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Characteristics and methanogenesis of the Balandra lagoon mangrove soils, Baja California Sur, Mexico

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Abstract

Soil characteristics and methanogenesis were investigated in Fluvisols of the Balandra lagoon mangrove in Baja California, Mexico in March/April 1995.

The grain size distribution was dominated by the silt fraction (54-92%), sand and clay contents were 6-44% and 0-19%, respectively. Bulk density was 0.6-1.5 g cm⁻³, the water content 290-690 ml l⁻¹ and the air content 38-200 ml l⁻¹. The soils always showed saline conditions (30-70 g kg⁻¹), mostly negative redox potentials (down to -202 mV), P contents from 0.8 to 16.0 g kg⁻¹, C_{org} contents from <2 to 140 g kg⁻¹ and neutral pH values. In one soil the pH dropped < 2.5 after peroxide treatment indicating, together with low carbonate/pyrite ratios (mostly < 3) sulfidic properties. The relative distribution of the porewater cations was always 74% Na, 17% Mg, 6% Ca, and 3% K. For the exchangeable and water soluble cation fraction it was 28-59% Na, 22-34% Mg, 12-32% Ca, and 2-5% K, with increasing Na- and decreasing Ca-concentrations in the transect from sea to land.

The methane concentrations were mostly lower than 2 μM. Methane production rates were between 1 and 23 nmol ml⁻¹ d⁻¹. Methane emission was not detectable. This indicates, that methanogenesis is balanced by methane oxidation processes within the soil. Higher methane concentrations (33 μM) and production rates (100 nmol ml⁻¹ d⁻¹) in one of the investigated soils were attributed to anthropogenic impact. Consequently, in case of human manipulation the potential of mangrove soils to emit methane seems to be high, thus mangroves are sensitive with respect to methanogenesis.

1. Introduction

Mangroves are important tropical and subtropical ecosystems in the transition between land and sea. They can be highly productive (Odum and Heald, 1975; Dye and Lasiak, 1986; Robertson, 1986), and export organic matter to the adjacent waters (Twilley, 1985; Boto and Wellington,

1988). It has been suggested that they contribute to the support of coastal marine communities (Odum and Heald, 1975; Odum et al., 1982). Mangroves may also act as sinks for carbon, nitrogen and phosphorus (Nedwell, 1975; Odum et al., 1982).

However, little information is available about soil characteristics of mangrove ecosystems (Walsh, 1974). In comprehensive studies, pedological items have only been touched (Clough, 1979; Day et al., 1987). Pedological studies have concentrated on the development to acid sulfate soils (ASS) (Pons, 1973; Dent, 1980, 1986), geo-microbiological ones on the turnover of carbon, nitrogen and sulfur (Nedwell et al., 1994; Kristensen et al., 1994). The present work was undertaken to investigate general physical and chemical properties of soils occurring within the Balandra mangrove. Because mangroves can be described as the tropical equivalent to the saltmarsh (Walsh, 1974), the Balandra soils are compared with soils of typical saltmarsh of the North Sea coast. Those saltmarsh soils mostly show a clayey or silty texture, low bulk densities ($< 1 \text{ g cm}^{-3}$), saline and neutral conditions (8-25 g l^{-1} and pH 7, respectively), 50-110 g kg^{-1} carbonate, mostly 10-40 g kg^{-1} organic carbon and 1-10 g kg^{-1} sulfur (Giani, 1992). As many tropical intertidal soils develop to ASS (Ponamperuma, 1972), it was concurrently the aim of this study to search for sulfidic (potentially acid) properties in the Balandra mangrove soils. Another point of interest was methanogenesis. There are only a few investigations on methanogenesis in mangrove soils (Harriss et al., 1988; Barber et al., 1988; Bartlett et al., 1989; Sotomayor et al., 1994). It is thought to be negligible (e.g. Neue et al., 1994) as it is for typical saltmarsh soils at higher latitudes (Bartlett et al., 1985). However, saltmarsh soils built up from marine sediments and ombrogenous peat material show thousandfold higher methane concentrations than typical saltmarsh soils because of sulfate depletion (Giani, 1993), as well as methane production rates comparable to those of rice paddies (Giani et al., 1996), and concurrently develop to ASS (Giani and Giani, 1990). Tropical saltmarsh soils are also often rich in organic matter (Langenhoff, 1986) and develop to ASS (Ponamperuma, 1972). The occurrence of sulfate-depleted soils found in a Jamaican mangrove (Nedwell et al., 1994) gave rise to the investigations on methanogenesis in mangrove soils performed in this study.

