Mangrove trees growing in a very saline condition but not using seawater

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Mangrove trees, which develop along tropical coasts, are known to use saline water uptake. In French Guiana, the high salinity condition is the result of seawater evaporation on mud banks formed from the Amazon sediment flumes. In the back mangrove a few kilometres inland, groundwater, soil water and the xylem sap uptake in the trees remain highly salty, and only very tolerant plants like *Avicennia germinans* can flourish, whereas the less salt-tolerant *Rhizophora mangle* is more difficult to find. Curiously, the same *Avicennia* trees propagate on the seafront. However, stable isotope ratio mass spectrometry (IRMS) measurements and ion analysis (high-performance liquid chromatography (HPLC) and inductively coupled plasma atomic emission (ICP-AES) spectroscopy reveal that the origin of the water in the back mangrove is not seawater. It is freshwater percolating into the sand bars from the inland marshes and rainwater during the wet season that redissolves a marine evaporite and gives a saline groundwater. The absence of barren saltine areas ('tanne') in French Guiana could be explained by this freshwater inflow, the aquifer being no longer linked with the ocean. Copyright

Mangroves are specific ecosystems developing along most tropical and subtropical coastlines and estuaries, and where saline seawater is mixed with continental freshwater. The zonation of species commonly observed in many regions, along a salinity gradient, shows *Rhizophora* species on the seaward fringe and *Avicennia* species on a landward zone of higher elevation. *Avicennia* trees are known to support a wide range of salinity, and can thus develop in areas submitted to higher evaporation and thus characterized by higher pore-water salinities. In French Guiana, *Avicennia* trees surprisingly develop both on the seashore and several kilometres inland, thus leading to questions on the origin of the water used by these trees.[1]

The French Guiana coast was formed by the deposition of Pleistocene sand banks. This region is now occupied by dry savannah and marsh (*pri-pri*). Further inland on the hinterland hills of the eroded granite shield is an area of pristine tropical rainforest. Since the Holocene, the near-shore marine area has received large deposits of mud derived from the Amazon outflow.[2] Since this time, mangrove forest has developed on the moving mud banks,[3] and the formation of these features over time is controlled by the erosion–deposition processes.[4] A succession of four main types of vegetation occurring on these features in the studied area is given in Fig. 1.

The drainage network is characterized by a high density, due to an annual rainfall of 2000 to 4000 mm/year, low relief of the landscape and relatively impermeable bedrock. The runoff water is characterized by its very low ion content, and numerous river waters are stained by humic acid. Inland, limited groundwater is localized under a laterite crust. Impermeable bedrock limits the infiltration depth. By contrast, in the sandy, coastal region there is an important groundwater aquifer.[5] This very pure inland water contrasts with the highly saline coastal water resulting from seawater evaporation. The very low inclination of the coastal region allows the tidal influence on the rivers to penetrate far inland.

Along with the specific properties of propagules, and the physicochemical characteristics of the sediment, water salinity is a key factor controlling the distribution of the various mangrove species.[6,7] For instance, on the huge new mud banks, Fiot and Gratiot have explained how the trapping of *Avicennia* propagules in mudcracks was responsible for its sprouting.[6] In addition, Marchand *et al*.[7] suggested that the shape of propagules could be the predominant factor controlling the recruitment of mangroves along this dynamic coastline, referring to the work of McKee,[8] Osborne and Berjak,[9] and Terrados *et al*.,[10] who explained that *Rhizophora* seedlings could not colonize coastal areas submitted to sudden sediment accretion. *Avicennia germinans* is the dominant species colonizing the mud banks. A gradient of increasing tree size, tree age and soil salinity is commonly observed with increasing distance from the sea. Thus the older trees are growing in the back mangrove on very highly saline substrates while in other

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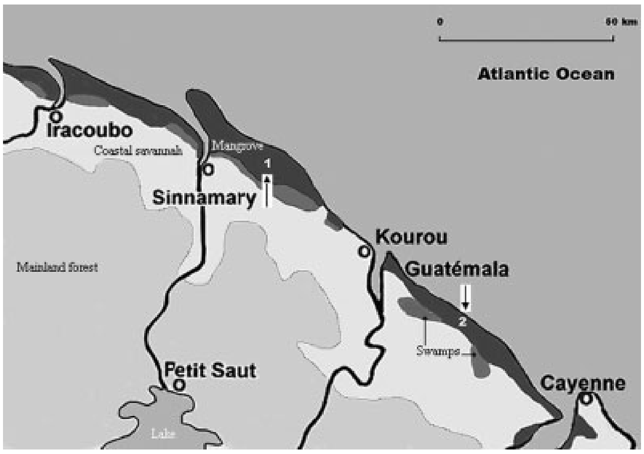

Figure 1. Location of the field sites along the French Guiana coast (1: Sinnamary; 2: Guatemala mangroves) and schematic representation of the four vegetation classes: salty coast mangrove, freshwater swamps, coastal dry savannah and mainland rainforest.

parts of the world the back mangrove is frequently occupied by the tanne, a highly saline formation without trees.

