FEATURES OF THE SOIL-WATER-PLANT RELATIONSHIP OF MANGROVES IN PHANGNGA, THAILAND

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We examined the relationship between plants, soils and water to mangroves in Phangnga, where the tidal range is about 2-3m.[1,2] Research sites are indicated in the map (Fig. 1).

Mangrove forest

Dominant plant species are *Rhizophora apiculata, R. mucronata, Bruguiera parviflora, B. sexangula, B. gymnorrhiza, Ceriops tagal* and *C. decandra*. Secondary plant species are *Avicennia alba, A. marina, A. officinalis, Xylocarpus moluccensis, X. granatum, Bruguiera cylindriera, Sonneratia sp.* and *Nipa sp.*

These plants are utilized for making charcoal, pillar and for other purposes. Planting of deforested land is done mainly by the people who use the mangrove trees. Sometimes, preferred species (e. g. *Rhizophora mucronata*) are planted by the government. Accordingly, a large part of the mangrove in Phangnga is not the primary forest.

Soil

1) Texture

Texture of the soils usually became more clayey from the head to the mouth of the canal. In addition, the soils of the delta near to the canal coast at low tide were more sandy, becaming more clayey inwards to the delta. This was especially true in place where the canal bank was concave. However, sandy soils were localized and most of the soils examined were clayey or loamy in texture.

2) Oxidation-reduction state of the soil and plant growth

Marked difference was found in the oxidation-reduction state of the soil ($<$50cm deep), which was estimated mainly by the morphological characteristics of the soil in the field. The soils examined can be arranged in an order of increasing oxidation state (Table 1). In this table, the soils are classified as a clayey series and a loamy series, according to soil texture. Each series is subdivided into a normal series and a abnormal series. The soils in the normal series do not smell bad but the soils in the abnormal series do smell bad. This bad smell may be caused by accumulation or over production of fermentation products such as organic acids and sulfur-containing compounds. In addition, suitability of these soils to each plant species is indicated in the table. The suitability was estimated by vigour and growth of plants in the field. This table suggests that the oxidation-reduction state of the soil less than 50cm deep is one of the important controlling factors for growth of plants in the mangrove forests of Phangnga.

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3) Oxidizing power of plant roots

It was considered that the relationship between the oxidation-reduction state of the soil and the plant growth was due to a balance between the oxidizing power of plant roots and the reducting power of the soil. It was possible in the field to make rough estimations for the oxidizing power of plant roots relative to the reducing power of the soil by comparing the oxidation-reduction state of rhizosphere with that of nonrhizosphere soil (Table 2). The result of

