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Soil Chemical Profiles Developed from Pyrite-containing Sediments under Banjarese Agricultural Practices in South Kalimantan

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Abstract

The reclamation of brackish sediments for agriculture involves the danger that pyrite minerals present in the deposits will be oxidized and produce unfavorable conditions for plant growth. Pyrite minerals are oxidized when the swamp is reclaimed by forest cutting, canal excavation and destruction of the peat cover.

In South Kalimantan, Banjarese people cultivate rice using a technique adapted to soils that originate from pyrite-containing sediments, especially where non-acidic water for flushing the toxic materials is available. However, the agricultural land in areas with pyrite-containing sediments is a fragile system. Even the productive rice plots are constantly threatened by the sudden collapse of the delicate balance.

To understand the effect of the Banjarese rice cultural practice on soil conditions in areas with pyrite-containing sediments, land use and water management practices were observed in the field, and eight auger samples were taken for laboratory analyses.

The results show that intensive leaching of the pyrite-containing sediments leads to the development of a specific soil chemical profile comprising an oxidized horizon, an acid-accumulating horizon, and a reduced horizon. This paper presents details of soil development processes and soil management problems.

I Introduction

The conversion of peat swamp forests to agricultural lands in South Kalimantan began around 1920 in the area between Banjarmasin and Martapura. Peasants from the upper villages who worked as laborers on construction of the Ulin road linking Banjarmasin with Martapura began to plant rice on both sides of the land that had been cleared. It became known that, drained of the toxic water deriving from the peat, the wetlands provided good agricultural land. The peasants planted rubber, coconut palms, and rice on the drained swampy area, but after several years rice became the most important agricultural commodity of the swampy areas [Furukawa 1994].

The success of the agricultural plots in the Martapura-Banjarmasin area prompted more

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peasants from the upper villages and also the Dutch government to open agricultural plots in swampy areas. Peasants from upper villages opened the swampy land on both sides of the Barito river. The Dutch government prompted these activities by constructing canals across the Pulau Petak delta, and it made several colony sites in the area. After independence, the Indonesian government was also interested in reclaiming the flat swampy areas of South Kalimantan for paddy fields, and it established several transmigration sites in the Pulau Petak area from 1970.

As a result of these activities, the natural peat swamp forest disappeared from the swampy lands of South Kalimantan, and most of the thick peat layers also disappeared. However, thin peat layers can still be found scattered on the small uncultivated areas. The agricultural lands in the Martapura-Banjarmasin area have become a stable rice-producing area. However, the condition of agricultural lands on the northern Alalak river and the Pulau Petak delta is uncertain. Although some plots are still productive, many have been abandoned and are occupied by *gelam* (*Melaleuca leucadendron*) and reeds (*Eleocharis sp.*).

Studies of the depositional environments clearly showed that the clay sediments in the swampy area of the northern Alalak river and Pulau Petak delta developed under a brackish swamp environment, while the clay sediments in swampy areas of Martapura-Banjarmasin developed under a freshwater swamp environment [Sumawinata 1998]. The brackish sediments usually contain a lot of pyrite minerals, and although the pyrite-containing sediments do not cause problems as long as they are wet and in a reduced state, they dry out and release sulfuric acid when the drainage channels for land reclamation are made slightly too deep. The soil pH then drops to as low as 2. Under these conditions any crops are difficult to grow.

Several means have been studied for improving the acid sulfate soils, such as addition of lime and fertilizer, and leaching. However, the results of experimental studies are sometimes inapplicable under field conditions. The amelioration of acid sulfate soils usually needs the addition of huge amounts of lime, rock phosphate, and other fertilizers. The results of experimental leaching studies by Ponnamperuma *et al.* [1973] and Breemen [1976] are also far from applicable to the field conditions. These studies were carried out in small, homogenized samples or in small pots where the percolation pattern and soil physical properties were greatly modified as compared to the real field conditions.

It is interesting to study the impact of Banjarese rice cultural practice on soil conditions. The Banjarese cultivate rice on soils that originate from pyrite-containing sediments, especially where non-acidic water for flushing of toxic materials is available. The sources of water may be either rivers or tide-affected canals, or rain water stored in the peat layers under secondary forests near the plots. The water management of Banjarese rice cultural practice can be summarized as follows: acidity is flushed out during the early rainy season, and the plots are kept in a reduced condition by closing the simple water gates of the *handil* (drainage channels) until the end of the vegetative stage of growth; then the plots are dried out from the generative stage of growth to the harvesting period [Sumawinata 1992].

This paper will discuss the effect of Banjarese agricultural practice on the chemical characteristics of soils derived from brackish sediments.

II Material and Methods

The study sites are located in swampy areas in the Pindahan Baru area and the Pulau Petak delta. The clay sediments underlying the peat layers were found to have developed under brackish swamp environments. Field observation and soil sampling were done at the end of the rainy season in March-April 1989. The location of the studied area and the soil observation sites are presented in Fig. 1.

To understand the effect of Banjarese agricultural practice on the soil characteristics, soils profiles were observed in water-reservoir forest, productive rice plots, and abandoned rice plots. For comparison, plots in the same area where the Banjarese rice cultural practice was not employed, such as upland plots, were also observed. During the field observation, all the studied plots except the upland plots in the Tarantang area were under continuous inundation by 20 to 40 cm of water. Soil samples from eight observation sites were taken for laboratory analyses. The water condition and land use at each observation site are presented in Table 1.

Since the purpose of this study is to understand the soil characteristics and the changes in soil profile which develop under the Banjarese rice cultural practice, soil samples for laboratory analyses were taken at definite depths, following a layering pattern. The chemical characteristics analysed were: soil pH, soil pH after treatment with hydrogen peroxide (pHox), electrical conductivity (EC) of soil paste (soil : water 1 : 5), exchangeable bases extracted with 1 N NH_4OAc (pH 7), cation exchange capacity (CEC) by the USDA method using 1 N NH_4OAc (pH 7), and total sulfur by the Begheijn method [1980].

III Results and Discussion

A. *Site Descriptions and Soil Characteristics*

1. *Water-reservoir Areas*

a. *Karya Tani Area*

Site BM 27 is located at the center of a water-reservoir area in Karya Tani village. The land is covered by *gelam* (*Melaleuca leucadendron*) and ferns, and there are no canals crossing this forest. The canals supplying water to the paddy fields start at the margin of the forest. The soil surface is still covered by peat, although this is shallower than in primary peat swamp forest. The lower parts of the peat layer remain wet even at times of severe drought, when forest fires are frequent.

The depositional environments of Karya Tani area are discussed in detail in a separate paper, and the soil morphology is summarized in Fig. 2. The mineral soil layers are unripe, and the soil color through the profile is dark gray (5Y4/1). The soil is considered to be minimally developed or undeveloped.

