

Geochemical evidence for different peat sources in the Siak estuary and along the east coast of Sumatra, Indonesia

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SUMMARY

The distribution pattern of selected biomarkers extracted from samples of outcropping peat from the Siak river, its estuary, the coast around Dumai and the island of Bengkalis have been investigated by gas chromatography (GC) and combined gas chromatography/mass spectrometry (GC/MS), and compared with samples of eroded peat washed ashore (re-deposited) on the coastline of Sumatra. Geochemical analyses of *n*-alkanes, *n*-alkanols, *n*-alkanoic acids, steroids and triterpenoids show that outcropping and re-deposited peats have different chemical compositions. The outcropping peats around Dumai, Bengkalis and in the Siak River estuary contain high concentrations of the pentacyclic triterpenoid taraxerol, a typical constituent of the mangrove species *Rhizophora*. A comparison with the lipid composition of leaves from the fringing mangrove species (*Avicennia alba*, *Sonneratia alba* and *Rhizophora apiculata*) showed that only *R. apiculata* contains significant amounts of taraxerol. Taraxerol was completely absent from the leaves of *A. alba* and *S. alba*. This suggests that the peats outcropping around Dumai, Bengkalis and in the Siak estuary must be formed by a dominant input of mangroves of the *Rhizophora* family. The *n*-alkane distribution patterns of the outcropping peats near Dumai and the Siak estuary are similar to those of the surrounding mangrove vegetation with a maximum at C₃₁ and a strong predominance of odd over even carbon numbers in all samples. Biomarker analysis of eroded peats washed ashore along the coastline around Dumai and the Siak estuary shows a different lipid composition with high amounts of the triterpenoids friedelin, α -amyrin and β -amyrin. These compounds are typical biomarkers for tropical forest vegetation as found along the Siak River and for peats eroding at upstream river banks. The *n*-alkanol distribution patterns of re-deposited peats also indicate a different origin for their organic matter. Peats re-deposited in the Siak estuary lack the C₃₀ *n*-alkanol that is typical of coastal peats, suggesting an upstream source.

KEY WORDS: biomarker; fatty acids; lipid, *n*-alcohols; *n*-alkanes; sterols; terpenoids

INTRODUCTION

Coastal areas are important for transport, recycling, degradation and accumulation of organic matter. The Indonesian-German project SPICE aims to characterise and quantify these processes in the coastal sea of eastern Sumatra, with emphasis on inputs from the Siak River and transformation processes occurring in its estuary. By including the river's drainage basin, the estuary and the river-influenced coastal ocean in one common sampling and analysis scheme, a complete coverage of a large variety of processes and compounds is achieved.

It is estimated that the area of peat soils in Sumatra was once 7.3–9.7 million hectares (Andriess 1974), or about one-quarter of all tropical peatlands (Driessen 1977). Peat is a heterogeneous mixture of organic carbon compounds which accumulates in various mires

(Grosse-Brauckmann 1990) and contain more than 60 % organic matter (Driessen 1977). Due to both legal and illegal logging, these soils become prone to erosion which transfers particulate organic carbon into the rivers draining them. Thus, the Siak presently exports large quantities of both dissolved and particulate organic matter into the coastal ocean (Baum *et al.* 2007).

Peat is formed mainly by microbial and physicochemical decay of plant materials in their usually waterlogged growth habitats. In the upper oxic layer of the ecosystem, decomposition is fast, and easily-utilisable plant constituents such as proteins and simple sugars are rapidly consumed by micro-organisms. Below the water table, the decomposition rate declines rapidly due to lack of oxygen. In the anoxic layer, the important oxygen source for degradation is oxygen-containing plant constituents. In parallel with the now slowly

proceeding degradation, the humification process begins. Decay-resistant compounds, especially lipids, are concentrated in the peat stock during this process. Unlike bulk vegetation, which is largely composed of readily degradable components such as carbohydrates and becomes increasingly unrecognisable as decomposition proceeds, lipid biomarkers can be preserved in a relatively unaltered state. Biomarkers have been widely used in marine settings as proxies for organic matter inputs (e.g. Brassel *et al.* 1986, Volkman *et al.* 1987, Pancost *et al.* 2002); however, molecular-based studies of terrestrial settings—and peat deposits in particular—are limited (Dehmer 1993, Ficken *et al.* 1998, Nott *et al.* 2000, Pancost *et al.* 2002). Several investigations have attempted to characterise the lipid constituents of peat-forming plants and identified profound variations that are also reflected in peat stratigraphy (Lehtonen & Ketola 1993, Nott *et al.* 2000, Pancost *et al.* 2002). In many cases, biomarker proxies have been shown to reflect the dominant vegetation, illustrating their potential for use in vegetation reconstruction. For example, Nott *et al.* (2000) showed that the relative abundances of *n*-alkanes and macrofossil distributions co-varied.

The goal of this work is to extend previous studies by testing established proxies (e.g. *n*-alkane distributions) in a new setting to determine whether relatively unexplored compound classes (e.g. triterpenoids, *n*-alkanoic acids) can also be used for identifying plant inputs in order to determine patterns of riverine, estuarine and near-coastal transport and transformation of natural organic compounds.

METHODS

Study area

The Siak River has a total length of 370 km. Estimated discharge in March is 642 m³ s⁻¹ and in September 99 m³ s⁻¹ (A. Baum, T. Rixen, pers. comm. 2006). The river drains a catchment area of 11,500 km², and about 45 % of this area is covered by peat soils which formed mostly under tropical peat swamp forest vegetation. Accordingly, the Siak is a blackwater river containing large quantities of dissolved humic compounds (Siegel *et al.* 2009). These give rise to low oxygen contents, e.g. O₂ concentration in the upper reaches rarely exceeds 3 mg L⁻¹ (own field measurements 2005–2007). The Siak estuary and the coast around Dumai and the island of Bengkalis are fringed by mangroves, mainly *Avicennia* spp. and *Rhizophora* spp., which

have formed peat layers several metres thick. Eroded peats are found washed ashore in the estuary itself and along the coast of East Sumatra. These may originate either from the local mangrove peats or from swamp forest peats outcropping upstream in the Siak River.

Collection of samples

Samples were taken at the locations indicated in Figure 1 in 2005 and 2006, and initially air-dried before transportation to the home laboratory. Outcropping peat was cut after removal of the exposed surface. Leaf samples collected in the estuary were thoroughly washed with distilled water.