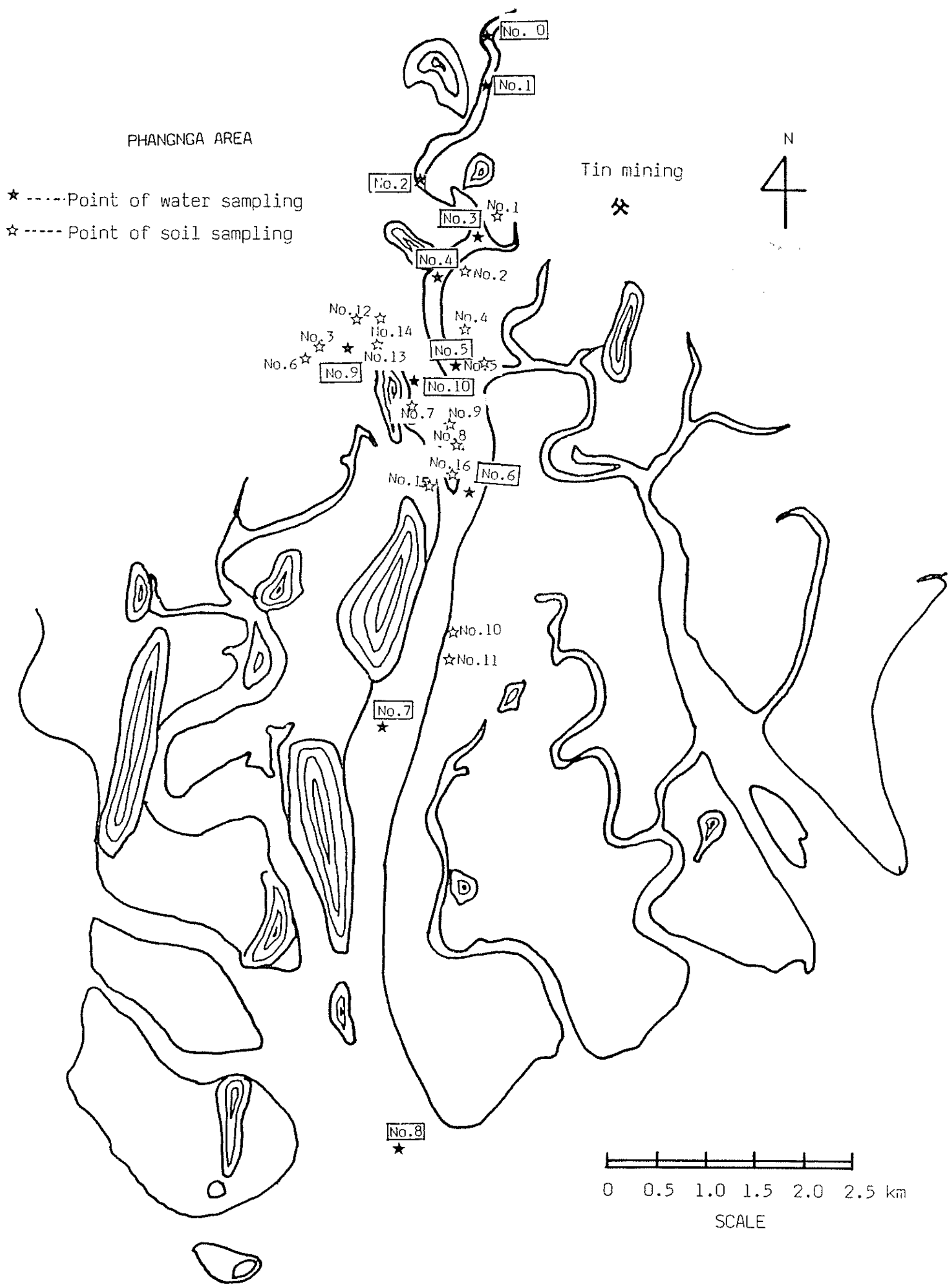


Fig 1 Sites of the area investigated.

these estimations can be combined with the above mentioned "order of oxidation-reduction state of the soil (non-rhizosphere soil)" to give a relative oxidizing power of the root for each plant species (Table 3). The potential oxidizing power of a root should be genetically determined; its actual oxidizing power may change according to the physiological state of the plant.

4) Oxidation-reduction state of the soil and relief of delta

Generally, the most aerated soil was situated at the highest level of the delta and the least

Table 1 Oxidation-reduction state of the soil and suitability of the soil to mangrove trees.

Clayey series

Normal Series

site No.	16	18	4-3	4-1	9	4-2	4-0	8	7	12	13	11	10	3
good for	S.	A.	A.a.	A.o	R.m.	A.m. R.a.	R.a.	R.a.	B.p.	R.a. X. B.g.	X.	X.m. (X.g.) C.t.	X.m. (X.g.) C.d.	C.d. B.s.
bad for						(A.m.) (R.a.)				(B.g.)		(X.g.)	(X.g.)	X.m. X.g.

reductive ←	strongly reductive	reductive	fairly oxidative	→ oxidative
	poorly aerated	poorly aerated	well aerated	

Abnormal Series

site No.	5-2	2-0	5-1	14
good for		Nipa	Nipa	
bad for	S.a. A.a.	R.m.	R.a.	R.a.

Loamy siries

Normal Series

site No.	1-2	1-1
good for		
bad for	A.o.	A.g.

Abnormal Series

site No.		2-1
good for		
bad for		S.a.

Table 2 The balance between oxidizing power of plant roots and reducing power of the soil.

Plant root		Soil	Processes in the soil
oxidizing power		Reducing power	
	$<<$		Even non-rhizosphere soil is oxidized.
	$>$		$Fe(OH)_3$ is deposited on and around the roots.
	$=$		Neither $Fe(OH)_3$ nor FeS is formed on or around the roots.
	$<$		FeS is formed on and around the roots.
	$<<$		The roots are suffocated and smell bad. Even non-rhizosphere soil becomes black by formation of FeS.

aerated soil at the lowest level of the delta. This may be called "hydrocatena". The major reason for the difference in aeration may be that the soil at the higher level is submerged for a shorter period and is drained more quickly due to the larger difference in hydraulic head. This tendency appeared to be accentuated by better development of the non-capillary pore system in the soil at higher elevation. The well aerated soil contained numerous non-capillary pores of various sizes from the soil surface to a depth of about 80cm, while the poorly aerated soil contained fewer non-capillary pores of large size (small size pores were non-existent) to a depth of about 10–15cm.