2. Material and methods

Fluvisols of Balandra mangrove in Balandra Bay (Fig. 1), covering an area of 10 ha (Gallo et al., 1980), were investigated in spring 1995. This mangrove receives fresh water only very occasionally and is a relatively undisturbed system (Holguin et al., 1992). The sediment stratigraphy in Balandra mangrove down to three or four meters consists of a Pleistocene marine coral unit, followed upwards by Holocene units which are confined to lagoonal deposits represented by a coral debris unit, two peat strata and two silt-clay strata (Pedrin-Aviles et al., 1990). Three mangrove species were present in all stages of development: *Rhizophora mangle* L., red mangrove growing nearest the sea, followed by *Laguncularia racemosa* Gaertn., white mangrove and finally *Avicennia germinans* (L.) Stern, black mangrove.

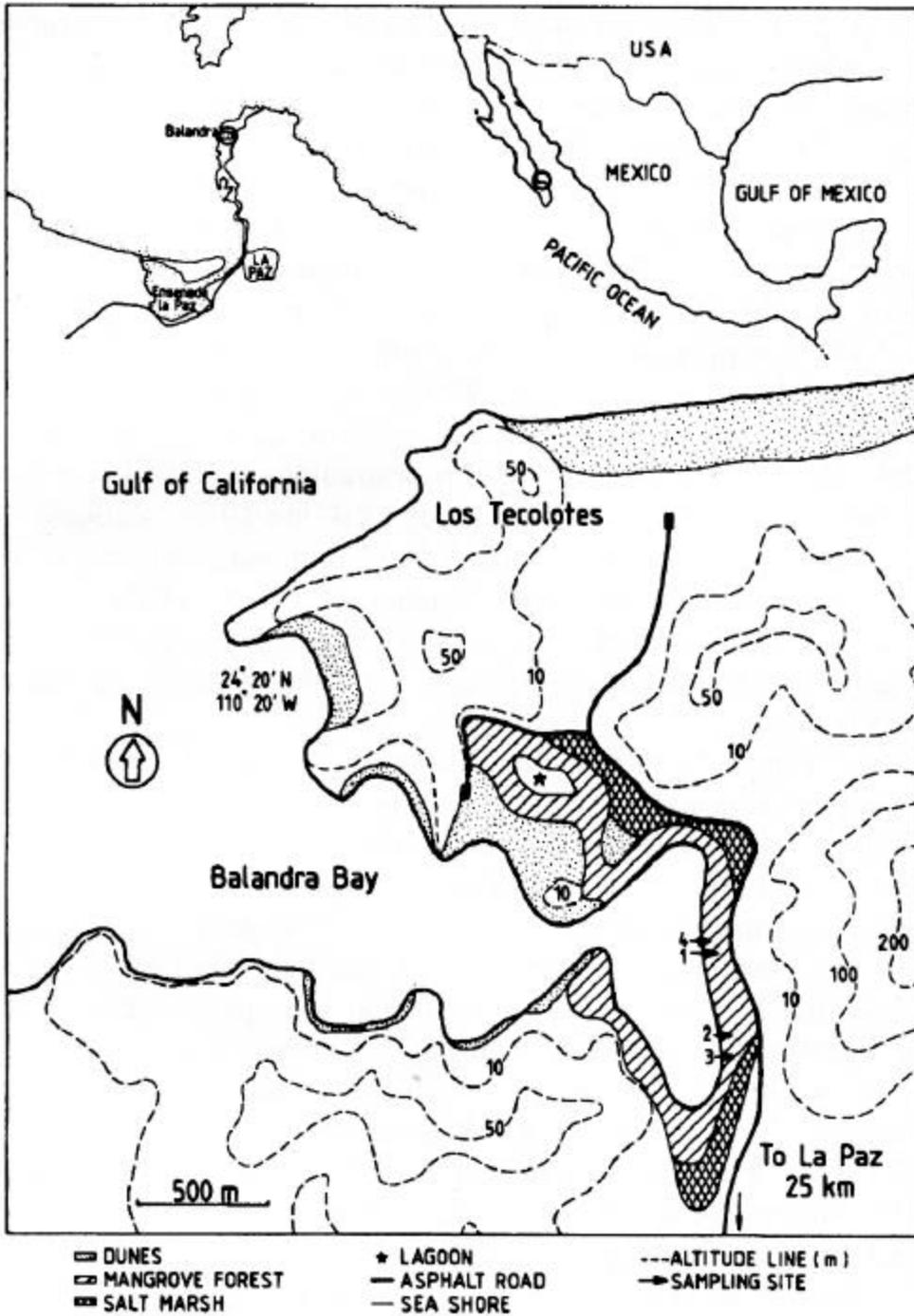


Fig. 1. Location of the sample sites on global (top right) medium (top left), and most exact (bottom) scale (modified from Holguin et al., 1992).

Samples from different sites were taken from 0-30 cm soil depth. At station 1 (Fig. 1) sampling followed a transect from sea to land. Sampling was performed in an area without vegetation (1.1), in the red mangrove (*Rhizophora mangels*) area (1.2) and in the black mangrove (*Avicennia germinans*) area (1.3). At station 2 (Fig. 1) sampling was performed in the red (2.1) and the black mangrove areas (2.2). The third station was near station 2 (Fig. 1) in a black mangrove area (3.1). The fourth sampling station (Fig. 1) was in an anthropogenically caused non vegetated area where, naturally, *Avicennia germinans* would occur (4.1). This site was cleared in order to get an entrance into the lagoon. Only methane data are available for this station. For comparison a fifth

sampling, in an area without vegetation (5.1) and a black mangrove area (5.2), was performed in another mangrove within Ensenada La Paz (Fig. 1), showing impacts of pollution because of sewage effluents from the city of La Paz.

According to the FAO classification the investigated soils belong to the major soil grouping "Fluvisols". With the exception of profile 3.1 which is a "Thionic Fluvisol" on the soil unit level, all profiles are "Salic Fluvisols". According to the German classification all profiles are "Rohmarschen" on the soil type level.