The first objective of this project was to determine if the back mangrove in Guiana was still linked with the ocean water, by studying the local groundwater origin and possible connections with other water pools. The second objective was to explore the influence of the vegetation, mainly with respect to evapotranspiration and salt excretion, on the salinity of the groundwater. For this purpose, the inland mature *Avicennia* mangrove forest was compared with the *Avicennia* seafront mangrove. The dry versus wet season influence was also investigated.

EXPERIMENTAL

Field sites

The field investigations took place in two areas, Sinnamary and Guatemala, during the dry season in November 2004, and during the wet season in March 2005 (Fig. 1).

The Sinnamary mangrove forest is one of the widest and largest of its type. It is nearly 25 km long and up to several km in width. The study site is located 3.5 km east of the Sinnamary village and near the Anse road. The road was built on an old sand bar (*chenier*) which separates the freshwater and saltwater areas (Fig. 2). This back mangrove forest is dominated by *Avicennia germinans* trees with a mean diameter of 12 to 14 cm, with some relict older trees measuring 24 to 46 cm across. A few small *Laguncularia racemosa* and *Rhizophora mangle* can also be found, but no adults. Six piezometers, 2 m long and 3.2 cm wide, were installed on the site. During the two field operations, the groundwater level was regularly observed with the installed dipstick.

The Guatemala site lies about 15 km east of the city of Kourou at a place where the shoreline is accessible on foot. The dominant mangrove tree is *Avicennia germinans* and the stem diameter ranges from saplings to small trees of 4 to 14 cm in diameter. A few large dead stumps and trees stems indicated the presence of a former mature mangrove forest here. No piezometers were installed in this seafront area, but the groundwater was accessible by numerous water holes.

Soil salinity profile

Soil profiles were sampled by a hand auger, and, every 10 cm depth, water from this non-saturated profile was extracted. The salinity was than measured by a hand refractometer (Atago Company Ltd., Tokyo, Japan).

Sap extraction

For medium- and large-sized trees, sapwood was extracted using an increment borer. For very small trees, a trunk section was collected and, after removal of the bark, the sap was released using a homemade wood squeezer, initially designed for soft wood.[11] The hardness of these tropical woods, however, obliged us to make a new extraction chamber using a stronger alloy.

Water stable isotopes

The different pools of seawater, river water and groundwater, as well as sap, were sampled, put into capped vials (10 mL for water, 2 mL for sap) and sent to Iso-Analytical Ltd., Sandbach, UK, for analysis. Oxygen-18 analysis of the samples was performed in triplicate by equilibration with carbon dioxide in septum-capped containers. Deuterium analysis of the samples was performed in triplicate by equilibration with hydrogen gas catalyzed by platinum in septum-capped containers. The headspaces of the containers were subsequently measured on a continuous flow isotope ratio mass spectrometer system (Europa Scientific ANCA-GSL and GEO 20-20 IRMS; Europa Scientific, Crewe, UK). The equipment was calibrated by using two water standards that are traceable to the primary reference standards, V-SMOW2 (Vienna-Standard Mean Ocean Water) and V-SLAP2 (Vienna-Standard Light Antarctic Precipitation), distributed by the IAEA, Vienna, Austria. A third traceable water standard was analyzed alongside the samples to check the accuracy of the data.

The results are expressed in per mil on the V-SMOW/SLAP scale, for oxygen:

$$\delta^{18}\mathrm{O}_{\mathrm{V-SMOW2}}(‰) = ((^{18}\mathrm{O}/^{16}\mathrm{O}_{\mathrm{sample}})/(^{18}\mathrm{O}/^{16}\mathrm{O}_{\mathrm{standard}}) - 1) \times 1000;$$

and for deuterium:

$$\delta^{2}\mathrm{H}_{\mathrm{V-SMOW2}}(‰) = ((^{2}\mathrm{H}/^{1}\mathrm{H}_{\mathrm{sample}})/(^{2}\mathrm{H}/^{1}\mathrm{H}_{\mathrm{standard}}) - 1) \times 1000.$$

Ion analysis

Indication of the global ion charge of water samples was given by conductivity and/or salinity measurements. A more complete analysis of some samples was undertaken to determine the anion amount (Cl^- and SO_4^{2-} by high-performance liquid chromatography (HPLC)) and the cation amount (Na^+, K^+, Ca^{2+} and Mg^{2+} by inductively coupled plasma atomic emission (ICP-AES) spectroscopy).