The soil chemical data are presented in Table 2. The chemical characteristics are closely

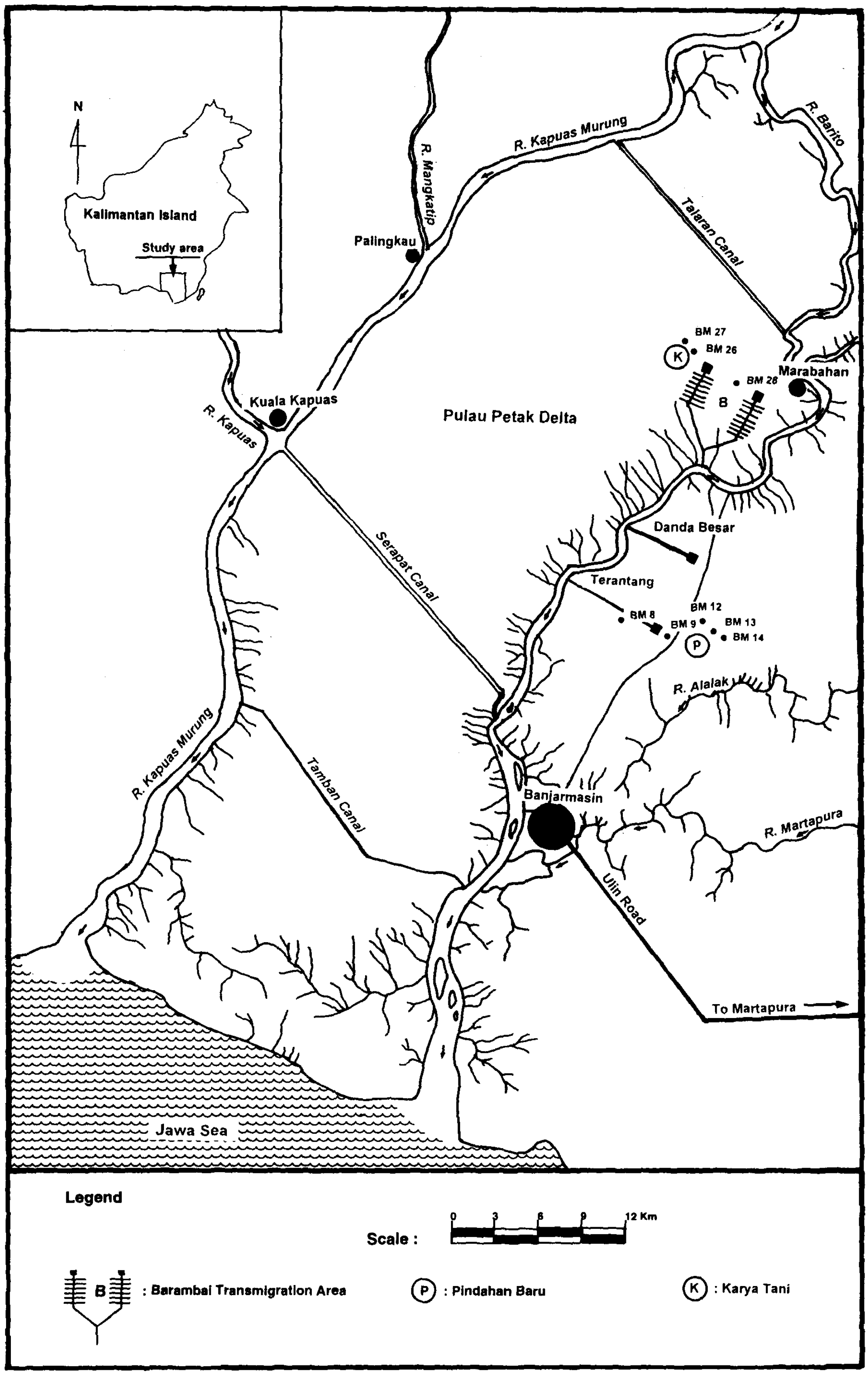


Fig. 1 Location of the Sites Studied and the Soil Observation Sites

Table 1 Land Use and Annual Water Condition of the Study Sites

No.	Land Use	Location	Water Condition*	Site No.
1	Forest as a water reservoir	Karya Tani	Water saturated	BM 27
		Pindahan Baru	Seasonally dried**	BM 9
2	Productive rice plots	Karya Tani	Seasonally dried	BM 26
		Pindahan Baru	Seasonally dried	BM 12
3	Abandoned rice plots	Pindahan Baru	Seasonally dried	BM 14, BM 13
		Barambai	Seasonally dried	BM 28
4	Upland plots	Tarantang	Never inundated	BM 8

* water condition in the root zone

** only dried during very long dry seasons

related with the four types of depositional environment found: peat swamp, mangrove swamp, mangrove marsh, and transitional mangrove marsh to mangrove swamp (transitional mangrove swamp). The mangrove marsh, mangrove swamp, and transitional mangrove swamp environments belong to brackish swamp environments. The peat swamp deposits are characterized by high CEC and high exchangeable Ca content, which in the case of BM 27/1 are 40.49 and 25.20 me/100g, respectively. The mangrove swamp is characterized by high content of total sulfur, which in the case of BM 27/3-4 varies from 2.02 to 2.23%. The transitional mangrove swamp deposits are characterized by moderate content of total sulfur and high exchangeable cation content: in the case of BM 27/5-6, the exchangeable Na, K, Ca, and Mg are 2.02-3.23, 0.34-0.39, 8.93-4.31, 14.51-14.04 me/100g, respectively, and total sulfur is 0.85-0.95%. The mangrove marsh deposits are characterized by low content of total sulfur: in the case of BM 28/7, the total sulfur is only 0.69%.

b. *Pindahan Baru Area*

Site BM 9 is located at the center of the water reservoir area in Pindahan Baru village. The water reservoir area is covered by *gelam* and ferns. Field observation and information supplied by informants confirmed that the land use history of the water reservoir of Pindahan Baru is different from that of Karya Tani. The water-reservoir forest area of Karya Tani has never been used for agriculture, and the secondary *gelam* forest has developed on devastated peat swamp after fires gutted the peat swamp forest during the long droughts of 1982-1983. The water-reservoir forest of Pindahan Baru, however, was formerly cultivated and later abandoned. During field observation we found many ditches crossing this *gelam* forest, confirming that the area had formerly been used for agriculture.

The depositional environments and soil morphology of the Pindahan Baru area are summarized in Fig. 3. Profile BM 9 shows a succession of depositional environments from transitional mangrove swamp to mangrove swamp and finally to peat swamp environments. In contrast to the Karya Tani area, the soil profile of BM 9 shows soil-forming features to some degree. The mangrove swamp deposits have differentiated into two distinct soil layers. The upper layer (Fig. 3) is characterized by brown (10YR5/3), half-ripe clay soil, while the lower