A single site (30 m X 10 m) from each mangrove zone was selected as representative of the studied soil. Sampling was performed with 100 ml cylinders for the bulked data, for the others it was done with an auger. With each sampling three separate cores were obtained in the direct vicinity. One core was used to quantify the dissolved methane concentrations, one for methane production measurements and the last one to determine other soil properties. The soil cores were subdivided into 10 cm sections.

In the field duplicate samples for methane concentration measurements were immediately put into preweighed serum flasks containing 1.5 N NaOH and sealed. After partitioning of the gaseous methane dissolved or trapped in the interstitial waters of the soil into the gas phase, the headspace was sampled with a gas-tight syringe and analyzed by gas chromatography.

For the measurements of methane production rates, duplicate samples (1 cm^{-3}) of each depth interval were extruded into vacutainers and sealed under N_2 atmosphere immediately after sampling. The tubes were flushed with N_2 after which an initial time point was established for the time course of methane production. The tubes were incubated at room temperature ($25\text{-}28^\circ\text{C}$) on the following days. Every 24 h, the headspace of the tubes was sampled with a gas-tight syringe and measured gas chromatographically. Methane accumulation in the headspace of the tubes was determined by the concentration change of methane per volume of soil in the tubes.

In situ methane flux measurements were made at stations 1 and 5 using a static chamber technique which consisted of a PVC chamber with a septum-closed serum flask at its top (12 l vol.) and an extra ring of steel. First the ring was installed (2-3 cm into the soil) to ensure that no gas emits when setting the chamber. The ring was filled with water and the chamber was put into the ring. Using a gas-tight syringe, aliquots (10 cm^{-3}) of the chamber air were withdrawn at the beginning and at the end (after 2-3 hours) of the experiment. The samples were transferred into vacutainers by displacing distilled water inside the vacutainer for storage. Quality control checks revealed that the vacutainers did not leak an appreciable amount of methane in 3 days, but samples were analyzed in the laboratory on the day after returning from the field.

