most likely to cause strong acidification. Concurrently, it supplies ferrous iron for the formation of iron oxide mottles via gleying. The mostly high groundwater level, which was at 55 cm below ground surface in summer conditions, resulted in the formation of a 17 cm thick peat layer.

A distinct peat formation occurred at the Ostplate as well (Profile 12), where, within approx. maximum 60 years, a 16 cm thick peat layer formed. The rate of formation is remarkably high in comparison to findings from other dune slacks on North Sea islands (e.g. Schiermonnikoog and Terschelling, Netherlands), where humic layers, significantly lower in SOC content, reached thicknesses between 3 and 8 cm within 30 years (Grootjans et al. 1998). The slack is connected to the sea and receives aperiodic flooding during storm surges (WSV 2017), which provide alkalic compounds, at least in the form of hydrogen carbonate (HCO_3). Nevertheless, the topsoil showed acidic reactions and the solum lacked carbonates throughout. This may indicate that the slack is supplied with predominantly rainwater (pH 5.03 at Spiekeroog, after Seibert et al. (2018)), thus promoting rapid acidification and accumulation of organic material (Grootjans et al. 2001). Acidic organic compounds that may form in the peat, possibly also contribute to acidification. Consequently, basiphilous plant species, typical in early stages of vegetation succession in wet dune slacks (Sival 1996), were absent. Contrary to the West, iron oxide mottles were absent, which is attributed to a different groundwater quality. The shallow groundwaters of the Ostplate are low in iron concentrations (Seibert et al. 2018). Since the groundwater is replenished predominantly by precipitation passing through the non-weathered, carbonate-buffered white dune sands, ferrous iron supply is insufficient for the formation of iron oxide mottles by gleying. Additionally, precipitation of siderit ($FeCO_3$) may also withdraw ferrous iron from the groundwater (Seibert et al. 2018).

Salt marshes

In general, all studied salt marsh soils evinced a two-layered solum. The thickness of the fine-grained material, superimposing coarser sediments, ranged between 11 and 33 cm. The greatest thickness was found in the older West (Profile 8). However, sedimentation is not solely a function of time, but also of geomorphological catchment settings, as has been shown by De Groot et al. (2011).

The high salt marsh soil in the West (Profile 7) was subjected to soil formation for the longest time period. This was reflected by the topsoil having the highest SOC content, and low carbonate content and pH of the soil. Accordingly, soil formation proceeded to a lesser extent in the younger high salt marsh soil in the East (Profile 14), shown by lower SOC in the topsoil, and high pH values and carbonate contents. However, the primary sediment carbonate content of the soils is unknown and might vary, thus potentially determining current carbonate contents to greater extent than soil formation.

The low salt marsh soils in West and East (Profile 8 and 15) differed only slightly from each other. It is particularly remarkable that in the West the carbonate content is higher, which might be the result of pedogenetic factors or possibly due to higher silt contents, since it is known that carbonate concentrations in salt marsh sediments of Spiekeroog are highest in this grain-size fraction (Giani et al. 2003). The humus contents were lower than in the high salt marsh, as theses soils are influenced by spring tides, which can set back pedogenesis (Brümmer 1968).

5.2 Aspects of German Soil Classification

The German Soil Classification System is based on a dynamic soil morphological approach. It focuses on the horizon sequence of a soil, which determines the soil type (Bodentyp) (Ad-hoc-AG Boden 2005). However, in some cases the topographic position co-determines the resulting soil type. Given fulfilled horizon sequence requirements, soils at the beach located between the mean low water level (mlwl) and mhwl are classified as 'Nassstrand'; and those above mhwl, as 'Strand'. However, the studied Strand soil in Profile 2 did not meet the required carbonate content of 2–< 75 % $CaCO_3$ (horizon prefix 'e') of an obligatory tmzeG horizon of a Strand classified soil (Ad-hoc-AG Boden 2005). The strict application of this criteria would preclude the designation of a Strand soil. Instead, the soil would be classified as a 'Lockersyrosem'. To overcome this shortcoming, we suggest excluding the requirement of a calcareous horizon in the definition of a Strand soil. Since carbonate content is not a requirement for the definition and classification of Nassstrand soils, the fact that soil parent materials below and above mhwl are identical would also be taken into account. Additionally, the firmly defined carbonate content (2 – < 75 % $CaCO_3$) seems arbitrary and inappropriate, considering primary sediment carbonate contents vary widely along the North Sea coast (Brümmer et al. 1970).