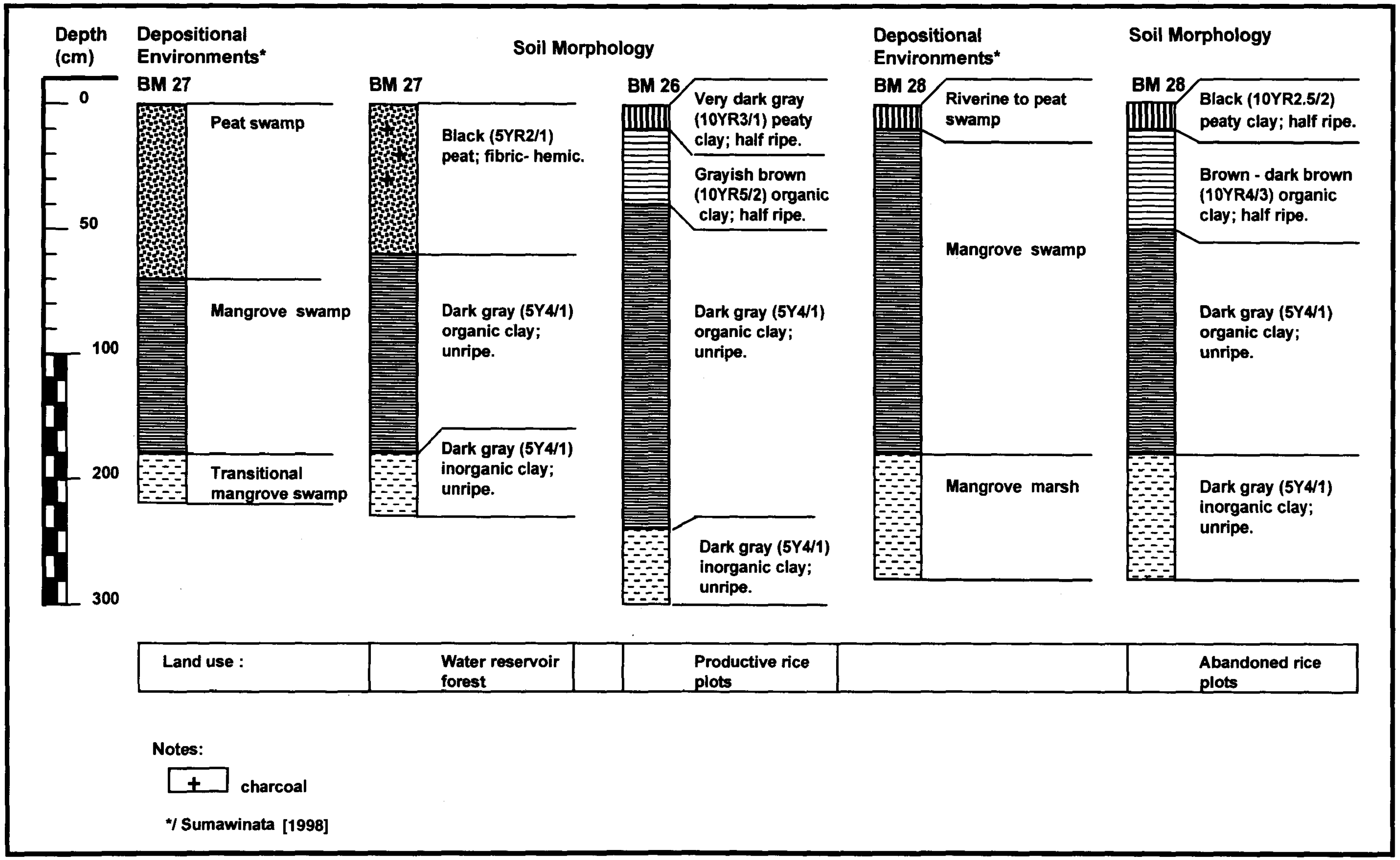


Fig. 2 Depositional Environments and Soil Morphology of the Study Sites in Karya Tani-Barambai

Table 2 Soil Chemical Characteristics and Depositional Environments of the Sites in Karya Tani-Barambai

Sample No.	Depth*	EC	pH	pHox	Exchangeable Cations				CEC	S Total	E**
					Na	K	Ca	Mg			
	(cm)	(µmhos/cm)			(............... me/100 g				...............)	(%)	
BM 27/1	20	140	6.20	2.40	0.73	0.18	25.20	1.97	40.49	-	P
BM 27/2	70	2,400	3.00	1.10	0.71	0.29	7.72	7.84	25.25	1.41	M
BM 27/3	120	1,600	3.70	1.40	1.11	0.26	9.58	12.44	31.17	2.02	M
BM 27/4	160	1,000	5.30	2.30	1.55	0.27	8.77	14.04	23.11	2.23	M
BM 27/5	190	1,200	5.60	2.10	2.02	0.34	8.93	14.51	24.20	0.85	T
BM 27/6	220	500	5.60	3.40	3.23	0.39	4.31	14.04	22.90	0.95	T
BM 26/1	0	260	5.40	1.90	0.75	0.39	11.14	2.77	45.37	0.37	-
BM 26/2	20	180	5.30	2.40	0.54	0.34	9.09	2.11	22.04	0.18	M
BM 26/3	70	1,000	3.00	1.40	0.18	0.05	2.26	7.37	17.66	3.03	M
BM 26/4	125	2,200	3.40	1.40	1.47	0.32	5.13	13.66	23.76	1.62	M
BM 26/5	220	1,800	5.40	2.90	2.66	0.40	7.26	14.98	20.01	1.35	M
BM 28/1	0	240	4.30	1.80	0.34	0.17	8.42	0.89	50.50	0.46	R/P
BM 28/2	20	180	4.40	2.10	0.30	0.25	8.41	1.26	22.36	0.18	M
BM 28/3	70	1,800	3.50	1.40	0.73	0.29	6.80	8.31	21.83	1.96	M
BM 28/4	120	2,000	3.70	1.90	3.53	0.41	5.67	14.70	22.36	0.81	M
BM 28/5	150	1,800	4.70	1.80	3.53	0.51	9.77	20.52	25.15	1.77	M
BM 28/6	190	1,200	6.10	3.10	3.45	0.44	5.47	16.11	21.83	0.75	-
BM 28/7	220	760	6.20	4.00	3.03	0.69	5.67	15.45	19.05	0.69	MM

Notes:

* The thickness of soil samples is about 4 cm.

** Depositional environments adopted from Sumawinata [1998]

P: Peat swamp R/P: Riverine to peat swamp M: Mangrove swamp

T: Transitional mangrove swamp MM: Mangrove marsh

layer consists of dark gray (5Y4/1), unripe soils. The brown coloration in the half-ripe soil layer confirms that the mangrove swamp deposits were affected by soil development processes when the former swamp forest was cleared and reclaimed for crop production. The drying of the deposits is considered to be an agent in the change from the dark gray, unripe clay to brown, half-ripe soils; drying leads to the oxidation of ferrous iron compounds to ferric iron compounds. The brown layers of the mangrove swamp deposits represent the initial phase of ripening to form an oxidized horizon, while lower unripe clay layers are still in an anaerobic or reduced state. The oxidized horizon of BM 9 is found at the depth of 0-60 cm, overlying the reduced horizon.