Duplicate samples for the other measurements were put into polyethylene bags under N_2 atmosphere. The tightly closed bags were immediately taken to the laboratory. After measurement of redox potential and pH, one portion of the samples was centrifuged. The porewater obtained was used for sulfate, salinity and cation measurements. Another portion was air dried and used for other measurements.

- Grain size distribution - after HCl and H_2O_2 treatment and dispersing particles $< 2 \text{ mm}$ by shaking in sodium polyphosphate solution using sieves and Atterberg cylinders.
- Volume data - gravimetrically and by weight loss on evaporation at 105°C .

- Redox potential - by Pt-Ag/AgCl electrode, referenced to a hydrogen electrode at 25°C. The determination upon reaching equilibrium was in triplicate.
- Porewater - by centrifugation.
- Salinity - by hand refractometer (0-10 g/100 g) (Krüss 4 RN 32).
- Sulfate - turbidometrically according to Kempf and Andres (1977).
- pH - electrometrical measurement with a glass electrode.
- Carbonate - with a Scheibler apparatus.
- Carbon and nitrogen - by C/N analyzer (Carlo Erba 1500) after grinding.
- Phosphorus - after ignition and HNO₃ treatment, photometrical measurement tinged with vanadate-molybdate reagent.
- Pyrite - HNO₃/HCl treatment according to Howarth and Merkel (1984) and sulfate determination.
- Exchangeable and water soluble cations - shaking threefold in 0.1 M SrCl₂ solution (soil/solution ratio: 1/4), spectrometrical measurement in AAS (Varian SpectrAA 300).
- Methane - determination by direct injection of 0.4 cm⁻³ sample into a Varian "vista series" gas chromatograph equipped with a flame ionization detector and a Hewlett-Packard silica capillary column (ID: 0.32 mm; length: 50 m) maintained at 70°C. Carrier gas was nitrogen and the flow rate was 7 cm⁻³ min⁻¹. Injector and detector temperature were set at 250°C. Sample peaks (recorded on LKB Bromma 2210) were compared to commercial preparations of 10 to 100 ppmv methane standards. The largest variation among methane standards was within 10%. The standard error of the mean was less than 30%.

3. Results

Full analytical data are given in Table 1 and salient points are highlighted below.

The grain size distribution was dominated by the silt fraction. Profiles of station 5 showed higher bulk densities (1.4 and 1.5 g cm⁻³) and lower water contents (293 and 385 ml l⁻¹) than the other stations. According to the different elevations above sea level, the lowest profiles without vegetation (1.1, 5.1) showed the lowest air content (38 and 50 ml l⁻¹) followed by the red mangrove profiles (1.2, 2.1) and then with values up to 207 ml l⁻¹ by the highest black mangrove profiles.

Red mangrove profiles showed the lowest, and black mangrove profiles the highest redox potentials. Redox potentials mostly increased with increasing soil depths. All profiles were saline and neutral. However, after peroxide treatment pH dropped dramatically to pH < 2.5 in the profile 3.1, and also in one section of profile 1.2. All profiles contained carbonate. Lowest contents (1.9-5.8 g kg⁻¹) occurred in the profiles 2.1 and 3.1, which showed the most striking pH drop. Soils of station 1 were the richest in carbonate with more than 200 g kg⁻¹ but with values decreasing with depth in the red and black mangrove area.

The C_{org} content varied in a wide range between < 2 and 139 g kg⁻¹. Even more than 400 g kg⁻¹ C_{org} was found in soils north of station 1 (data not shown), clearly showing peaty conditions. The nitrogen contents were < 0.3-5.7 g kg⁻¹, the C/N ratios 8-39. The phosphorus content of the soils

Table 1
Physical and chemical soil properties of the Balandra mangrove soils (1-4) and the Ensenada La Paz soils (5)