Macro-remains and micro-fossils

Attempts were made to identify the plant species contributing to the peats by microscopic investigation of macro-remains after removal of humic material with 10 % KOH. In no case were identifiable residues found (H. Freund, pers. comm. 2005). Also, microfossils such as e.g. diatom tests were not present (J. Barkowski, pers. comm. 2006). Thus, the samples were in an advanced stage of decomposition and identification of the plant sources was feasible only by chemical techniques.

Chemical analyses

After lyophilisation (freeze-drying), peat and plant material was ground in an agate ball mill for 30 minutes at 200 r.p.m. Extracts were prepared by ultrasonic extraction using solvent systems of sequentially increasing polarity: 1) *n*-hexane, 2) *n*-hexane/dichloromethane (50:50 v/v), 3–5) dichloromethane/methanol (90:10 v/v); which correspond in polarity to hydrocarbons, alcohols and polar N,S,O compounds respectively. The combined lipid extracts were rotary-evaporated to dryness and a mixture of squalane, 5 α -androstanol, 5 α -androstanone and erucic acid was added to provide internal standards. The *n*-alkanes were separated from the total extracts using a 1.0 x 20 cm glass chromatography column packed with activated silica gel (100–200 mesh). About 10 mm of anhydrous Na₂SO₄ was placed on top of the silica gel to retain remaining water. After adding an aliquot of the re-dissolved total lipid extract to the column, *n*-alkanes were eluted with 15 ml of hexane and polar compounds were eluted with a mixture of 40 ml

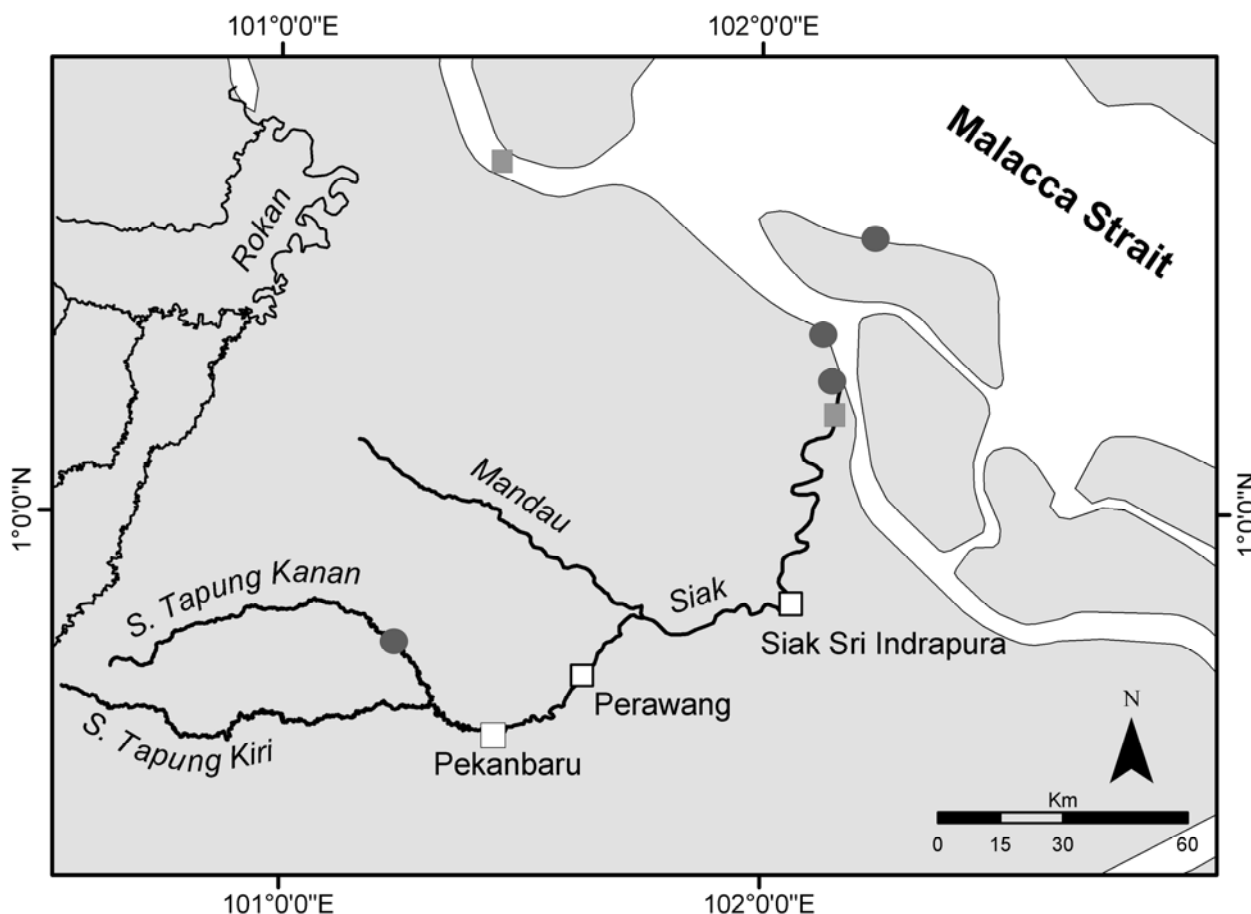


Figure 1. Map of the study area showing the locations at which peat was sampled. Open squares: towns; filled circles: eroding peat outcrops; filled squares: re-deposited eroded peats.

dichloromethane/methanol (9:1 v/v) (see Nichols 2011).

Long chain *n*-alkanes ($n\text{-C}_{16}\text{--C}_{39}$) were analysed with a Hewlett Packard 5890 series II gas chromatograph equipped with a cold injection system (KAS 3, Gerstel), a FID detector and a J&W DB 5 capillary column (30 m length, 0.25 mm inner diameter, 0.25 μm film thickness) programmed from 60 °C to 300 °C at a rate of 6 °C min^{-1} and held at 300 °C for 30 minutes. Helium was used as carrier gas with a flow rate of 1.2 ml min^{-1} . Individual *n*-alkanes were identified on the basis of retention time of authentic standards. Concentrations were calculated by comparison with the response of the corresponding internal standard (squalane).