The number and species of soil animals seemed to be different between the well aerated and the poorly aerated soil. In the poorly aerated soil, a few species of large burrowers were present in the soil. However, in the well aerated soil, large burrowers and various species of relatively small animals, which probably included speices of *Insecta*, *Arachnida*, *Oligochaeta* and others, appeared to exist. Furthermore, in the well aerated soil, small angular blocky aggregates surrounded by cracks were formed which increased the number of small size non-capillary pores.

Microrelief of the delta made the "hydrocatena" to be more complex. For instance, if a certain area of the delta at a high level was slightly depressed, the soil in this area entered a reductive state probably because the surrounding ridges not only hinderd removal of water from the depressed area but also supply water to it.

Table 3 Oxidizing power of mangrove tree roots.

S. A. A.o. R.m. R.a. B.p. X.m. C.t. B.g.

X.g. C.d.

strong $\longleftrightarrow$ weak

oxidizing power of roots

ABBREVIATIONS

S. : *Sonneratia sp.*
A. : *Avicennia sp.*
A.a. : *Avicennia alba*
A.m. : *Avicennia marina*
A.o. : *Avicennia officinalis*
R.a. : *Rhizophora apiculata*
R.m. : *Rhizophora mucronata*
B.g. : *Bruguiera gymnorrhiza*
B.p. : *Bruguiera parviflora*
B.s. : *Bruguiera sexangula*
X.g. : *Xylocarpus granatum*
X.m. : *Xylocarpus moluccensis*
C.d. : *Ceriops decandra*
C.t. : *Ceriops tagal*

In this respect, lobster mounds were interesting. If there were many large lobster mounds in an area, the patches among and near these mounds were depressed, because large amounts of soil were piled up at the mounds. The main part of the lobster mounds was in an oxidative state; the soil in the depressed patch was strongly reductive. In this area, was scattered large amounts of dead stubble of *Rhizophora apiculata*, cut by man. *Xylocarpus moluccensis* grew well at the lobster mounds. These observations may mean that originally this area was not depressed, was more aerated and *Rhizophora* grew well accompanied by a few lobster mounds. After *Rhizophora* was cut, the number and the size of lobster mounds increased and the soil subsequently became unsuitable for *Rhizophora* (It was recognized that the first invader of a deforested land was the crab, the second was the lobster). Since the large part of the lobster mound was strongly acid, *Xylocarpus moluccensis* can be most tolerant to this soil among the various plant species in the mangrove area and succeed in monopolizing the mounds.

Mangroves near the road were often damaged. Construction of roads seems to have a similar effect upon the oxidation-reduction state of the soil and plant growth as the formation of lobster mounds because the road usually hinders the movement of water.

4) Accumulation of organic matter

Two processes were considered to be responsible for accumulation of organic matter in mangrove soils. The one is sedimentation of organic particles during formation of deltas. The other is supply of dead roots from plants after establishment of mangrove forests.

Both fresh and slightly decomposed plant debris (leaves and twigs) floated on the surface of canals and sea water. More decomposed, small plant debris were recognized along coast line of canals at low tide. These observations suggest that the small, decomposed plant debris is moved along the canal by sediment transport and tiny organic particles are moved along the canal by suspended transport and that coase textured and fine textured sediments tend to be enriched with the small, decomposed plant debris and the fine organic particles, respectively.

Colonizing plants will add new organic matter to the sediments. The fallen leaves may not all be incorporated into the soil, because some will float on the surface of water at high tide and will be removed to the canal at low tide. This appears especially true for *Sonneratia* and *Avicennia* which grow near the canal, their root systems not being complex enough to trap fallen leaves. On the contrary, the dead roots should not be removed so easily from the soil, because the greater part of them are deposited inside the soil. Therefore, profile of organic matter content in the soil may be largely determined by distribution pattern of plant roots.[3]

5) Lamination of the sediment

Laminated sediments were recognized in bare areas near canals and uppermost thin layers of the soil along the upperstream of the large canal. Disapearance of the laminae in the main part of forested areas may be due to faunal pedorurbation. The thin laminated uppermost layer may be newly formed under the influence of tin mining, because the tin mining heavily loads the canal with suspended substances.