Although the soil morphology of BM 9 shows that parts of the mangrove swamp deposits have been oxidized, a parallel change in soil chemical properties such as leaching or accumulation of the elements is not detected so clearly. However, compared to BM 27 and the oxidized horizon of BM 9, the laboratory results (Table 3) of the upper part of the reduced horizon of mangrove swamp deposits (layer no BM 9/4) show sharp decreases in pH value and

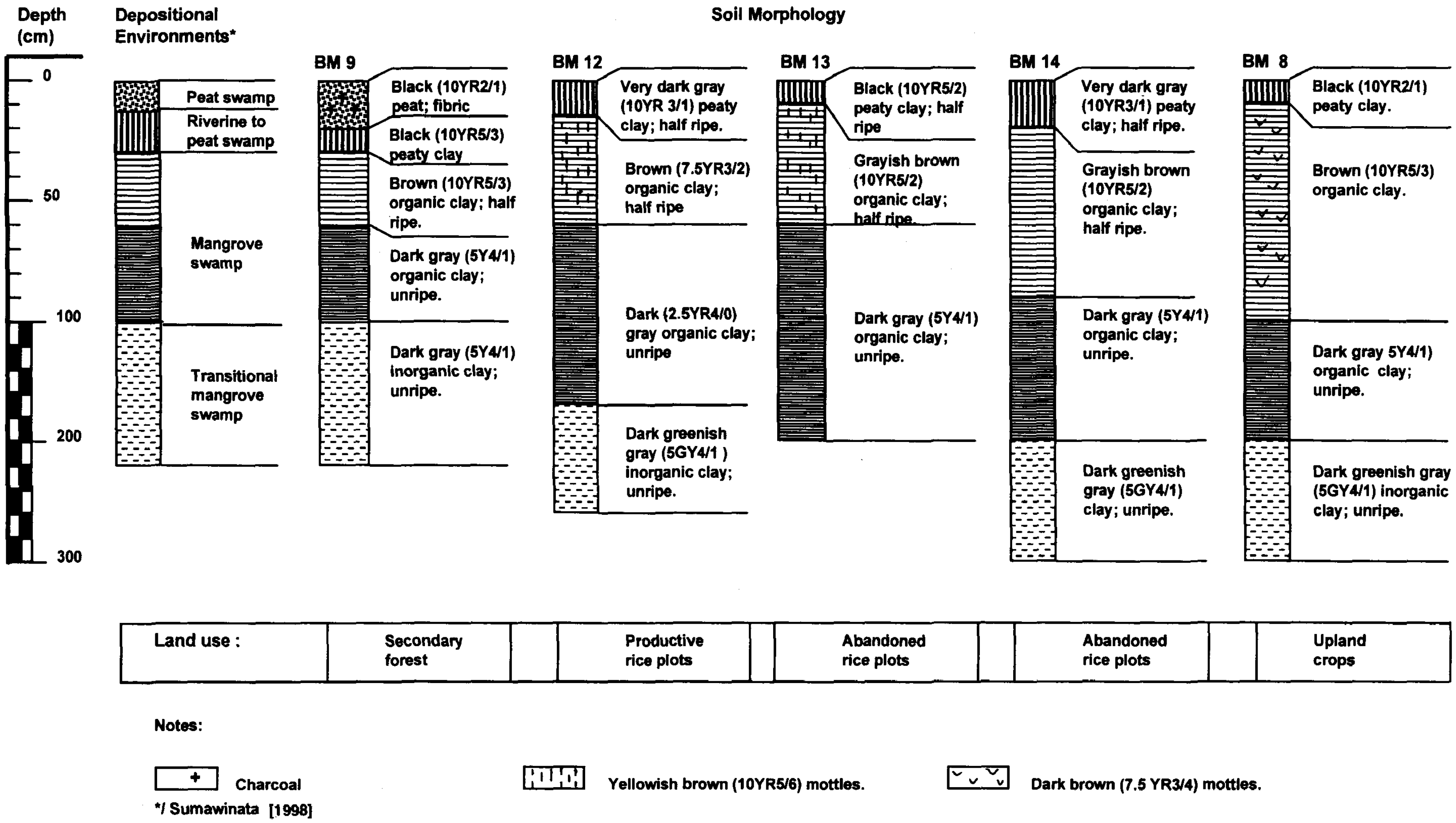


Fig. 3 Depositional Environments and Soil Morphology of the Study Sites in Pindahan Baru

Table 3 Soil Chemical Characteristics and Depositional Environments of the Sites Studied around Pindahan Baru

Sample No.	Depth* (cm)	EC (μmhos/cm)	pH	pHox	Exchangeable Cations				CEC	S Total (%)	E**
					Na	K	Ca	Mg			
					(............... me/100 g ....)						
BM 9/1	10	600	5.70	3.60	0.17	0.20	12.00	0.35	37.50	0.68	R/P
BM 9/2	20	340	4.70	2.20	0.17	0.18	8.00	0.48	23.65	0.22	R/P
BM 9/3	40	670	4.20	1.40	0.35	0.23	6.25	1.46	32.01	1.40	M
BM 9/4	70	4,600	2.40	1.10	0.09	0.02	0.83	3.88	24.42	2.07	M
BM 9/5	130	1,200	5.80	3.20	3.29	0.56	4.97	14.65	27.28	0.86	T
BM 9/6	170	1,400	5.80	3.00	4.55	0.69	4.61	14.41	27.72	0.82	T
BM 9/7	220	2,400	5.20	2.50	5.51	0.80	10.27	18.38	26.93	1.00	-
BM 12/1	5	190	4.20	2.90	0.21	0.24	3.40	0.65	20.38	0.22	-
BM 12/2	20	300	3.90	3.00	0.18	0.24	3.09	0.67	20.54	0.16	M
BM 12/3	80	5,200	2.40	1.50	0.04	0.01	0.38	3.20	18.54	5.17	M
BM 12/4	130	3,000	3.80	1.90	2.07	0.19	8.74	20.18	24.75	3.65	M
BM 12/5	170	2,000	5.00	2.50	3.71	0.46	8.82	16.96	24.42	1.67	M
BM 13/1	0	490	4.80	3.10	0.54	0.27	6.48	1.81	19.49	0.37	-
BM 13/2	30	160	4.80	3.00	0.25	0.21	4.18	1.60	19.40	0.18	M
BM 13/3	80	7,000	2.30	1.30	0.09	0.01	0.65	6.50	23.33	4.89	M
BM 13/4	130	2,400	3.70	1.90	2.38	0.35	3.70	14.65	24.42	1.67	M
BM 13/5	180	2,400	4.20	2.00	3.44	0.45	4.89	18.60	28.86	1.67	M
BM 14/1	10	720	4.30	2.70	0.80	0.14	4.00	2.12	20.65	0.25	-
BM 14/2	30	920	4.00	2.90	0.99	0.26	3.33	2.43	18.87	0.23	M
BM 14/3	60	1,500	3.50	3.10	1.51	0.27	2.85	3.87	21.98	0.29	M
BM 14/4	90	4,700	2.70	1.40	0.12	0.01	0.92	6.86	21.09	4.64	M
BM 14/5	130	3,800	3.20	1.50	2.09	0.13	4.99	22.85	25.20	2.88	M
BM 14/6	170	2,100	5.50	2.10	6.35	0.72	7.54	19.31	25.54	2.64	M
BM 8/1	0	180	4.40	2.20	0.10	0.35	0.77	0.56	23.63	0.14	M
BM 8/2	10	120	4.40	2.60	0.17	0.20	0.60	0.70	18.48	0.14	M
BM 8/3	30	140	4.10	3.10	0.14	0.24	0.35	0.35	18.53	0.14	M
BM 8/4	70	180	4.10	2.70	0.17	0.28	0.54	0.61	20.49	0.13	M
BM 8/5	90	200	4.10	3.00	0.16	0.25	0.70	0.49	18.92	0.14	M
BM 8/6	120	3,600	3.00	1.40	0.23	0.04	1.67	12.35	21.45	4.72	M
BM 8/7	170	3,200	3.30	1.50	1.48	0.18	4.79	17.78	21.98	1.92	M
BM 8/8	220	2,400	4.20	2.00	3.31	0.46	7.84	18.55	23.17	1.15	T

Notes:

* The thickness of soil samples is about 4 cm.