Sample	1.1	1.2	1.3	2.1	3.1	5.1	5.2
Vegetation	none	<i>Rhizophora m.</i>	<i>Avicennia g.</i>	<i>Rhizophora m.</i>	<i>Avicennia m.</i>	none	<i>Avicennia g.</i>
Grain size distribution (%)							
2000-630 μm	0.0	0.0	0.0	0.0	0.0	0.0	0.0
630-200 μm	1.3	2.0	2.1	0.1	1.1	1.4	0.2
200-63 μm	18.9	32.7	44.2	5.7	11.2	31.7	40.5
63-20 μm	70.3	50.8	43.1	26.5	23.3	64.3	56.8
20-6.3 μm	6.9	9.3	7.0	53.5	19.0	1.8	1.6
6.3-2 μm	1.6	1.6	3.6	11.7	26.6	0.8	0.9
<2 μm	1.0	3.7	0.0	2.5	18.7	0.0	0.0
Bulk density ($\text{g}\cdot\text{cm}^{-3}$)	1.0	1.1	1.0	0.9	0.6	1.5	1.4
Air ($\text{ml}\cdot\text{l}^{-1}$)	38	100	207	56	94	50	196
Water ($\text{ml}\cdot\text{l}^{-1}$)	569	492	427	614	689	385	293
Solids ($\text{ml}\cdot\text{l}^{-1}$)	393	408	366	330	217	565	511
Depth (cm)	0-10	10-20	20-30	0-10	10-20	0-10	10-20
E_h (mV)	-169	-129	-37	-202	-161	-190	-68
pH (H_2O)	7.8	7.8	7.9	7.1	7.4	7.5	7.4
pH (Per.) ^b	5.9	5.9	6.8	6.0	6.3	2.3	5.6
CaCO_3 ($\text{g}\cdot\text{kg}^{-1}$) ^c	146.0	164.0	188.0	209.0	92.0	57.0	253.0
Pyrite-S ^c ($\text{g}\cdot\text{kg}^{-1}$)	2.9	3.3	7.5	2.8	12.6	17.5	2.6
C_{org}^c ($\text{g}\cdot\text{kg}^{-1}$)	23.5	24.2	23.1	37.1	25.7	20.3	37.7
N_t^c ($\text{g}\cdot\text{kg}^{-1}$)	1.0	0.8	0.6	2.1	0.8	0.7	1.6
C/N	23.5	30.3	38.6	17.7	32.1	28.9	23.6
Salt ($\text{mS}\cdot\text{cm}^{-1}$)	41.3	n.d.	46.7	40.0	41.3	40.0	56.0
Total P ^c ($\text{g}\cdot\text{kg}^{-1}$)	1.3	1.3	1.3	1.6	0.9	0.8	1.7
SO_4^c (mM)	38	n.d.	n.d.	36	n.d.	36	n.d.
	0-10	10-20	20-30	0-10	10-20	0-10	10-20
	-169	-129	-37	-202	-161	-190	-68
	7.8	7.8	7.9	7.1	7.4	7.5	7.4
	5.9	5.9	6.8	6.0	6.3	2.3	5.6
	146.0	164.0	188.0	209.0	92.0	57.0	253.0
	2.9	3.3	7.5	2.8	12.6	17.5	2.6
	23.5	24.2	23.1	37.1	25.7	20.3	37.7
	1.0	0.8	0.6	2.1	0.8	0.7	1.6
	23.5	30.3	38.6	17.7	32.1	28.9	23.6
	41.3	n.d.	46.7	40.0	41.3	40.0	56.0
	1.3	1.3	1.3	1.6	0.9	0.8	1.7
	38	n.d.	n.d.	36	n.d.	36	n.d.
	0-10	10-20	20-30	0-10	10-20	0-10	10-20
	-114	-172	-80	-71	117	372	n.d.
	8.1	8.0	8.0	8.0	8.1	8.0	8.0
	5.0	n.d.	5.5	4.8	5.0	n.d.	4.8
	6.4	18.0	14.0	11.0	6.4	18.0	11.0
	0.5	0.5	0.6	0.9	0.5	0.6	0.7
	<2.1	<2.1	<2.1	3.4	<2.1	3.4	<2.1
	<0.3	<0.3	<0.3	0.4	<0.3	0.4	<0.3
	n.d.	n.d.	n.d.	8.5	n.d.	n.d.	8.5
	n.d.	n.d.	n.d.	54.7	n.d.	n.d.	54.7
	6.1	16.0	2.7	7.1	6.1	16.0	2.7
	51	n.d.	n.d.	50	n.d.	n.d.	50
	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

n.d. = not determined.