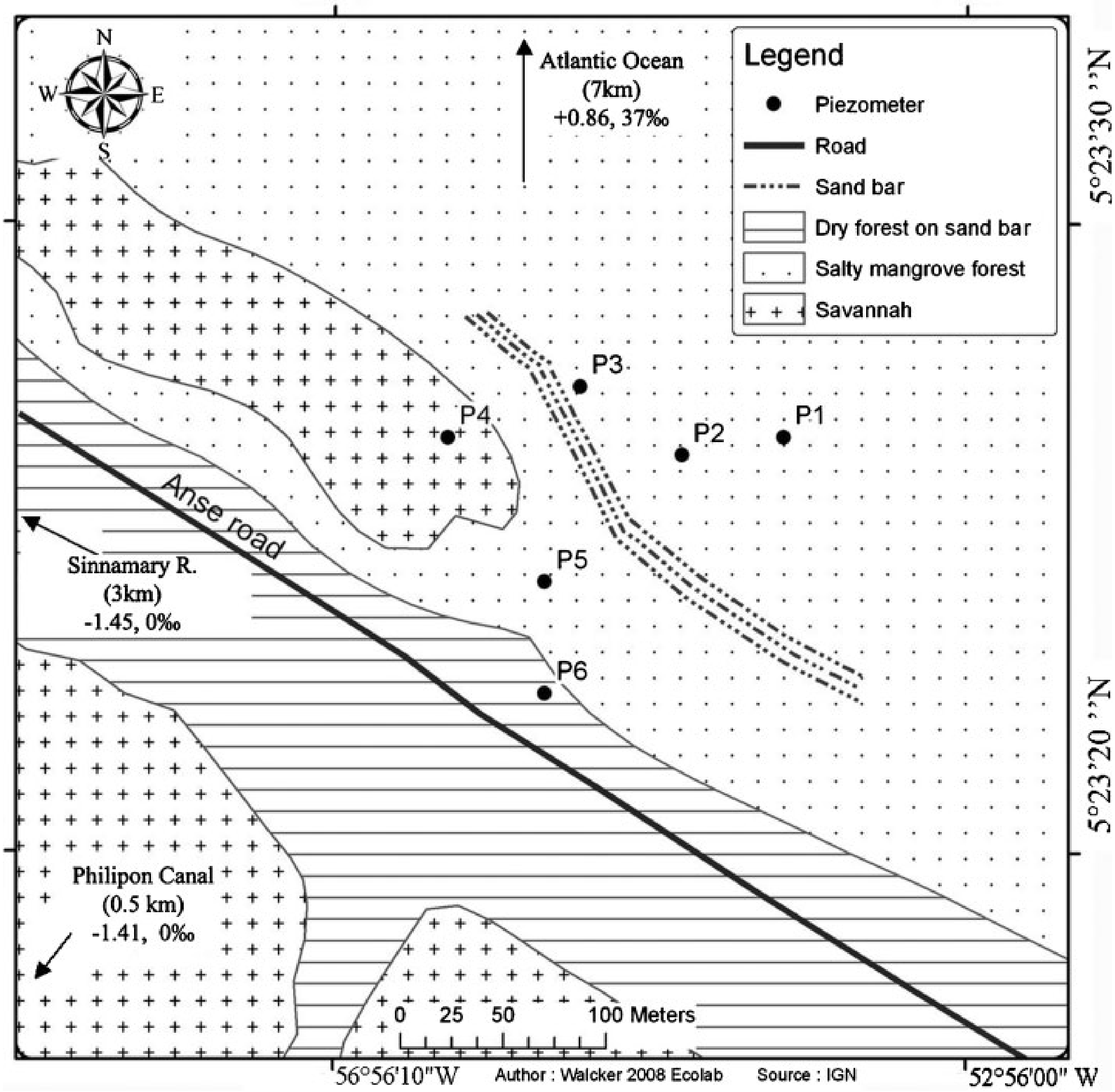

Figure 2. Positions of the six piezometers on the Sinnamary field site from GPS data, with the distance and direction of the different nearby water pools, i.e. Atlantic Ocean, Sinnamary River and Philippon Canal. The δ^{18}O and salinity values in per mil of the three pools are reported using the dry season measurement (November 2004).

RESULTS

Salinity and isotopic measurements

Except for the piezometer P6 close to the road, the groundwater in the Sinnamary mangrove was more saline than the seawater (up to a factor 2) during the dry season (Table 1). During the wet season, the mangrove was permanently flooded, with a water surface salinity below 5‰. Additional measurements made on the sea front, in the natural water holes between the young *Avicennia*, gave indications of evaporated seawater (39–49‰) in the dry season, and slightly diluted seawaters (27–30‰) in the wet season. Thus the seasonal salinity range for the sea front mangrove groundwater was much smaller than in the back mangrove. Salinity analysis of water in the non-saturated soil profiles (Table 2) revealed a higher salt content at depth than at the surface, with the exception of a reverse soil profile in Guatemala in November 2004.