** Depositional environments adopted from Sumawinata [1998]

R/P: Riverine to peat swamp M: Mangrove swamp T: Transitional mangrove swamp exchangeable Na, K, and Ca.

These characteristics are considered to indicate that oxidation and leaching have proceeded to a considerable degree, and soil-forming processes have begun.

2. *Productive Rice Plots Area*

a. *Karya Tani Area*

Site BM 26 is located in the productive rice plots of Karya Tani village. The land, which was cleared around 1972, is not affected by tidal or river flooding. All the farmers of this area still follow the Banjarese rice cultural practice, which was reported by Sumawinata [1992]. The Banjarese rice cultural practice on land with pyritic sediments usually needs non-acidic water for flushing away toxic materials that are released during the dry season.

The soil morphology and the depositional environments of the Karya Tani area presented in Fig. 2 show that below the thin peat layer (peaty clay layer) is a clay layer rich in plant remains (organic clay) that is grayish brown (10YR5/2-4/3) and half-ripe, and below that is a dark brown (5Y4/1) layer in unripe condition. Since BM 26, BM 27, and BM 28 are located very near to each other, the organic clay deposits of these profiles can be considered identical mangrove swamp deposits. However, in contrast to BM 27, which is largely intact, BM 26 and BM 28 have developed a grayish brown layer, i.e., a slightly oxidized horizon. The oxidized horizon of BM 26 is found at the depth of 0-40 cm overlying the reduced horizon.

The soil chemical data in Table 2 show that the sulfur content of the oxidized horizon (BM 26/2) is much lower than that of the deposits under the reduced horizon (BM 26/3-4): 0.18% vs. 3.03-1.62%. This difference may be partly attributable to an original difference, but part is also due to the oxidation of pyrite and the leaching of sulfate as a result of the Banjarese agricultural practice.

It is interesting that the total sulfur content increases sharply again in the upper part of the reduced horizon (BM 26/3). The total sulfur content of the upper part of the reduced horizon reaches 3.03%, while that of the lower reduced horizon (BM 26/4) is only 1.62%. However, the soil pH and exchangeable cations of the upper layer (BM 26/3) are much lower than those of the lower layer (BM 26/4) (Table 2). In view of the homogenous morphology through the organic clay layer, it is probable that this sharp difference in chemical constituents has largely been generated by the water management of Banjarese rice culture. It seems probable that the leaching of sulfuric acid takes place in the oxidized layer (BM 26/2) and its accumulation takes place in the upper part of reduced layer (BM 26/3). The characteristics of the accumulation layer are high total sulfur content and very low exchangeable cations content. The data strongly suggest that the pyrite oxidation products, which are high in acidity and sulfate ions, are leached out from the oxidized horizon and accumulated in the lower horizon. The hydrogen ions in soil solution then replace the cations in the exchange sites, resulting in the very low exchangeable cation content.

b. *Pindahan Baru Area*

As in the Karya Tani area, the Pindahan Baru area is not affected by tidal or river flooding. Here, too, flushing water is sought in the rainwater accumulated in the peat of the secondary forest. The availability of non-toxic water is very important for rice cultivation on the land with pyritic sediments. It is important not only to keep the plots continually wet, but also to flush away toxic materials that develop during dry periods.

According to informants, the first rice plots in this area were opened in around 1934. These plots were used for a few years, then abandoned when the soils became very acidic and the harvests declined sharply. After the government completed the canalization project in this area around 1960, this area again began to be used for rice cultivation.

BM 12 is the site of the productive rice plots in Pindahan Baru area. As in the rice plots of Karya Tani area (BM 26), the soil morphology of BM 12 also shows an oxidized horizon and a reduced horizon. The oxidized horizon is found at the depth of 0-60 cm, while the reduced horizon is found below (Fig. 3). The oxidized horizon is brown, half-ripe clay.

The soil chemical data of BM 12 (Table 3) show that the sulfur content and the exchangeable cations are much lower in the oxidized horizon (BM 12/2) than the reduced horizon (BM 12/4). The third horizon (BM 12/3) shows high content of total sulfur (5.17%), low soil pH (2.4), and low exchangeable cations content: Na, K, Ca, and Mg being 0.04, 0.01, 0.38, and 3.20 me/100g, respectively. This horizon is an acid-accumulating horizon, similar to BM 26/3.

3. *Abandoned Plots*

a. *Barambai Area*

An abandoned plot in the Barambai transmigration area was studied for comparison. This transmigration area was reclaimed in around 1972. The canal systems were designed and installed completely by government. Transmigrants from Jawa and Bali islands came in to cultivate rice on the former peat swamp forest. The agricultural plots opened in this area were not affected by tidal or river flooding. Since the canal systems were very different from the Banjarese system, in size and designed purpose, the farmers did not follow the Banjarese rice cultural practice. There was no water reservoir forest for flushing away toxic materials formed during dry periods. After the soils became very acidic, rice could no longer be planted, and *purun kudung* (*Eleocharis sp.*) began to appear in the plots. According to the informants, the rice plots were cultivated for about 5 to 10 years, then abandoned when the harvests decreased severely. This implies that the leaching processes may not be as intensive when the Banjarese rice cultural practice is observed.

The soil profile of BM 28, which represents an abandoned area, is presented in Fig. 2. It shows the riverine to peat swamp deposits resting on peaty clay layers. Brown to dark brown (10YR4/3), half-ripe organic clay and dark gray (5Y4/1), unripe organic layers are thought to have been deposited under mangrove swamp environments. The brown, half-ripe clay layer at the depth of 0-50 cm is an oxidized horizon, and the dark gray, unripe clay layer below is a reduced horizon.

The chemical data presented in Table 2 show that the sulfur and exchangeable cations content become minimal in the oxidized horizon of mangrove swamp deposits (BM 28/2). The third horizon may be an acid-accumulating horizon. The sulfur content is the maximal in this horizon, but differences are found from the accumulating horizons in other profiles, which were characterized by minimum pH and exchangeable cations content. In the case of BM 28, the minimum value of soil pH and exchangeable cations content do not coincide with the acid-accumulating horizon. The oxidation and leaching processes of pyrite at this site are considered less intensive than in the plots under the Banjarese rice cultural practice. This is probably because the farmers abandoned their plots when the harvests failed due to the appearance of severe acidity. Ultimately, this failure was due to the fact that farmers could not follow fully the Banjarese rice cultural practice.

b. *Pindahan Baru*

Sites BM 13 and BM 14 are located in abandoned plots of Pindahan Baru village. As mentioned, the rice plots in the Pindahan Baru area were started again from around 1960. The abandoned plots of BM 13 are covered by a reed called *purun kudung* (*Eleocharis sp.*), while the abandoned plots of BM 14 are covered by dense *gelam* (*Melaleuca leucadendron*) trees, of around 10 cm in diameter. Since site BM 14 is covered by *gelam* trees, it has presumably been abandoned longer than site BM 13. The former canal system still can be found in the abandoned area, but because of the dense *purun kudung* and *gelam* standing in the ditches, they do not work well for draining the toxic water.