Polar compounds were analysed using an Agilent 5973 GC-MS System operating at 70 eV with a mass range of m/z 50–650 in the scan modus. The specifications of the fused silica capillary column, the carrier gas and the temperature program were the same as for long chain *n*-alkanes above. Before measurement, the polar compounds were derivatised to trimethylsilyl ethers by adding 50 μl of N-methyl-

N-(trimethylsilyl)-trifluoroacetamide (MSTFA) to each sample. Components were identified by comparison of their mass spectra and retention times with synthetic standards or published data. The different internal standards added prior to sample extraction were used for quantification.

RESULTS

n-alkanes

Geochemical analyses of the *n*-alkanes present in outcropping and re-deposited peats are compared with the *n*-alkane distributions for litter from three major mangrove species that fringe the Siak estuary and the coasts around Dumai and the island of Bengkalis in Figure 2. The mangrove litter is dominated by C_{29} , C_{31} and C_{33} compounds (Figure 2), and their *n*-alkane patterns closely resemble those of the outcropping Siak peats, both upstream and in the estuary, as well as those on the Dumai coast. In the sample from the Bengkalis

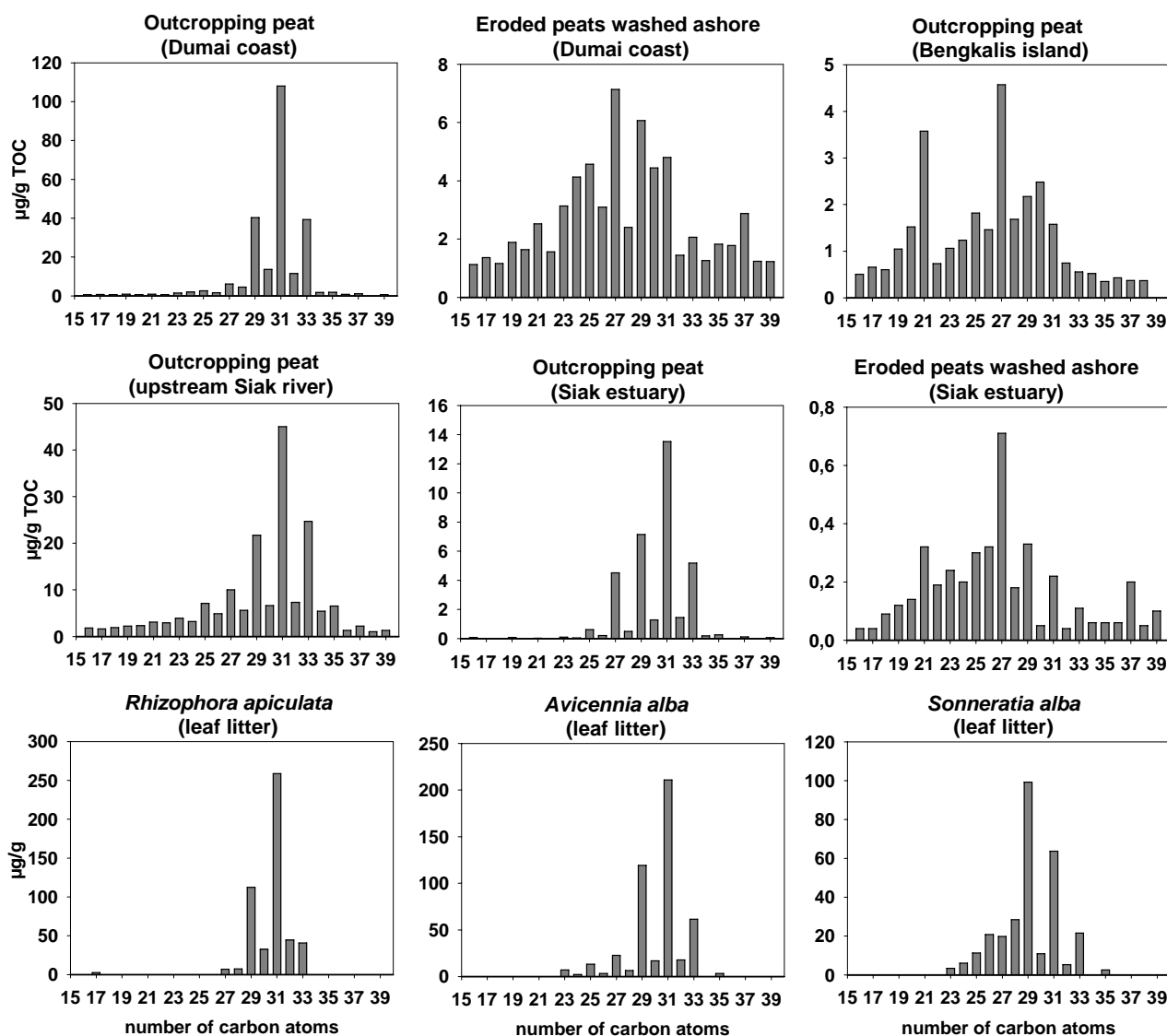


Figure 2. *n*-alkane distribution patterns for outcropping and eroded peats and three mangrove species from the Siak river, its estuary and the ocean coasts around Dumai and the island of Bengkalis.

outcrop, on the other hand, C_{21} and C_{27} alkanes are major components and significant amounts of even-numbered alkanes (C_{16} – C_{38}) are also present. The eroded peat washed ashore in the Siak Estuary is dominated by C_{21} and C_{27} compounds, and thus closely resembles the peat outcropping at Bengkalis Island. Thus, the data indicate significant erosion of coastal peat around Bengkalis, its transport by (tidal) currents towards and into the Siak Estuary, and deposition both on the coast and in the estuary. On the other hand, the outcropping (swamp forest) peat sampled upstream in the Siak, being dominated by the C_{29} , C_{31} and C_{33} *n*-alkanes, closely resembles that outcropping in mangrove communities on the coast and in the estuary (Figure 2). Therefore, this compound class does not appear to be suitable for differentiating between peats derived from mangroves and swamp forest.

n-alkanols

In the leaf litter of the mangroves analysed, *n*-alkanols are present in the range C_{18} – C_{30} , dominated by even-carbon components. The distributions are more variable than those of the hydrocarbons and are dominated by the C_{28} homologue in leaf litter of *A. alba* and by C_{30} in leaf litter of *S. alba* (Figure 3). The C_{18} *n*-alkanol is the only homologue in *R. apiculata*, although the total amount of this compound is much lower than the quantities of *n*-alkanols present in the leaf litter of the other two species.