Indication of the origin of the water could be deduced from the ^{18}O isotopic data. The values for the Sinnamary piezometers are given in Table 1. The two groups could be easily distinguished from their δ^{18}O values during the dry season: the piezometers closer to the road (P4–P6, mean value -1.05 ± 0.22), which are supplied by water coming from inland, and the second group located deeper inside the mangrove forest (P1–P3, mean value -0.44 ± 0.11). The water origin is certainly the same, just modified by the intense evapotranspiration. Furthermore, the dipstick record in P1 shows no amplitude cycling of the groundwater level, and thus there was certainly no connection with the marine saltwater front 5 km away. During the wet season, the flooding water reduced the difference between the two groups which then had similar values (-0.30 ± 0.01), probably because the common surface water was equally evaporated. On the sea front, the isotopic values for the water available for the vegetation range from $+0.8$ to $+2.23$.

Table 1. Variations in the ground water characteristics in the Sinnamary back mangrove during the dry season (November 2004) and the wet season (March 2005). The P1–P3 group represents the piezometers located towards the sea, and the P4–P6 group the piezometers closer to the road. Values for P1, P2 and P6 in November 2004 are extracted from Lambs *et al.*[1]

	November 2004		March 2005	
Sinnamary	Salinity	$\delta^{18}O_{\text{V-SMOW}}$	Salinity	$\delta^{18}O_{\text{V-SMOW}}$
Piezo	(‰)	(‰)	(‰)	(‰)
P1	52	−0.33	4.1	
P2	70	−0.56	5.0	
P3	72	−0.44	5.0	−0.29
Mean ± std dev	**65 ± 11**	**−0.44 ± 0.11**	**4.7 ± 0.5**	
P4	34	−0.83	2.6	−0.31
P5	60	−1.04	4.9	
P6	21	−1.28	3.1	
Mean ± std dev	**38 ± 20**	**−1.05 ± 0.22**	**3.5 ± 1.2**	**−0.30 ± −0.01**

Table 2. Examples of soil salinity profiled (in ‰) in the Sinnamary and Guatemala field sites during the dry season (November 2004) and the wet season (March 2005). The Sinnamary site was permanently waterlogged in March 2005, with a salinity below 5‰, and soil profiles could not be made. OM = presence of organic matter, GW = ground water, depth in cm. In the Guatemala site, the soil profile could be sampled during the wet season

	nov-04	nov-04	nov-04	nov-04	nov-04	march-05	march-05	march-05
	Sinnamary	Sinnamary	Sinnamary	Sinnamary	Guatemala	Guatemala	Guatemala	Guatemala
Soil depth	P1-1	P1-2	P2-1	P2-2	A	A	B	C
0–2 cm	35 (OM)	55	30 (OM)	65	120	25	31	33
10–12 cm	55	60	68	70	65	39	50	47
20–22 cm	55	63	61	66	60	44	59	50
30–32 cm	55	61	61	66	50	51	58	55
40–42 cm	53	57	69	79	45	51	62	54
50–52 cm	52	60	65	82	41	58	61	50
GW salinity	*52*	*52*	*70*	*70*	*48*	*29*	*27*	*30*
GW depth	**59**	**59**	**87**	**87**	**40**	**15**	**10**	**15**

This water origin analysis from the soil and groundwater was confirmed by the analysis of the water used by the trees. For this purpose, eleven sap extractions were performed on *Avicennia* on the two sites. All gave very high salinity values ranging from 80 to 120‰ during the dry season of November 2004, regardless of the site position, as reported in Table 3. Lower sap salinity was found to correspond to less concentrated salinity in nearby groundwater. During the wet season in March 2005, the sap salinity was about 40‰ lower. At the Sinnamary site, no sap extractions were made in the area of P6 due to the absence of mangrove trees in the vicinity. The vegetation comprised small *Astrocaryum vulgare*

Table 3. Sap characteristics for the Sinnamary and Guatemala sites

		November 2004		March 2005	
Location	diameter	Salinity	$\delta^{18}O_{\text{V-SMOW}}$	Salinity	$\delta^{18}O_{\text{V-SMOW}}$
Sinnamary	(cm)	(‰)	(‰)	(‰)	(‰)
P1	46,5	100	−0.87		
P1	37,7	110	−0.96		
P2	146	100	−0.99		
P2	138	120	−1.08		
P3	76,2	120	−1.1	80	−0,46
P3	74,3	110	nd		
P4	109	80	−1.02		
P5	104	85	−1.27		
	Mean ± std dev	**103 ± 14**	**−1.04 ± 0.12**		
Guatemala					
Plot A	3	130	nd		
Plot B	4		nd	95	1.69
Plot C	5		nd	90	1.77