The soil morphology of BM 13 and BM 14 is presented in Fig. 3. BM 13, BM 14, BM 12, BM 8, and BM 9 are located very near each other, and the depositional environments of BM 9 are thought to be identical to those of sites BM 13 and BM 14. The organic clay layers of BM 9, BM 13, and BM 14 are considered to have deposited under mangrove swamp environments. Grayish brown (10YR 5/2), half-ripe organic clay, which represents the oxidized horizon, is found at the depth of 0-60 cm at site BM 13, and at the depth of 0-85 cm at BM 14.

The soil chemical data of the abandoned plots under the Banjarese rice cultural practice (BM 13 and BM 14) are different from those of the abandoned plot under the governmental system (BM 28). As noted before, the soil chemical data of BM 28 show lower degrees of oxidation and leaching. However, the soil chemical data of the abandoned plots under Banjarese rice cultural practice (BM 13 and BM 14) clearly show the effects of oxidation, leaching, and acid-accumulation (Table 3). The sulfur and exchangeable cation contents of the oxidized horizon (BM 13/2, BM 14/2-3) are much lower than those of the reduced horizons other than the acid-accumulating horizon (BM 13/4-5, BM 14/5-6). The acid-accumulating horizon (BM 13/3, BM 14/3) shows high sulfur and low exchangeable cation contents. These characteristics are similar to the soil characteristics of BM 12 and BM 26 at the sites of productive rice fields.

4. *Upland Plots*

Change in the soil characteristics of an upland plot were studied at site BM 8. This site is located near the primary canal of the Terantang transmigration area, which was reclaimed by the government in around 1980 (Fig. 1). The primary canal is about 8-10 meters wide and about 2-3 meters deep. River water does not inundate the area, and the plots are never inundated with rain water even during the rainy season, since BM 8 is not far from the primary canal. The farmers at this site usually plant upland rice or corn during the rainy season, like farmers in an upland area. During field observation, the rice and corn plants in the plots were seen to be in very poor condition.

Since BM 9 and BM 8 are located very near to each other, the brown (10YR5/3) organic clay and dark gray (5Y4/1) organic clay were assumed to have developed under mangrove swamp environments. The brown organic clay layer is an oxidized horizon, while the dark gray organic clay layer is a reduced horizon. The oxidized horizon of BM 8 is very deep, reaching a depth of 105 cm, while the reduced horizon is found below.

The chemical data presented in Table 3 show that the oxidized horizons of mangrove swamp deposits (BM 8/1-5) have very low content of total sulfur (0.13-0.14%) and exchangeable cations: Na, K, Ca, and Mg ranged 0.10-0.17, 0.20-0.35, 0.35-0.77, and 0.35-0.70 me/100g, respectively. The acid-accumulating horizon (BM 8/6) shows very high sulfur content of 4.72%. The exchangeable cation content of the acid-accumulating layers was also much lower than that of the reduced layer (BM 8/7).

B. *Soil Profile and Processes: A Hypothesis on Sulfate-mediated Morphology*

The morphology and chemical characteristics of the studied soils (Figs. 2 and 3) show that the land use has a large impact on the soil development. Under natural conditions, mangrove swamp deposits are dark gray (5Y4/1). Under cultivated plots, however, the mangrove swamp deposits develop into two groups. The first consists of brown layers, and the second of dark gray layers (5Y4/1). Since the brown layers are thought to have developed under oxidizing conditions, these layers are termed an oxidized horizon. The thickness of the oxidized horizon at each site is controlled by the depth of canals or ditches and the distance of the site from the canal systems. Figs. 2 and 3 show that the thickness of the oxidized horizon of the plots with the Banjarese drainage system varies from 40 to 60 cm, while in the governmental systems it varies from 50 (site BM 28) to 105 cm (site BM 8).

The presence of the oxidized horizon or brown layer in the upper part of mangrove swamp deposits is not only found in the studied sites. All of the soil samples from rice plots and abandoned rice plots along a transect from the south to the north of the Pulau Petak delta affirm the presence of oxidized layers overlying the dark gray clay layers [Sabiham 1988]. Diemont *et al.* [1993] also showed the presence of the brown layers underneath the ombrogenous peat of South Kalimantan. They confirmed that the brown layers found on the top of pyritic material were low in iron oxides. They interpreted the iron depletion of the brown layers to be due to gleying in the freshwater floodplains.

The present study has shown clearly that the brown layers and dark gray layers are deposits formed under mangrove swamp environments. In the reclamation process, brown horizons develop in the upper part of the mangrove swamp deposits. All brown layers show a depletion of the cations and sulfur (Tables 2 and 3). The depletion of iron, sulfur, and cations in the brown layers is considered to be a result of soil oxidation and soil acidification that are directly followed by leaching. This process is accelerated particularly by Banjarese farmers who practice intensified water management.

The data of the chemical analyses (Tables 2 and 3) show that most horizons located on the upper part of a reduced horizon, are low in exchangeable K, Na, and Ca, but high in sulfur content. These horizons are considered to represent acid-accumulating horizons, in other words, horizons where acid and sulfur compounds leached from the oxidized layers accumulate. It is considered that, in the acid-accumulating horizons, sulfate ions and ferric ions will be reduced, and ferrous sulfide compounds will be formed.

The acid-accumulating horizons are difficult to detect under field conditions. The pH values of the soil samples of the sites studied under field conditions varied in the range of 4-6. Because of this, the thickness of the acid-accumulating horizon can not be determined clearly in the field; but chemical analyses show that samples taken up to 30 cm below the boundary layer between oxidized and reduced horizons still show the results of acid-accumulating processes (Table 4). The presence of the acid-accumulating horizon can be predicted by observing the presence of yellow mottles developed below the boundary between oxidized and reduced horizons of the incubated auger samples. Such mottles are present in greater numbers in the samples that are predicted to represent an acid-accumulating horizon. The yellow mottles are developed through the oxidation of pyrite. The X-ray diffraction patterns of the yellow mottles confirm that they are natrojarosite minerals [Sabiham and Sumawinata 1989].