Both outcropping and re-deposited peats exhibit wider *n*-alkanol distribution patterns (Figure 3). Here, compounds with chain lengths < 26 are also present. The C_{30} *n*-alkanol is found in all coastal peats, whereas it is absent from the upstream one. It

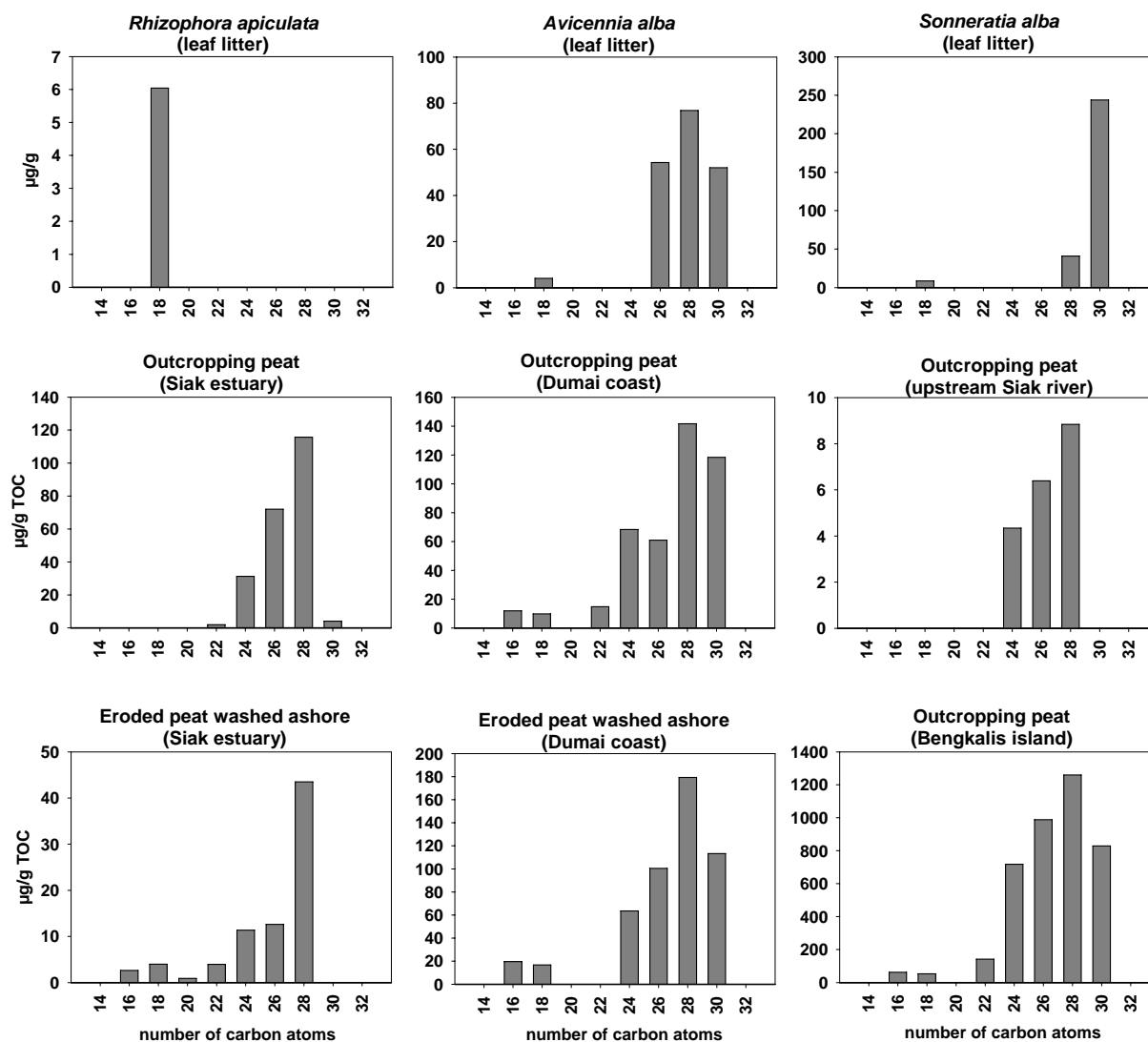


Figure 3. *n*-alkanol distribution patterns for plants and peats of the Siak river, its estuary and the coastal ocean.

is also to be found in the re-deposited peat at Dumai but not in the Siak Estuary sample. This suggests that the latter sample may have originated from peat eroded upstream on the Siak.

n-alkanoic acids

The distribution patterns for all of the major modern mangrove species fringing the Siak River and its estuary show a predominance of the 16:0 saturated acid together with moderate amounts of C₁₄ and C₁₈ saturated acids in the leaf litter (Figure 4). These compounds are also dominant in the outcropping peats upstream on the Siak River and in the eroded peats washed ashore in the Siak Estuary. Small amounts of long-chain saturated fatty acids are also present, but they represent less than 10 % of the total fatty acids of the three major plant species.

Most of the peat samples display a different distribution pattern with a predominance of compounds in the higher molecular weight region (>C₂₀). The C₃₀ fatty acid was the most abundant fatty acid in the eroding outcropping peats in the Siak estuary. The eroding outcropping peats on the coast of Bengkalis showed a predominance of the 26:0 homologue; whereas the 28:0 fatty acid was predominant in the outcropping peats on the coast around Dumai. Thus, the fatty acids appear to have little potential as source-specific biomarkers for *in-situ* or re-deposited peat in the Siak system.