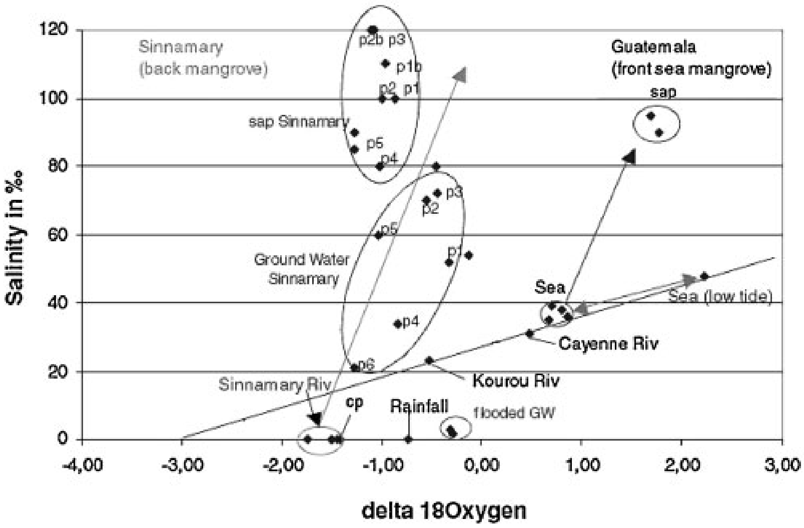

Figure 3. Relationship between the δ^{18}O values and salinity for water and sap extractions. The black diagonal line represents mixing between the fresh and saline water pools to which the estuaries align. The two diagonal arrows point to the possible water origin for the Sinnamary back mangrove (left) and the coastal Guatemala mangrove (right).

palm trees and *Acrostichum aureum* ferns. The sap isotopic measurements confirm the different water origin for the two sites; the results are shown in Fig. 3. For the Sinnamary site during the dry season, the δ^{18}O values range between -1.27 and -0.87, not far from those for the groundwater, or those from the local fresh water pool. During the wet season, the sap δ^{18}O values increased to -0.46, as observed for the floodwater. In contrast, at the Guatemala site, the isotopic sap value was much higher with $\delta^{18}\mathrm{O} = +1.7$, showing evaporation of seawater, which has a common value of $\delta^{18}\mathrm{O} = +0.76$.

The salinity of the leaves during the dry season was also high, and similar to that found in the piezometer and trunk at 75 to 120‰ ($n = 3$), whereas during the wet season this salinity dropped in much the same way as in the trunk, to 20 ± 3‰ ($n = 22$). Unfortunately, isotopic measurements could not be made on the leaves.

In a previous study[1] on the mixing between fresh water and seawater in seven Guianese rivers, we showed that, in a rectangular diagram combining both salinity and δ^{18}O values, the mixing between the two water pools could be ranked along a straight line, as reported in Fig. 3. In this present study, additional data collected at the soil, groundwater and vegetation level are distributed along two parallel diagonal arrows showing the probable distinct water origins according to the site: freshwater for the back mangrove in Sinnamary and seawater for the front sea mangrove in Guatemala.

Water ion analysis

Salinity measurements only gave information on salt content, but no indication of the ions involved, or their possible sources. Thus, the main water pools and the Sinnamary groundwater were analyzed for their ion content during the dry and wet seasons (Table 4). In river or canal, no balance between cations and anions was achieved. This is certainly due to the presence of carbonate. In the Sinnamary River, there is almost no difference in the anion content from above

Table 4. Ion concentrations for the different water samples expressed in mM, in November 2004, except submerged P3 and P4 taken in March 2005

	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
Location						
Sinnamary Up	0.232	0.016	0.055	0.018	0.065	0.014
Sinnamary Down	0.292	0.019	0.059	0.019	0.093	0.011
Philippon Canal	0.435	0.021	0.046	0.042	0.245	0.021
Open sea	476.294	10.230	11.203	50.596	567.306	43.850
Sea shore	473.249	11.509	11.502	50.926	551.678	38.058
P1	617.660	6.573	4.341	60.140	733.653	34.296
P2	717.703	9.949	14.795	138.749	956.474	90.322
P3	704.654	5.703	15.494	135.582	833.145	87.746
P4	379.295	1.995	9.506	60.140	447.334	43.537
P5	626.359	3.734	5.489	102.304	778.138	50.375
P3 submerged	58.721	1.586	1.395	4.936	68.999	5.710
P4 submerged	57.851	1.662	1.644	5.265	68.181	4.692