Many soil scientists have reported on the unique characteristics of the acid sulfate soils of South Kalimantan, particularly the absence of jarosite minerals [Diemont *et al.* 1993; Sutrisno *et al.* 1990]. In many parts of the world, the presence of jarosite minerals is taken as an indicator

Table 4 Depths of Boundary Layers between Oxidized and Reduced Horizons, and Samples Still Showing Evidence of Acid-accumulation Processes

Site No.	Depth of Boundary Layer between Oxidized and Reduced Horizons (cm)	Depth of Samples Showing Evidence of Acid-accumulation (cm)	Difference (cm)
BM 8	105	120	15
BM 9	60	70	10
BM 12	60	80	20
BM 13	60	80	20
BM 14	85	90	5
BM 26	40	70	30
BM 27	0	-	-

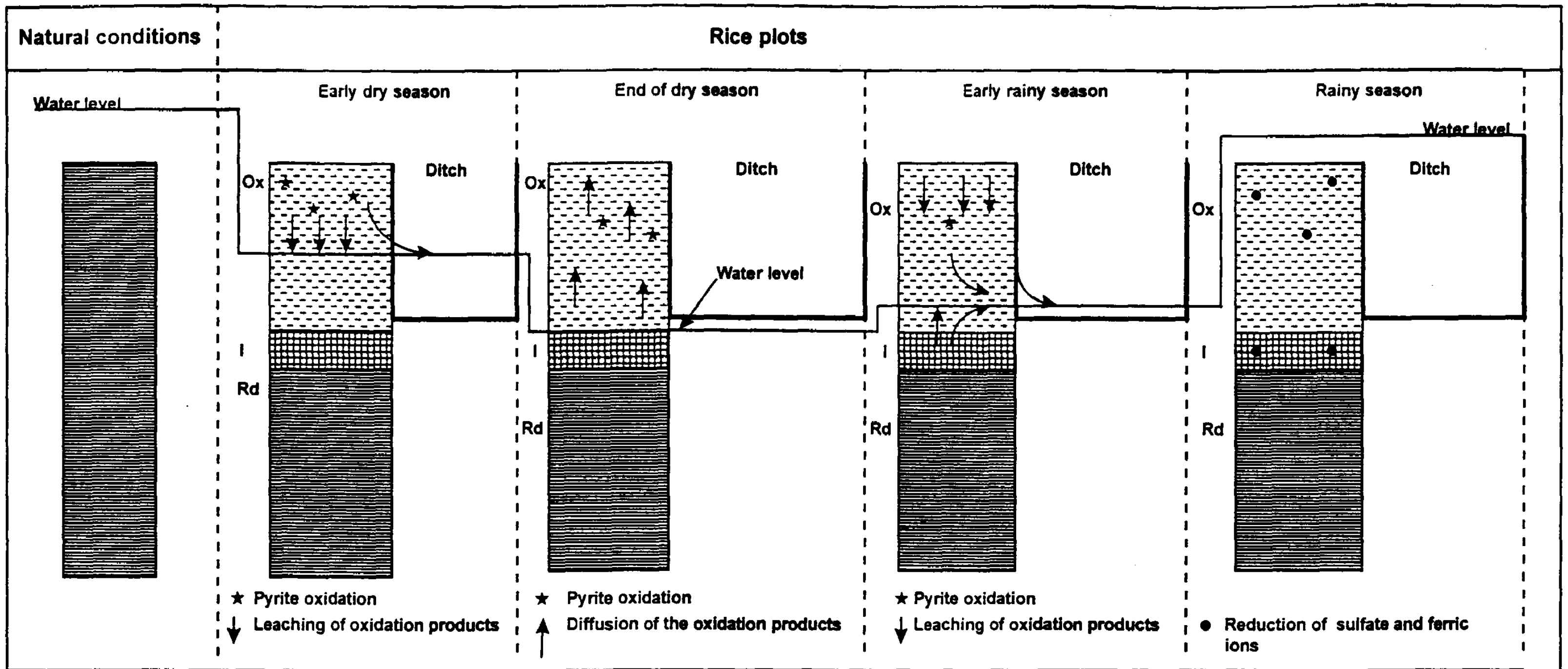
of acid sulfate soils; and the absence of the jarosite in the acid sulfate soil profiles of South Kalimantan has been suggested to due to the humid tropic conditions.

In addition to climatic conditions, the mode of water management adopted in agricultural plots is expected to play an important role in soil development. The difference in the thickness of the oxidized horizon (Figs. 2 and 3) is due to the effect of different water management regimes in lowland soil development. The most important reactions in lowland soil development process such as oxidation, leaching, accumulation, and the reduction processes, depend on water table fluctuation. The water table in the reclaimed plots is controlled by water management systems. As discussed by Sumawinata [1992], the Banjarese rice cultural practice and water management are closely related to the seasons. During the early dry season, the rice plants on the plots reach the generative stage. Drying the plots is then begun by opening the water gates on the ditches. Drying of the solum proceeds to a considerable degree. When the rainy season comes, the first step in land preparation is to remove acidity from the soil. The water gates in the ditches are kept open until the peak of the rainy season, then they are closed. The land is then prepared for planting, and finally the rice seedlings are transplanted. The effects of the Banjarese system on the soil chemical processes are summarized in Fig. 4.

The sequence of soil profile development processes under the Banjarese agricultural practice is considered to be as follows. When the water gates in the ditches or *handil* are opened in the early dry season, the water table falls. The soils above the water table will be in an oxidized state, and the remaining pyrites minerals will be oxidized at this time. The chemical and biochemical oxidation of pyrite will release SO_4^{2-}, H^+, and Fe^{3+} ions (reaction 1 in Fig. 5). These pyrite oxidation products make the soil solution strongly acidic. Such a change in the cation composition in the soil solution causes a change in that on the soil adsorption complex. The H^+ ions from the soil solution causes a change in that on the soil adsorption complex. The H^+ ions from the soil solution will replace the cations on the exchange sites, and the cations in the adsorption complex will be released into the soil solution. This process is called soil acidification (reaction 2, Fig. 5). The pyrite oxidation and soil acidification processes result in strongly acidic soil which has low exchangeable bases, and the soil solution becomes strongly acidic, high in sulfate and hydrous ferric oxide compounds (reaction 3, Fig. 5).

The cations and sulfate ions in the soil solution are highly mobile. They can move downward through the oxidized horizon and leach out from the soil to a drainage system, depending on the water table conditions. Since the rain still falls and the water table is still higher than the ditch surface in the late rainy season or early dry season, it is considered that the leaching processes continue at this time.

When rainfall decreases, the water table also drops. According to informants, the soil surface of the rice plots cracks and the ditches dry up in a normal dry season, and during the very long dry seasons these phenomena proceed remarkably. During the very dry conditions of 1985 and 1997, wide and deep cracks developed in the soil surfaces of nearly all rice plots and



Soil chemical processes				
1. steady state	**Oxidized horizon (Ox)** 1. Pyrite oxidation 2. Soil acidification 3. Leaching of oxidation products	**Oxidized horizon (Ox)** 1. Pyrite oxidation 2. Soil acidification 3. Diffusion of oxidation products	**Oxidized horizon (Ox)** 1. Pyrite oxidation 2. Soil acidification 3. Leaching of acidification products	**Oxidized horizon (Ox)** 1.Development of reducing conditions; reduction of sulfate and ferric ions
	Acid-accumulating horizon (I) 1. Accumulation of oxidation products. 2. Soil acidification	**Acid-accumulating horizon (I)** 1. Diffusion of oxidation products 2. Soil acidification	**Acid accumulating horizon (I)** 1. Diffusion of oxidation products	**Acid accumulating horizon (I)** 1. Development of reducing conditions reduction of sulfate and ferric ions
	Reduced horizon (Rd) 1. Steady state	**Reduced horizon (Rd)** 1. Steady state	**Reduced horizon (Rd)** 1. Steady state	**Reduced horizon (Rd)** 1. Steady state