Sterols

The distribution patterns of sterols in the different mangrove species are quite similar to one another (Figure 5) and clearly dominated by β -sitosterol

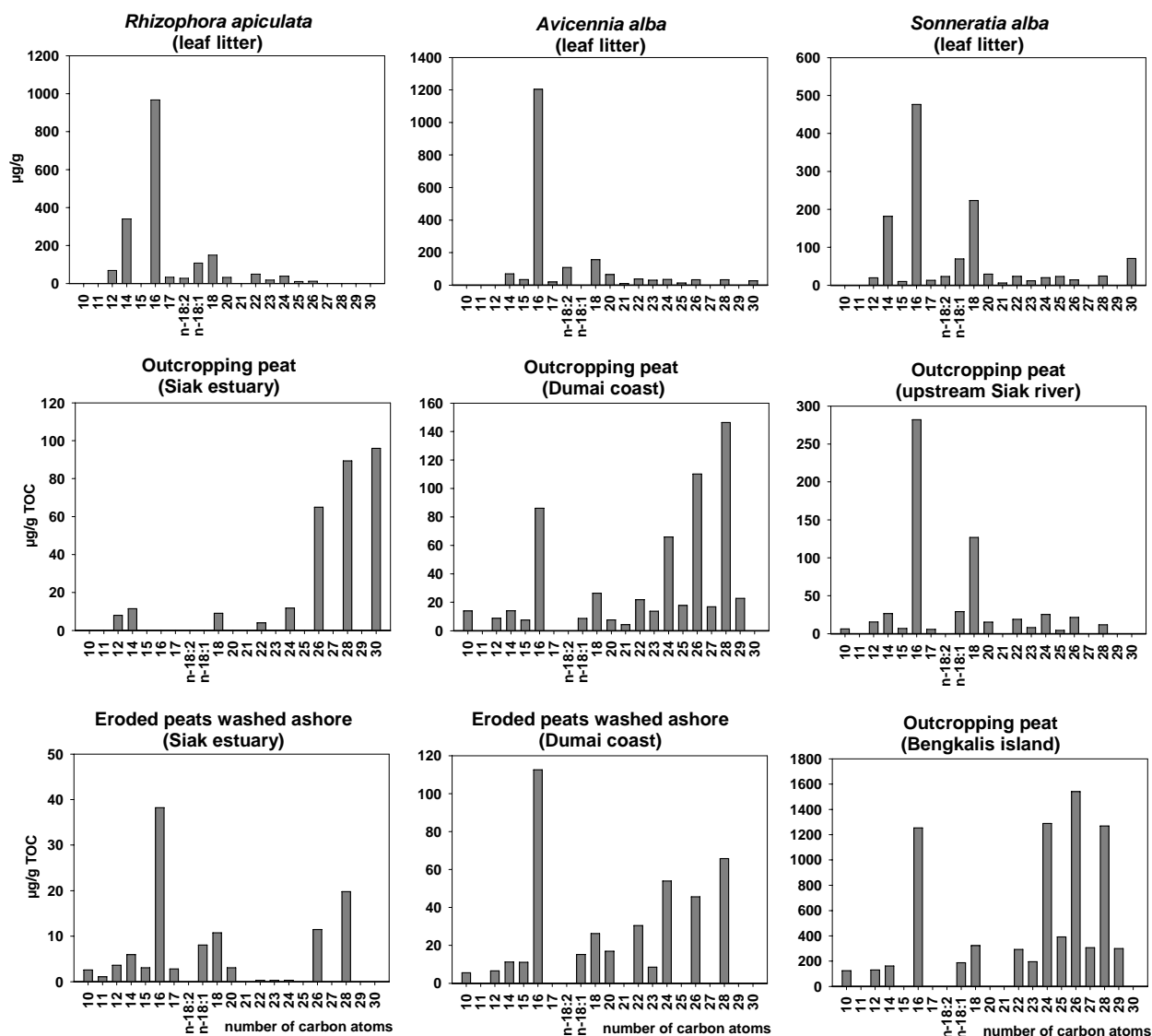


Figure 4. *n*-alkanoic acid distribution patterns for plants and peats of the Siak river, its estuary and the coastal ocean.

(C_{29} -ethylcholest-5 α -3 β -ol, Compound 11) and C_{29} -24-ethylcholesta-5,22-dien-3 β -ol (Compound 9), which are typical predominant sterols of higher plants. The outcropping peats in the Siak estuary and on the coastlines of Bengkalis and Dumai are also clearly dominated by C_{29} sterols (Compounds 8–12). In contrast, the distribution pattern for the outcropping peat upstream in the Siak River is not dominated by C_{29} sterols only. Rather, this peat contains significant amounts of C_{27} -cholest-5 α -3 β -ol (Compound 1), C_{27} -5 α (H)-cholestan-3 β -ol (Compound 2) and C_{28} -24-methyl-5 α (H)-cholesta-5,22-dien-3 β -ol (Compound 3), which are typical compounds for organisms from aquatic/lacustrine environments. 24-Ethyl-5 α (H)-cholestan-3 β -ol (Compound 12) is present only in the upstream peat sample and re-deposited peats.

Triterpenoids

The leaf litter of all the mangroves analysed contains significant amounts of triterpenoid-alcohols and -acids. The triterpenoid alcohol lupeol is found in all three mangrove species (Figure 6) while other triterpenoids such as α - and β -amyrin, betulin, taraxerol, oleanolic, betulinic and ursolic acids occur in one or two species only.

The eroding outcropping peats at Bengkalis Island, on the Dumai coast and in the Siak estuary contain large quantities of taraxerol, indicating a mangrove input. As taraxerol is completely absent from the leaves of our specimens of *A. alba* and *S. alba* from Sumatra, the peats outcropping around Dumai and in the Siak estuary must have formed from a dominant input of mangroves of the