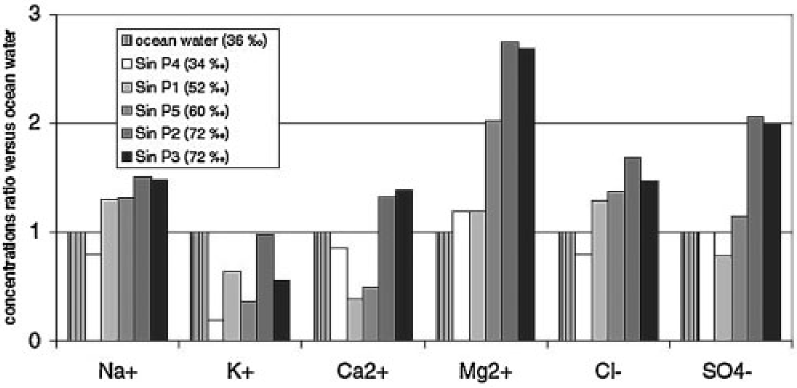

Figure 4. Relative amount of each ion in comparison with ocean water for the groundwater of the Sinnamary back mangrove extracted in the piezometers in November 2004.

and below the dam. In the freshwater pool (Sinnamary River and Philippon Canal), the main ions are Na > Cl > Ca (except for the possible carbonate). The Philippon Canal displays a rather higher content of NaCl, as it follows the back mangrove. There is also almost no difference in ion content between the shoreline non-evaporated seawater and a sample taken from 20 km offshore. Compared with seawater, groundwater samples taken in the piezometers of the Sinnamary mangrove forest had higher ion concentrations of Na, Mg, Cl and SO_4, and lower concentrations of K and Ca (Fig. 4).

DISCUSSION

Water pools

Conductivity or salinity coupled with ^{18}O measurements are useful tools in the identification of water pools in wetlands.[1,11–13] The oceans form the largest global water reservoir, and are the reference point for the isotopic standard of zero. In tropical regions, positive values are caused by strong evaporation,[14] as here with the $\delta^{18}O$ value of $+0.76$.[1]

In French Guiana back mangroves, sand bars often separate two water pools: freshwater on the inland side with a conductivity of 40 to 250 μS, and salty water on the ocean side where mangroves develop with groundwater salinity that can reach two to three times the sea salinity during the dry season. The local freshwater pool is formed by the downstream Sinnamary River ($\delta^{18}O = -1.6$) and the coastal rainfall as seen by the Philippon Canal ($\delta^{18}O = -1.4$), which is a channeled small river that drains the local marsh (pri-pri). Compared with the upper Sinnamary River ($\delta^{18}O = -2.7$),[1] this fresh costal water is certainly evaporated after passing through the Petit Saut Dam, or after migration through the marsh. The amount of seawater coming from the Sinnamary estuary should, however, remain low as the conductivity does not excess 238 μS. The piezometers close to the road, i.e. P4–P6, where the fresh water passes through the sand bar during the wet season, display isotopic values close to this local fresh water pool: -1.3 to -0.8, but with high salinity, 21–60‰. For the more inland piezometers, P1–P3, located after a second sand bar, the isotopic value is much more evaporated (around -0.44) but is still different from that of the ocean water ($+0.86$) and the salinity remains high. Isotopic values for evaporated ocean water will increase to more positive values as observed for the Guatemala site.

Saline water evaporation

The foremost question regarding the occurrence of such saline water is what hydrologic regimes and geochemical processes have led to its formation? In our case, the cause of salinity can be either seawater intrusion or subsurface saline groundwater. All our soil profile salinity measurements reveal high ion content with, in general, a more concentrated pool at the bottom; similar results have be found on a wider scale.[7] This salt accumulation under the mangrove forest, certainly due to convection process, can lead to brine formation during the dry season, which can be diluted during the wet season. The fundamental requirement for brine formation is a closed or semi-closed type of hydrological regime with a high temperature such that dissolved solutes can build up within a subaerial water body. A number of geochemical processes modify the chemical and isotopic composition of saline water over time. These include the compaction and dewatering of rock formations; redox reactions involving dissolved and gaseous materials; maturation and decay of organic matter; and various water–soil interactions.[15]

The behaviour of stable oxygen and hydrogen isotopes of water is well understood with regard to the major hydrological and geochemical processes that produce saline water. Water molecules evaporating from a surface water body into the atmosphere are invariably depleted in both heavy isotopes, leaving the remaining water enriched in these isotopes as a consequence. The magnitude of this enrichment depends on many physical factors such as temperature, relative humidity, and salinity. In addition, hydrological influences include inflow, outflow and the fraction of remaining water. In the $\delta^{2}H$-$\delta^{18}O$ diagram, the trajectory of evaporating water bodies has a slope of 4 to 6, depending on these factors. We observed an evaporation line very close to the water mixing line, with a slope of around 6 (Fig. 5), from the upstream Sinnamary River to the evaporated seawater from the Guatemala site.