Fig. 4 Effect of the Banjarese System on Soil Chemical Processes

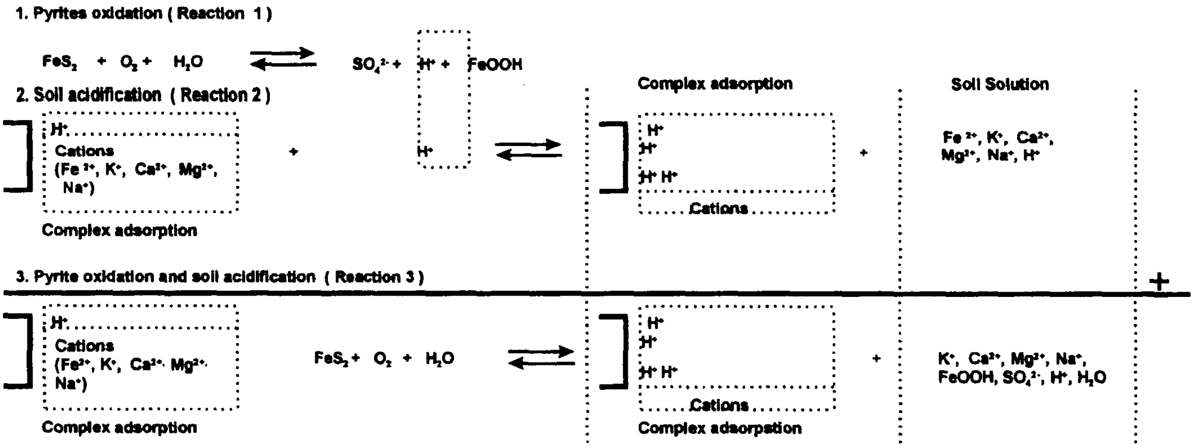


Fig. 5 Simplified Processes of Pyrite Oxidation and Soil Acidification

ditches. The soil pH in the field ranges from pH 3 to 4. When the water table surface becomes very low, the leaching processes stop, and the pyrite oxidation and soil acidification products accumulate in the layer that we call the acid-accumulating horizon. As discussed above, the acid-accumulating horizons of the study sites showed the dark gray color typical of a reduced layer, although it is likely that the acid-accumulating horizons are sometimes oxidized, especially during very long dry seasons. During the dry season, the oxidation products that have accumulated in the acid-accumulating horizon diffuse upward through the horizon because of the evapotranspiration effect. Thus, as discussed before, the soil becomes strongly acidic during prolonged drought.

When the rainy season comes, the water gates are kept open, and the pyrite oxidation and soil acidification products from the previous season will be leached out downward or into the ditches. When more rain falls, the leaching processes of the upper soils work very intensively. The fluctuation of the underground water table during the early rainy season is very important for soil leaching processes. When the water table of the plots is higher than the ditch surface, water carrying a high content of pyrite oxidation and soil acidification products drains into the ditches. With the peak of rainfall, the water table rises above the boundary layer between the oxidized and reduced horizons. In this situation, the products that have accumulated in the acid-accumulation horizon will partly diffuse upward and be leached out into the ditches.

The presence of a water reservoir near the rice plots, as in the case of BM 26 and BM 12, promotes the leaching of pyrite oxidation products and soil acidification products. Water flows continuously in the ditches from the early rainy season to the end of the rainy season, and the oxidation and soil acidification products of the previous season are leached out from the area of the plots.

After the water gates on the ditches are closed, the plots become inundated with water, and the farmers then start to prepare the land by cutting the grasses in the plots. The cut grasses are left to decompose on the plots, and this promotes the soil reduction processes. The ferric and sulfate ions remaining from the previous processes are then reduced to ferrous ions, elementary sulfur and sulfide ions, and the soil pH rises to close to neutral. In the field, the productive soils vary from pH 6 to 6.5 and the abandoned plots from about pH 4 to 5.

From the explanations above, the soil chemical processes which are prompted by the Banjarese farmers when cultivating rice on pyritic sediments involve pyrite oxidation, leaching of part of the oxidation products, and reduction of the remaining oxidation products. These processes play an important role in the successes of rice cultivation on soils developed from brackish swamp deposits. The chemical data in Table 3 show that the surface layers of the abandoned plots such as BM 13 and BM 14 are not greatly different in their chemical characteristics from the productive plots such as BM 12. The source of the problems in the abandoned plots is complex, but the lack of non-toxic water for leaching processes means that soils are permeated by acidic water. Under strongly acidic conditions, the supply of easily decomposed organic matter is also decreased severely, so that the reduction processes do not work well. Rice cannot grow under such conditions.

C. *Land Management Problems*

The Banjarese farmers first cultivated rice on shallow peat land, but when the peat subsided and disappeared, they cultivated rice on the brackish swamp deposits. The former drainage systems of the peat land system should be reformed in order to adjust the water table to a suitable depth. The draining of the brackish swamp deposits promotes the oxidation of pyrite minerals, and the oxidation products are very toxic for the rice plant. As already discussed, however, the intensive flushing and leaching processes allow rice to be planted on the brackish sediments. The chemical data in Tables 2 and 3, however, show that the leaching processes of the toxic substances also removes cations from the exchange sites. The chemical data of BM 8 are an example of excessive leaching processes producing acidic soil of poor base status.

The sulfate ions and soil acidification products flow from the drainage systems of the rice plots into the canals and rivers and cause drastic changes along these waterways. In the acid-affected phase, the hydrous ferric oxide substances which were precipitated along the waterways are dissolved and transferred downstream. The water in the canals becomes clear, highly acidic, high in sulfate content and of very high EC (Table 5). In the neutralized phase, the ferric hydroxides are precipitated on the soil surface in the pedon along the canals and river banks.

The agricultural land on brackish swamp deposits is a fragile system. Even the

Table 5 Chemical Composition of the Clear Water Produced by Weathering of Pyrites Sediments

No.	Location	pH	EC.	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}
			(μmhos/cm)	(...............		mmol/L		...............)
1	Tarantang secondary canal	2.6	1,400	2.58	0.87	0.09	0.12	0.67
2	Stagnant water in ditch of BM 28	3.3	380	1.00	0.28	0.08	0.08	0.28
3	Stagnant water on the abandoned plots of Pindahan Baru	3.1	480	0.86	0.38	0.05	0.09	0.70

productive rice plots are constantly threatened by sudden collapse, triggered by the breakdown of the delicate balance in the system. A long dry season causes cracking of the soil to develop, promotes the oxidation of pyrite and other sulfur compounds which are enriched in the acid-accumulating horizon, and causes the diffusion of sulfuric acid and other acidifying material toward the soil surface. Moreover, the peat of the secondary forest or water-reservoir areas may dry out and easily catch fire. The reduction of peat volume will reduce the volume of water that can be stored. When the volume of water decreases, the acidity in the field increases. This causes the failure of the rice production.

The development of the acid-accumulating horizon is not only dependent on natural characteristics such as deposit characteristics and climate, but also on the drainage system that has been constructed in the area. Because of these artificial factors, the depth of the reduced horizon formed varies. It is difficult to express this variation correctly in the soil mapping. Bregt *et al.* [1992], who conducted a survey at Pulau Petak, found that the variation of the pyritic layers in the Pulau Petak area is very high: differences of more than 50 cm in the depth of the pyritic layer are found within 25 meters' distance. Another factor is that the non-pyritic layers accumulated sulfuric acid, which was released in other horizons and translocated within the solum.

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