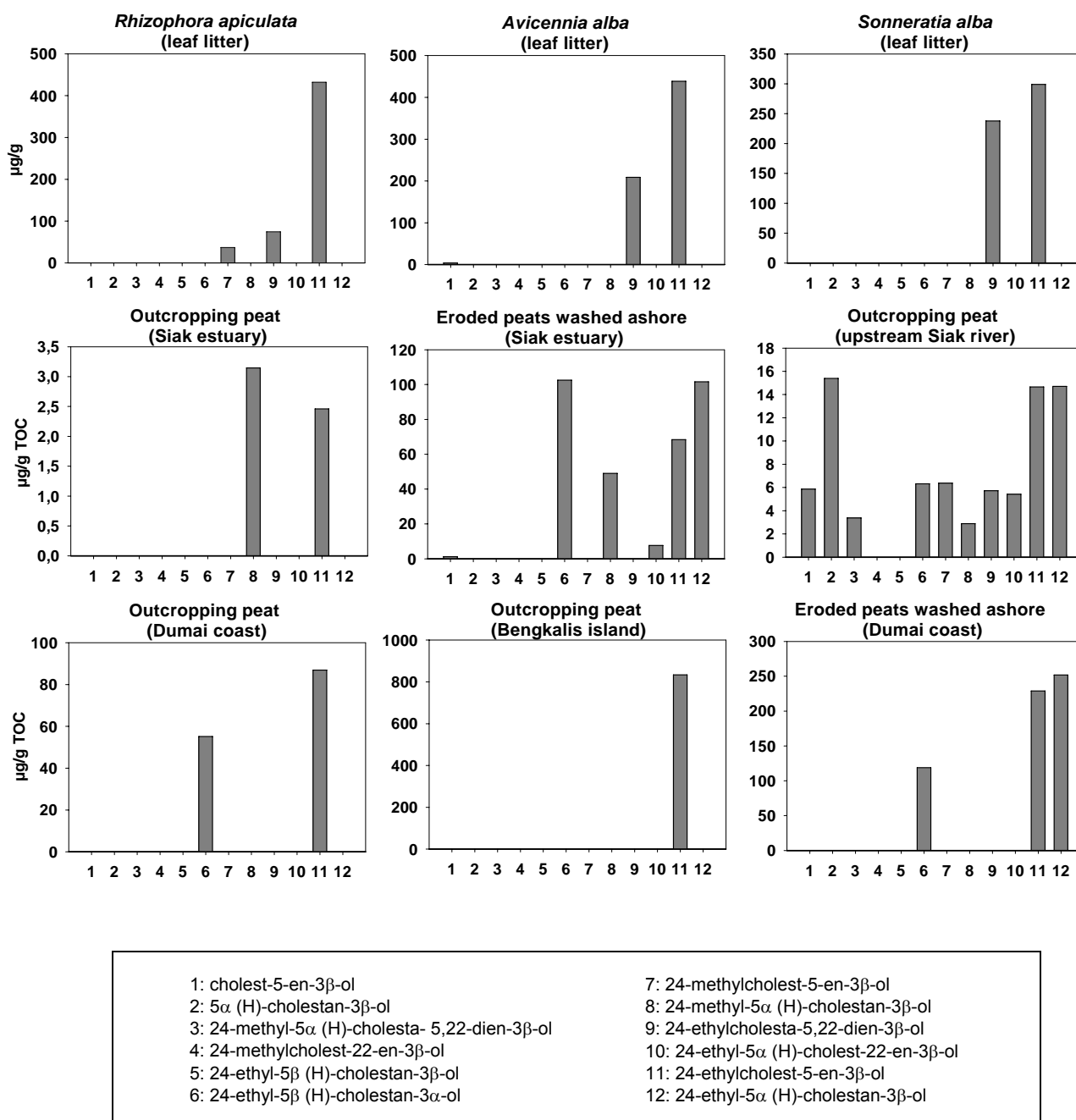


Figure 5. Steroid alcohol distribution patterns for plants and peats of the Siak river, its estuary and the coastal ocean.

Rhizophora family. The absence of betulin, the second dominant triterpenoid of *A. alba* and *S. alba*, from both outcropping and re-deposited peats also indicates that these mangrove species have not contributed significantly to local peat deposits.

The re-deposited peats from the coastline around Dumai and the Siak estuary show a different lipid composition with high amounts of friedelin, α -amyrin and β -amyrin. While the amyryns also are

present in mangroves, friedelin is a typical biomarker for peat swamp forest vegetation such as that occurring along the Siak River, and for eroding peats upstream (Figure 6). This, together with the absence of lupeol, indicates that the re-deposited peats are derived from this source; and hence that there is significant peat erosion along the Siak river together with active transport and deposition of organic matter in the estuary and along the coastline.