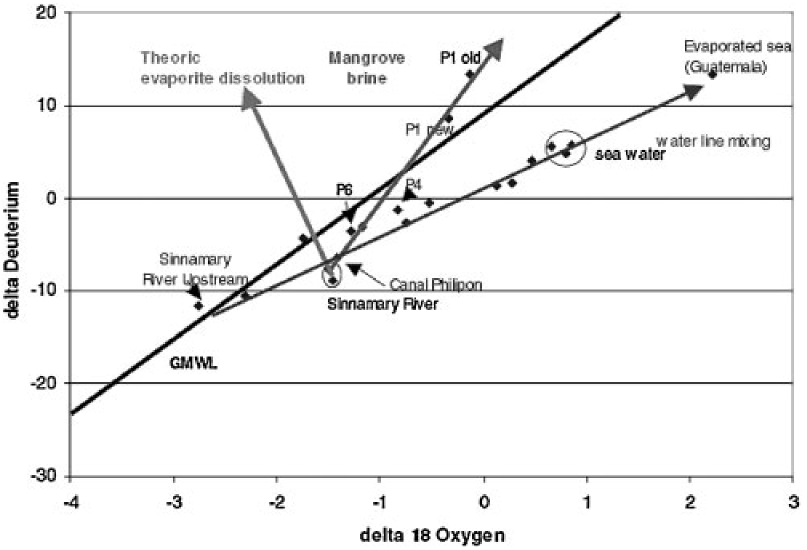

Figure 5. δ^2H-δ^{18}O diagram (modified from Lambs *et al.*[1] with the local water pools, and comparison with the Global Meteoric Water Line (GMWL, slope = 8), the line of water mixing between the fresh and saline pool (slope = 6) which is close to the evaporation line, and the Sinnamary mangrove brine line (slope approximately 14) beginning at the freshwater pool (Sinnamary River and Philippon Canal) and ending with the saline groundwater (P1).

Transpiration

Of the mangrove tree species, *Avicennia* spp. are more tolerant to high salt content, whereas *Rhizophora* spp. can better accommodate fluvial freshwater. *Avicennia* is consequently normally dependent on saline marine conditions, and it is therefore surprising to find it in an area supplied by freshwater. A similar paradox was noted in a report by Dawson and Ehleringer,[16] who showed, by isotope measurements, the same riverbank trees not using stream water. In French Guiana, *Avicennia germinans* is the more abundant species, even along the river estuary, since the marine water penetrates far inland. In the Amazon delta, *Rhizophora* is the main mangrove tree present, since the huge river discharge displaces any oceanic influence. In French Guiana, even in the back mangrove, *Avicennia* remains the predominant species.

Our measurements show that there is freshwater percolating through the sand bars in the back mangrove, but why does this area remain so saline? Could it be caused by salt coming from the evaporation of seawater, or by excretion by *Avicennia* leaves? Some authors[7] have also noticed a higher salt content under healthy *Avicennia*, able to evapotranspirate high volumes of water. Salinity increases with plant development and is strongly influenced by the seasonal variation.

Sap flux measurements on *Avicennia* trees located between the P1 and P3 trees in Sinnamary also show that the tree water uptake was more important during the wet season than in the dry (E. Muller, L. Lambs and F. Fromard, to be published), certainly due to lower osmosis. This implied also that there was a stronger concentration process by the vegetation during the wet season with less charged surface water. Tanne formation was not observed, unlike in the African situations, nor is there a dilution of the salt to enable *Rhizophora* forest development. The specific geo-climatic conditions maintain this high saline environment supplied by fresh inland water.

There has been only one other report on the use of freshwater by *Avicennia*. Sternberg and Swart[17] measured the sap isotope content of mangrove trees in Florida, and found that one of the four *Avicennia* trees studied was taking up freshwater. However, no salinity measurements were performed, either in the soil or in the groundwater. Piezometers were not employed, and so these authors give no information on the groundwater under the mangrove. In our case, it is not just one tree but a part of the back mangrove forest that occupies many hundreds of square metres where the groundwater displays freshwater signals.

Since mangrove vegetation excludes salt during water uptake (*Rhizophora* genus), or excretes it through the leaves (*Avicennia genus)*, transpiration will also increase the salinity of the residual water.[18] Recently, Fass *et al.*[19] described the groundwater characteristics of a *Avicennia marina* mangrove forest in Australia. The water was highly saline and enriched in heavy isotopes relative to seawater. The chlorine concentration was up to three times that of seawater, and radiogenic measurements show that this was an isolated groundwater source of seawater about 4000 to 6000 years old. In our case, the dynamics of the Guiana coast promotes a fast renewal, and the isolated marine aquifer under our field site is not more than 15 years old.