^a PASS.

^b After peroxide treatment.

^c Dry weight.

^d Porewater.

Table 2
Absolute contents and relative distribution of exchangeable and water soluble cations of the Balandra mangrove soils (1-4) and the Ensenada La Paz soils (5)

Sample	Depth (cm)	Exchangeable and water soluble cations (mmol eq·kg ⁻¹) ^a					Relative distribution (%)			
		Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CEC	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
1.1	0-10	139	127	03	17	182	29	26	42	4
	10-20	160	133	184	17	184	32	27	37	3
	20-30	173	140	204	22	272	32	26	28	4
1.2	0-10	159	138	251	19	176	28	24	44	3
	10-20	213	185	279	24	365	30	26	40	3
	20-30	214	197	247	26	403	31	29	36	4
1.3	0-10	156	173	282	20	223	25	27	45	3
	10-20	236	358	623	28	448	19	29	50	2
	20-30	343	476	875	39	578	20	28	51	2
2.1	0-10	203	341	483	27	331	19	32	46	3
	10-20	173	341	455	28	339	17	34	46	3
3.1	0-10	256	683	1099	48	581	12	33	53	2
	10-20	309	818	1195	55	544	13	34	50	2
5.1	0-10	56	95	235	16	137	14	24	59	4
	10-20	55	72	143	15	133	19	25	50	5
	20-30	81	110	298	19	151	16	22	59	4
5.2	0-10	69	150	335	19	144	12	26	59	3
	10-20	61	93	237	18	150	15	23	58	4
	20-30	45	90	212	17	140	12	25	58	5

^a Dry weight.

investigated at Balandra mangrove was mostly 0.8-1.7 g kg⁻¹ but distinctly higher phosphorus concentrations, up to 16 g kg⁻¹, occurred in the soils (5.1, 5.2) of the mangrove of Ensenada La Paz.

The relative distribution of the main cations of the porewater determined for the Balandra profiles always was 74% Na, 17% Mg, 6% Ca and 3% K. The fraction of exchangeable and water soluble cations (mobile cations) also showed values decreasing in the order Na > Mg > Ca > K. However, the Na-concentrations were smaller (28-59%) and the concentrations of Mg (22-34%), Ca (12-32%) higher than those of the porewater (Table 2). Following the transect from 1.1 to 1.3 from sea to land, the profiles showed decreasing Ca- and increasing Na-concentrations.

The profiles of station 5 showed the lowest pyrite contents (< 1 g kg⁻¹). Highest contents (3-26 g kg⁻¹) with increasing values with increasing soil depth were found at station 1. The sulfate concentrations of the porewater were between 36 and 76 mM, thus showing no sulfate depletion.

The methane concentrations of the soils mostly were lower than 2 μM (Table 3). In some profiles and soil sections the methane concentration even was below the limit of

Table 3
Methane concentration and methane production rates of the Balandra mangrove soils (1-4) and the Ensenad La Paz soils (5)