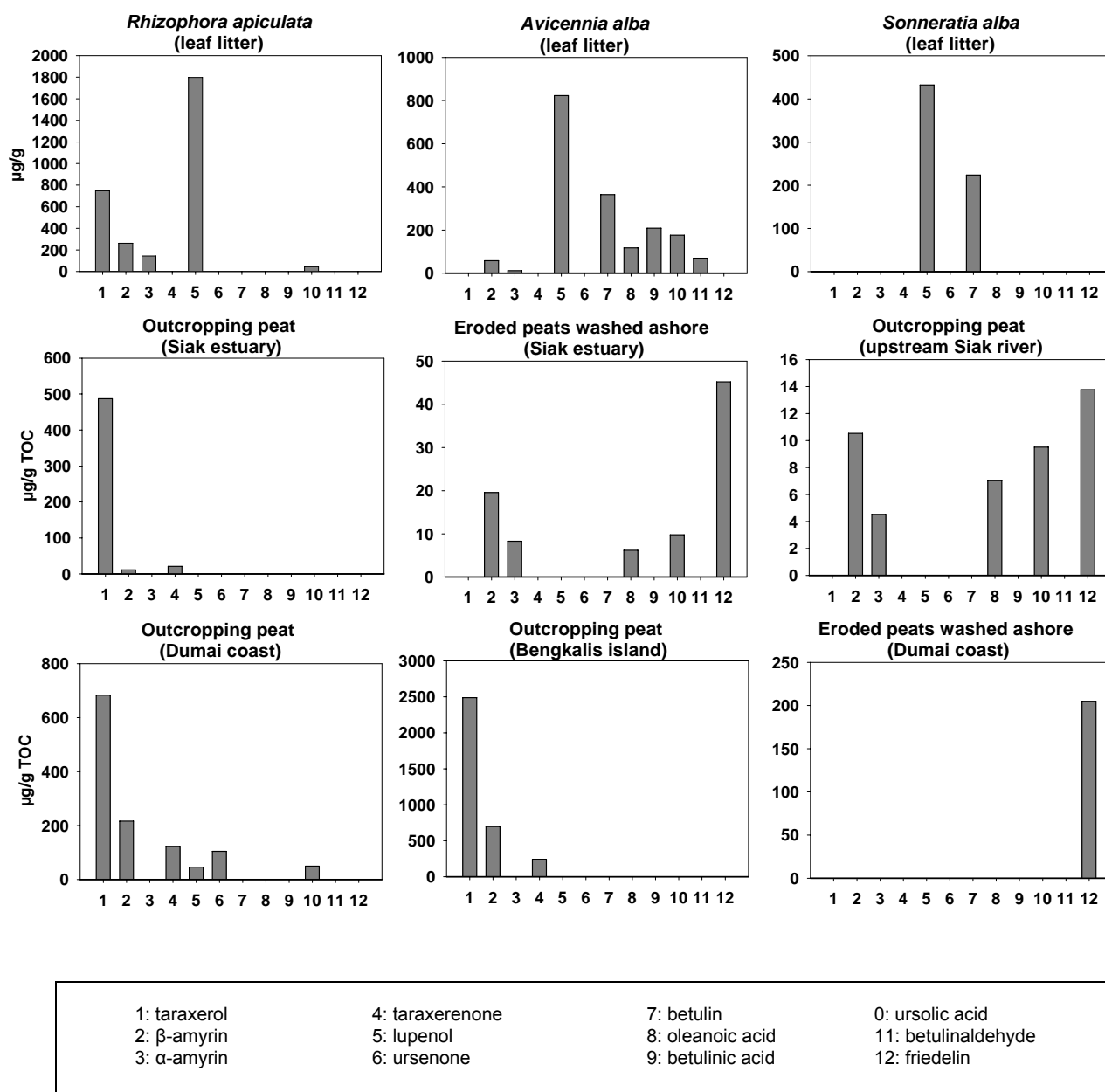


Figure 6. Triterpenoid distribution patterns for plants and peats of the Siak river, its estuary and the coastal ocean.

Overview and interpretation

Occurrences of the various characteristic compounds identified above, according to sampling site, are summarised in Table 1.

Two of the compound classes, namely *n*-alkanes and *n*-alkanoic acids, emerge as unsuitable for differentiating between peats derived from mangroves and tropical forest, because C_{29} , C_{31} , C_{33} *n*-alkanes and C_{14} , C_{16} , C_{18} *n*-alkanoic acids are all present in mangrove litter and at least some of the peat outcrops—notably including the outcrop of

swamp forest peat upstream in the Siak River. The main evidence they provide for sediment transport is the exclusive presence of C_{21} and C_{27} *n*-alkanes in the outcropping peat on Bengkalis and the re-deposited peat in the Siak estuary; indicating that there is significant erosion of coastal peat around Bengkalis which is transported by (tidal) currents into the estuary.

The distributions of the other three biomarker groups offer evidence for both peat origin and patterns of erosion/re-deposition that is to some degree inter-consistent. The outcropping peats of the

Table 1. Summary of distribution of potential biomarkers amongst the various materials sampled. Compounds that are common to mangrove litter, *in-situ* outcropping peat and re-deposited peat are potentially useful, especially if they are differentially present within at least one of these groups. X indicates presence in a sample; (X)* indicates that a group including a more-specifically identified biomarker was present; e.g. for *n*-alkanols, (C₁₈–C₃₀)* includes C₁₈, C₂₈ and C₃₀.

Biomarkers		Mangrove litter			Peat outcrops			Re-deposited peat	
		<i>Avicennia alba</i>	<i>Sonneratia alba</i>	<i>Rhizophora apiculata</i>	Siak upstream	Siak estuary Dumai coast	Bengkalis Island	Siak estuary	Dumai coast
<i>n</i>-alkanes									
(C ₁₆ –C ₃₈ even-C)*	C ₂₉ , C ₃₁ , C ₃₃	X	X	X	X	X			
	C ₂₁ , C ₂₇						X (X)*	X	
<i>n</i>-alkanoic acids									
C ₁₄ , C ₁₆ , C ₁₈		X	X	X	X		X	X	X
C ₂₆							X		
C ₂₈ , C ₃₀						X	X	X	X
<i>n</i>-alkanols									
C ₁₈				X					
C ₂₈		X			X	X	X	X	X
C ₃₀			X			X	X		X
C ₃₀ absent					X			X	
sterols									
C ₂₇ , C ₂₈ = Cmpds. 1–3					X				
(Cmpds. 8–12)*	Cmpds. 9, 11	X	X	X	X	(X)*	(X)*		
	Cmpd. 12				X			X	X
triterpenoids									
betulin		X	X						
taraxerol				X		X	X		
lupeol		X	X	X					
α-amyrin		X		X	X			X	
β-amyrin				X	X	X	X	X	
friedelin					X			X	X

Siak estuary, Dumai coast and Bengkalis all contain mangrove litter biomarkers, although the evidence from *n*-alkanols implicates *Sonneratia alba* as the main peat-forming species whereas that from triterpenoids suggests that it is *Rhizophora* peat. The swamp forest peat outcropping upstream on the Siak River is distinguished by its lack of mangrove biomarkers and the presence of the sterol 24-Ethyl-5 α (H)-cholestan-3 β -ol and friedelin (a triterpenoid).

Whilst the triterpenoid evidence suggests inputs of both swamp forest and mangrove peats to the re-deposition sites, that of the sterol biomarkers indicates re-deposition of mangrove peat only. The *n*-alkanol evidence, on the other hand, suggests that mangrove peat is washed ashore on the Dumai coast, but that the likely source of re-deposited peat in the Siak estuary is swamp forest peat outcropping upstream on the Siak river.

DISCUSSION

Biomarkers

n-alkanes

Odd carbon-numbered long-chain *n*-alkanes, typically in the range C₂₅–C₃₅, are characteristic components of the epicuticular leaf waxes of higher plants (Eglinton & Hamilton 1967). Although even-chain alkanes can also be found in plants, they are usually present as minor components. The atypical presence of significant amounts of C₂₁, C₂₇ and even-numbered alkanes (C₁₆–C₃₈) in the outcropping peat on Bengkalis Island may indicate that plants other than mangroves contributed to the peat. On the other hand, it is possible that this atypical alkane composition has arisen through microbial degradation of the plant materials that originally formed the Bengkalis Island peat (Wentzel 2007).

n-alkanols

Although the C₁₈ *n*-alkanol is unique to *R. apiculata*, it appears not to provide a useful signal in the outcropping and re-deposited peats sampled, perhaps because the concentration is so low; but also perhaps due to microbial degradation. The potential of the C₁₈ *n*-alkanol for distinguishing between different types of leaf litter inputs to mangrove peats at local scale may, nonetheless, be worthy of investigation.

n-alkanoic acids

n-fatty acids are also a major compound type in plant epicuticular waxes. They usually have straight chains with an even number of carbon atoms and chain lengths ranging from C₁₄ to C₃₆ (Kolattukudy

1976). They are essential components of all living cells and cell membrane lipids and a source of metabolic energy. Straight-chain fatty acids are dominantly present in leaf material, whereas roots and stems contain comparatively little of these compounds. The relative proportions of the C₁₆ (predominant), C₁₄ and C₁₈ (moderate amounts) saturated acids in the mangrove leaf litter (Figure 4) are similar to those reported previously for other members of the *Avicenniaceae*, *Rhizophoraceae* and *Chenopodiaceae* families (Misra *et al.* 1987).