Transpiration will usually not alter the δ^{18}O/δ^2H composition of the residual water.[20] However, Lin and Sternberg[21] have shown that there can be a significant hydrogen fractionation during water uptake in coastal wetland plants such as salt-excluding halophic mangroves, which can lead to deuterium depletion from 3 to 9 units per mil in the stem fluid relative to the source water. Therefore, soil water beneath mangrove forests in coastal wetlands might show a small deuterium enrichment. As *Avicennia* is a leaf salt secreter, this root isotopic discrimination should remain low.

Figure 3 displays all the salinity and $\delta^{18}O$ isotopic values plus the sap values for the *Avicennia* trees. The oblique line represents the mixing line between the freshwater pool around −3.0, and the marine pool. Nearly all the previously sampled river estuaries such as the Cayenne and Kourou Rivers are close to this line. The two oblique and parallel arrows in the figure point to the local water supply sources from the water pool and groundwater to the water uptake by the trees. This representation also reflects the distinctly different origin of these waters for the inland and seafront mangroves, although in both case the salinity is very high.

Evaporites

Our results show (Fig. 4) that the ion composition of the Sinnamry groundwater is changed relative to the ions present in the seawater. Marchand *et al*.[7] suggest that the high salt level in the soil basal layer could come from the convection process. Also the dry season strongly enhanced the evaporation process and minimized runoff, thus increasing the salt concentration and the dissolved organic matter.[22] How do all these processes affect the ion composition? The sequential precipitation order from seawater is:

$$CaCO_3 > CaSO_4,2H_2O > \mathbf{NaCl} > \mathbf{MgSO_4} > \mathbf{MgCl_2} > NaBr > KCl$$

The first two minerals are the least soluble, and may precipitate, so only the next three, NaCl, $MgSO_4$ and $MgCl_2$, are found in excess in the studied groundwater. In a few low altitude areas of this mangrove forest, some small patches remain without vegetation, but retain a white and brown deposit on the surface, and these could be precipitates of these salts. The last two salts, NaBr and KCl, are the most soluble, and, as such, they are easily washed out of the area. This could explain the reduced amount of K. If we calculate the $Na + K/Cl$ ratio for seven piezometer values (5 in the dry and 2 in the wet season), the mean value derived is 0.85 ± 0.04, and this is very close to the shoreline value of 0.88, whereas the freshwater pool ratio ranges from 1.8 to 3.8. Furthermore, for the $Ca + Mg/SO_4$ ratio, the mean piezometer value is 1.63 ± 0.29, close to the shoreline value of 1.64, and far from the freshwater pool value of 4.2 to 7. These results suggest an evaporite origin for this saline water.

The dissolution of evaporite deposits does not change the isotopic composition of water, although it does change the isotopic activity ratios; however, the dissolution of hydrated minerals does affect the isotopic composition ratios of water. Various hydrous minerals are enriched in ^{18}O but depleted in deuterium, compared with water from which they precipitate at isotopic equilibrium. Therefore, the remaining water becomes progressively depleted in ^{18}O and enriched in deuterium during the precipitation process.[15,23]

The δ^2H-$\delta^{18}O$ relationship, given in Fig. 5, reports the Global Meteoric Water Line (GMWL) with a slope of 8, where the upstream rivers are on this line (see Fig. 2 in Lambs *et al*.[1]). Here only the Sinnamary upstream taken above the Petit Saut Dam is on this line. From this point one can draw a water mixing line in the direction of the seawater pool with a slope of about 6. Most of the estuary rivers are on this line. This line also represents the evaporated line, and we find on it the points for the downstream Sinnamary River and the Philippon Canal. From this local freshwater pool, the groundwater points line up on a new arrow with a slope of 14. On Fig. 5, we can also draw the theoretical evaporite dissolution line (slope of about −10),[15] and we can see that the groundwater line could be a combination of the evaporation and the evaporite dissolution.

CONCLUSIONS

Stable isotope mass spectrometry measurement can reveal the origin of the water in the mangrove forests. As the signal is not affected by the presence of salt, very fresh and very salty water samples can be compared. This comparison shows that this back mangrove forest is now completely isolated from the ocean that initially brought the substrate Amazon mud, the floating propagules of the trees and the evaporated seawater ions. This system did not transform into extreme conditions like tanne that might lead to death of the trees due to the influx of freshwater through the nearby marsh and sand bars. This water ingress compensates for evaporation from the soil surface and tree evapotranspiration. By contrast, the freshwater floods of the wet season do not dilute the ion pools sufficiently to create conditions for the establishment of less salt-tolerant species like *Rhizophora*. The *Avicennia* ecosystem will continue to function until marine erosion again encroaches upon this part of the coast to remove the sand, soil and vegetation and re-deposit them elsewhere.

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