Similar difficulties concern the classification of the salt marsh soils. In general, these soils fulfill the criteria of a 'Rohmarsch'. However, the carbonate contents in the Gr horizons were insufficient for the application of the horizon prefix 'e' (Ad-hoc-AG Boden 2005). Consequently, the soils do not meet the required horizon sequence of a Rohmarsch (for which it is mandatory to include tmzeGr horizons) and technically could not be classified as such. For the same reason as for the Strand soils, the firmly defined carbonate content seems arbitrary and inappropriate. We suggest, defining an additional horizon prefix to indicate carbonate concentrations of $> 0 - < 2\,\%$ $CaCO_3$. This would permit the Rohmarsch soils, with primary carbonate contents lower 2 % $CaCO_3$, to be classified as such. The same applies for the classification of other types of salt marsh soils e.g. 'Kalkmarsch' and 'Kleimarsch', which evolve from Rohmarsch soils.

6 Outlook on future landscape and soil formation

Beach plains

Since the beach soils are affected by continuous marine and aeolian sand deposition, as well as erosion and deflation, progression in soil formation is precluded. A dynamic equilibrium determines soil forming factors and soil properties. However, in the East, the extent and spatial distribution of microbial mats might change in reaction to destructive forces (Stal 1985) and / or changing pedo-hydrological conditions.

Dunes

Given sufficient supply of wind-blown sand exceeding possible sediment losses caused by deflation and erosion, new dunes will form north of the white dune chains in the West and East, as described in the conceptual model of island tail development by De Groot et al. (2017). Sedimentation is currently active, observable by the ongoing formation of shallow pioneer dunes at the beach. As soon as these dunes have developed to white dunes, sand movement at the currently present white dunes will decrease. This will result in the white dunes beginning to alter into gray dunes. The current gray dunes will further decalcify and acidify, and provoked by braunification and podzolization, transform into brown dunes. Podzolization in the current brown dunes will proceed and affect deeper parts of the solum. The formation of illuvial horizons, which have not formed yet, may lead to the development of mature Podzols. Ultimately, a dune complex comprised of white, gray and brown dunes, as already established in the West, will develop in the East.

Dune slacks

Given steady pedo-hydrological conditions in the West dune slack (Profile 6), peat formation is likely to proceed. In the East, sediment deposition during future storm tide events may fill the dune slack, and accompanying pedo-hydrological changes may preclude further peat formation. This development is most likely, since no peats are present in the transition of dunes and salt marshes in the West. However, it is equally probable, that new dune slakes will form in the yet to be establish dune complex mentioned above.

Shallow dunes and isolated dune mounds

The shallow dunes and isolated dune mounds south of the white dune chain in the East are stabilized by dense vegetation cover. By the time the current white dune chain will have evolved to a brown dune, it is likely to become partly unstable and affected by wind erosion, as has been shown by Sindowski (1970) for the dune complex in the West. Thus, a future scenario may entail the shallow dunes being buried by wind-blown dune sands. Further south, deposition of marine sediments will level the surface height differences between the dune mounds and the salt marsh.

Salt marshes

In West and East, humus enrichment, decalcification and acidification will proceed in the soils of the high salt marsh. Proceeding soil formation in the low salt marshes is expected to be expressed mainly by further humus enrichment in the topsoil. However, the extent is restricted by back-setting periodical and episodical tides.

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