The large amounts of long chain fatty acids in most of the peat samples indicate a source of leaf epicuticular waxes which is different from the current mangrove-dominated vegetation in this area. However, it should be borne in mind that the biodegradation of short chain fatty acids (> C₂₀) is more rapid than that of long chain fatty acids and this could significantly affect the distribution pattern of fatty acids in the peats. Thus, the potential of fatty acids as source-specific biomarkers appears to be limited by early biodegradation effects, and interpretations should be made cautiously (Pancost *et al.* 2002).

Sterols

Sterols with 27–29 carbon atoms are present in all plants and animals. Although many combinations of C₂₇–C₂₉ structural and optical isomers are theoretically possible, less than ten distinctively structured C₂₇–C₂₉ sterols comprise more than 90 % (by weight) of biological sterols (Huang & Meinschein 1979). C₂₇ and C₂₉ sterols are the most abundant sterols in plankton and marine invertebrates, whereas C₂₉ sterols are the predominant sterols in higher plants and animals (Killops & Killops 2005). However, some sterols are widely distributed in biological systems, which limits their value for assigning sources of organic matter in aquatic sediments (Volkman 1986).

Because a marine source for the suite of sterol compounds found in the outcropping peat upstream in the Siak can be excluded, a plant source must be assumed. We found C₂₇ sterols in the water hyacinth *Eichhornia crassipes*, which constitutes a large part of the floating aquatic biomass in the Siak and its tributaries. This species is, however, not peat-forming and hence another, as yet unidentified, plant must have contributed this sterol.

Although the pattern of occurrence of Compound 12 (stigmastanol) appears to give a clear signal that peat from upstream in the Siak is re-deposited in the estuary and on the Dumai coast, it is notable that the concentrations in re-deposited peat (around 100 and 250 $\mu\text{g g}^{-1}$ TOC in the Siak estuary and on the Dumai coast respectively) are 6–

17 times that in the upstream peat (around $15 \mu\text{g g}^{-1}$ TOC). The stanols have long been recognised as the microbial products of their corresponding sterols (in this case β -sitosterol) (Gaskell & Eglinton 1976, Nishimura 1977, Lehtonen & Ketola 1993) and an alternative source seems possible.

Triterpenoids

Triterpenoids are widespread in the plant kingdom where they occur free or as glycoconjugates, although their biological significance has not yet been fully clarified. They are closely related to sterols from a biosynthetic and structural point of view, but they cannot efficiently replace this compound class in biological systems such as membrane constituents or as precursors, for example, of insect hormones (Gülz 1994).

Unconjugated triterpenes are often found in the epicuticular waxes of plants where their main function is to prevent water loss and to constitute the first defensive barrier against bacteria, fungi or insects (Tulloch 1976). The diversity of structures is truly impressive, as several thousand different triterpenes with more than 80 different carbon skeletons have been identified (Breitmaier 1999).

Taraxerol is a well established biomarker for tracing organic matter derived from *Rhizophora* species in peats and marine sediments (Koch *et al.* 2003, Versteegh *et al.* 2004). In *Rhizophora mangle*, the amyryns are major components of the epicuticular wax of the leaves, whereas taraxerol is largely bound in the cutin fraction of the leaves (Frewin *et al.* 1993, Killops & Frewin 1994). Another mangrove species, *Avicennia germinans*, contains smaller amounts of β -amyryn and taraxerol (Killops & Frewin 1994). Most of the other compounds found in the present study have already been identified by Ghosh *et al.* (1985), although these authors found betulin only in *R. mucronata* whereas α - and β -amyryns were isolated from several mangroves including some species of *Rhizophora*.

Indications for river basin sediment dynamics

The data presented here suggest that peats eroded upstream may constitute a significant fraction of the particulate organic matter transported by the Siak and deposited in its estuary. Nevertheless, the geochemical evidence about the origin of transported peat is conflicting. While the *n*-alkane distribution suggests transport from Bengkalis into the estuary, the sterol and triterpenoid information indicate transport in the opposite direction. The latter would be in accord with remote sensing data

which show a general flow of the river plume northwards towards the Strait of Malakka (Siegel *et al.* 2009). Despite this, tidal currents may be responsible for upstream transport of peat eroded at Bengkalis Island, especially as a reversal of the surface flow reaching as far as Perawang (Figure 1) was regularly observed at incoming tides during fieldwork. In addition, only three mangrove species, albeit the dominant ones, have so far been analysed for the complete suite of constituents with biogeochemical importance; while data on peat forming forest plants are not yet available. Moge & Mansur (2000) report that a total of 131 species can be found in the peat swamp forest covering an area drained by the Siak Kecil, a small river discharging into the sea to the north of the Siak. Biological and chemical alterations of the original plant signals must also be taken into account. Thus, while the data at hand indicate two sources (one local and one upstream) for the eroded peats found in the Siak estuary and along the coastline of East Sumatra, further information is needed before the magnitudes of the individual contributions can be estimated.

Concluding remarks

The Siak estuary is an active mixing zone of organic matter of marine and terrestrial origins. The terrestrial input is not limited to the riverine runoff of dissolved organic matter. The active erosion of the Siak river shoreline contributes soil- and peat-derived organic matter which is transported and deposited in the estuary and on the surrounding coastline. Eroding mangrove peats at the coast of Bengkalis island and the coastline along Dumai are an additional source of terrestrial organic matter which is transported by tidal currents into the Selat Panjang and Strait of Malakka. The flux of this mangrove-derived organic matter into tidal creeks and the Siak estuary is ultimately important for coastal zooplankton and fish populations (Schwammborn *et al.* 1999), and thus for the local fishery. Our data also attest to the importance of recycled ancient organic material in the carbon cycle of this near-coastal environment.

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