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Sample	Vegetation	Depth (cm)	Methane concentration			Methane production rates		
			Average ($\mu\text{M CH}_4$)	SEM ^a	N ^b	Average ($\text{nmol} \cdot \text{ml}^{-1} \cdot \text{d}^{-1}$)	SEM ^a	N ^b
1.1	none	0-10	< 0.2	n.d.	2	1.83	1.3	4
		10-20	< 0.2	n.d.	2	< 0.26	0.6	5
		20-30	< 0.2	n.d.	2	1.57	0.9	6
1.2	<i>Rhizophora m.</i>	0-10	2.09	2.2	2	7.62	4.9	8
		10-20	1.55	0.1	2	2.49	2.4	5
		20-30	1.90	0.6	2	< 0.26	0.6	5
1.3	<i>Avicenna g.</i>	0-10	< 0.2	n.d.	2	23.3	17.7	8
		10-20	< 0.2	n.d.	2	1.84	2.6	5
		20-30	< 0.2	n.d.	2	1.45	0.2	2
2.1	<i>Rhizophora m.</i>	0-10	1.14	n.d.	1	n.d.	n.d.	n.d.
		10-20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
2.2	<i>Avicennia g.</i>	0-10	0.43	n.d.	1	1.25	0.4	4
		10-20	0.37	n.d.	1	1.05	0.8	4
3.1	<i>Avicenna g.</i>	0-10	0.72	n.d.	1	0.56	0.5	4
		10-20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
4.1	none	0-10	33.1	n.d.	1	97.5	41.5	3
5.1	none	0-10	0.48	0.1	3	n.d.	n.d.	n.d.
		10-20	0.57	0.2	3	n.d.	n.d.	n.d.
		20-30	0.74	0.1	2	n.d.	n.d.	n.d.
5.2	<i>Avicennia g.</i>	0-10	0.51	0.3	3	2.03	1.1	4
		10-20	0.57	0.3	3	n.d.	n.d.	n.d.
		20-30	0.64	0.1	2	n.d.	n.d.	n.d.

^a Standard error of the mean.

^b Number of determinations.

detection. Only the soil of station 4 showed much higher values with 33 μM . Methane production rates showed a similar pattern with values between 1 and 23 $\text{nmol ml}^{-1} \text{d}^{-1}$ except at station 4. There the methane production rate was 100 $\text{nmol ml}^{-1} \text{d}^{-1}$. Methane emissions were not detectable. This was also true for experiments in which gas domes covered the pneumatophores of *Avicennia germinans*.

4. Discussion

4.1. Soil characteristics

Some properties of the Balandra mangrove soils - high variability in texture absence of the coarse sand fraction, negative redox potentials, low air volumes, neutral pH reactions, saline

conditions, the relative cation distribution of the porewater and the occurrence of carbonate and pyrite - are comparable with those of saltmarshes of the North Sea coast (Brümmer, 1968; Giani, 1992). However, the variability and the amount of salt, phosphorus, carbonate, pyrite, C/N ratios and organic carbon are higher in the mangrove soils investigated.

The high variability in texture and organic matter of the Balandra soils poses a difficulty for classification in that, within one mangrove system, several types of mangrove can occur, which are classified as reef, sand, mud and peat type (Chapman, 1940 and Rutzler, 1969 in: Walsh, 1974). In all mangrove types found in Balandra the same vegetation zonation occurred.

In contrast to saltmarsh soils of the North Sea coast, where the Na-concentrations of the mobile cations decrease from 67 to 47% and the Ca-concentrations increase from 11 to 22% in the transect from sea to land as a consequence of salt leaching and carbonate solving (Giani et al., 1993), the Balandra soils show increasing Na-concentrations from nearly 40 to 50% and decreasing Ca-concentrations from 30 to 50%. This may be attributed to the increasing accumulation of salts from sea to land in the Balandra mangrove. Since salt accumulation by evaporation is often caused by arid conditions, it is characteristic of mangroves - like Balandra - at the border of subtropical and arid climates. For many mangroves, increasing freshwater influence is described (Walsh, 1974), as a floristic consequence *Avicennia germinans* is found nearest to the sea (Alongi, 1989). In Balandra *Avicennia germinans* was found in a belt closing the mangrove swamp landwards. The increasing Na-concentration of the mobile cations in the transect from sea to land also indicates the further soil succession. Adjacent to the mangroves a strongly saline zone of saltmarsh occurs, carrying sparse *Salicornia* shrubs.

4.2. Potential acid sulfate soil (PASS) properties

PASS are indicated by a sulfur (pyrite) content higher than 7.5 g kg^{-1} , a less than threefold amount of carbonate and a pH drop after peroxide treatment to 2.5 or less (Dent, 1986). Profile 3.1 shows these properties, thus it is a PASS, whereas profile 1.2 is not, although one section also shows a pH value less than 2.5 after peroxide treatment, obviously caused by incomplete dissolution of carbonate during peroxide treatment.

Nevertheless, the possibility of ASS development is given in Balandra mangrove, whereas it is not in typical temperate saltmarsh soils (Giani, 1992). In marine semi-terrestrial soils an intensive or long-term sulfur accumulation leads to PASS. High amounts of organic matter are necessary for this. Some Balandra soils have as much or even more organic matter than humus rich saltmarsh soils of the North Sea coast that developing to ASS (Giani and Giani, 1990). The following aspects however, suggest a long-term ASS developing process in Balandra mangrove soils: (i) Mineralisation rates are often low in mangrove ecosystems (Nedwell et al., 1994; Kristensen et al., 1994). (ii) In Balandra soils highest pyrite contents did not correlate with highest C_{org} contents. (iii) No sulfate depletion was found. (iv) No high methane concentrations occurred. As stated for other mangrove ecosystems (Walsh, 1974), Balandra soils showed a tendency of humus accumulation with C_{org} contents up to more than 400 g kg^{-1} , raising the question about the reason for the high C_{org} variability within one mangrove system and the role of mangrove soils as a carbon sink and their general role within the global carbon cycle.

4.3. Methanogenesis

Generally, rates of methane production in Balandra soils were 1 to 23 nmol ml⁻¹d⁻¹. Highest rates in the topsoil samples might be attributed to a subsurface pool of labile carbon, as found in the top of Jamaican mangrove soils (Nedwell et al., 1994). Overall the values are similar to those found for other marine mangroves investigated so far (Sotomayor et al., 1994), but considerably higher than those found for marine surface sediments and saltmarsh soils of higher latitudes, in which methane production rates of less than 1 nmol ml⁻² d⁻¹ have been measured (Warford et al., 1979; Senior et al. 1982).

In spite of higher rates of methane production, methane concentrations were low as similar to those found e.g. in typical saltmarsh soils at the North Sea coast (Giani et al. 1996). Moreover, methane emission was not detected. This indicates, that methanogenesis is balanced by anaerobic or aerobic methane oxidation processes. A high oxidative potential is likely for the Balandra soils, caused by intensive crab bioturbation, typical of mangrove soils (e.g. Kristensen et al., 1994). This result differs from that of Sotomayor et al. (1994) who found higher methane concentrations and emission of methane but similar production rates in Puerto Rico mangrove soils. Thus, low methane concentrations do not indicate low rates of methanogenesis (Rudd and Taylor, 1980) but might be an indicator of low methane release and/or balance between methanogenesis at methane oxidation.

The considerable methanogenesis may be attributed to the higher amounts noncompetitive substrates (e.g. methylated amines, DMS; King, 1984) - used by methanogenic bacteria but not by sulfate reducers (King, 1984) - in mangrove soils compared with typical saltmarsh soils of higher latitudes. As their distributional availability are controlled by the biomass of organisms containing these compounds (King, 1984), crabs occurring in high populations in Balandra mangrove soils might be source of these noncompetitive substrates (Yancey et al., 1982). Because of the high sulfate content and its conservative behaviour, methanogenesis based on competitive substrates (H₂/CO₂, acetate) is unlikely.

Methane increase in the atmosphere plays an important role for greenhouse warming (Aselmann and Crutzen, 1990). Though the few investigations on methanogenesis in mangrove soils so far available do not indicate that mangrove soils contribute significantly to the global atmospheric methane increase, anthropogenic disturbance of the ecosystems might change the situation dramatically. Indications were obtained by Sotomayor et al. (1994) who found that freshwater and nutrient supply leads to increased loss of methane to the atmosphere. Our study showed that methane concentrations more than 33 µM and methane production rates ten fold higher than those normally found occur even under marine conditions. These higher concentrations and production rates of methane are probably caused by a reduced oxidation potential of this cleared site. The destruction of vegetation leads to the fact that no oxygen is brought into the soil by the specialized root system. In contrast to the other soils investigated in Balandra mangrove, profile 4.1 showed reduced morphological features near the surface. Thus, the potential of mangrove soils to emit methane to the atmosphere seems to be high case of anthropogenic impact. The wide distribution of mangrove ecosystems and the

rapidly increasing use for shrimp and clam aquaculture recommend further research on the sensitivity of these ecosystems with respect to methanogenesis.

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