Fine textured laminae was more reduced than coase textured laminae probably because the former were more enriched with decomposable organic matter than the the latter. This means that the fine organic particles are better susbtrates for microorganisms than the small, decomposed plant debris.

6) Decomposition of organic matter and reduction of the soil

Black patches were recognized in many profiles and were frequently associated with roots or large plant debris. These facts suggest the following:

1. Microbial activities are enhanced by the supply of organic matter from plants and produce H_2S actively which is changed to FeS or FeS_2. The black patches indicate the places where organic matter is supplied from the plant. As discussed previously, if black patches are as-

Table 4 Soil-plant relationships at Phangnga.

I. Soil-plant Relationship

I-1 Normal series

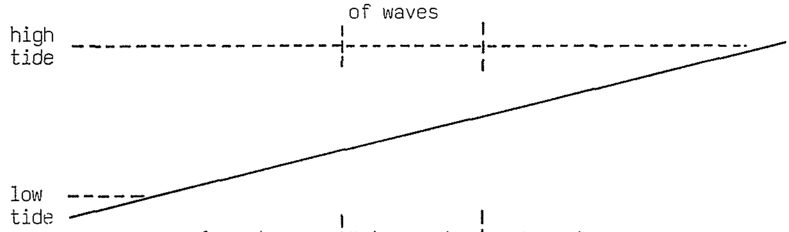
Plant

Species: S.sp. A.sp. | R.m. | R.a. | B.p X.sp. C.sp. B.g. (L.sp)

oxidizing power of roots: strong ⟵⟶ weak

pressure of trees upon the soil: low ⟵⟶ high

tolerance to disturbing effect of waves: low ⟵⟶ high



Soil

Taxonomy: ⟵ Aquents ⟶ | ⟵ Intergrades ⟶ | ⟵ Aquepts ⟶

reducing power of soil: strong ⟵⟶ weak

bearing capacity of soil: low ⟵⟶ high

slope of the bank of the delta: flat ⟵⟶ sharp

I-2 Abnormal series (Plant roots are suffocated with a build up of fermentation products in and on the roots)

Possible causes:

- Stagnant *water (depressed area----- road construction,* lobster mounds)
- Low buffering capacity for oxidation-reduction reactions (poor in mafic minerals, small number of non-capillary pores)
- Deficiences in plant nutrients (P and N)
  Substances toxic or injurious to plants

I-3 Areas with huge lobster mounds

site No.	6	14	
good for	X.m.	X.m.	lobster mounds: oxidative, acidic
bad for	R.a.	R.a.	between lobster mounds: strongly reductive (abnormal series)

II. Effect of human activities

Tree cutting
Tin mining
Road construction
Boat cruising
Garbage disposal

sociated with living roots, this indicates that the oxidizing power of roots is couteracted by the reducting power of the soil.

2. The organic matter contained in the delta sediment itself is insufficient to convert all the active Fe in the soil into FeS or FeS_2. The remaining Fe can react with newly formed H_2S by the enhanced microbial activity.

3. Soils which are colonized by plants sometimes appear to be more reduced than uncolonized soils. This is especially true for poorly aerated soils.

The oxidized layer was usually recognized in both colonized and uncolonized soils. This may be due to the removal of fallen leaves from the soil surface by tidal action.

In the poorly aerated soils, the oxidized layer was often underlain by black patches, which were sometimes observed even inside the oxidized layer. These black patches may be formed when fallen leaves are retained in the soil and decomposed there, even though in most cases the shapes of leaves were hardly recognizable in the field (in one of the sites (site No. 15), the black patches were clearly associated with leaves).

In the well aerated soils, the black patches, if present, were confined to the upper part (0-20cm) of the soil profile and were associated with dead fine roots. Inside the black patches, young fine roots were oxidizing the rhizosphere soil and were stained reddish brown with ferric hydroxide. This fact suggests that in the well aerated soils, the number of fine roots is large in the upper horizons and that they are active, but their turnover time is short.

7) Soils of the abnormal series

In some of the poorly aerated soils, the black patches extended to the depth of the soil profile and were associated with primary roots. This may mean that in these soils, even the deep seated primary roots are attacked by microorganisms and the rhizosphere soil is strongly reduced, forming H_2S. In the soils of the abnormal series, deep seated primary roots as well as all other roots were stained black and smelled very bad. Probably these roots are suffocated and, being decayed, several fermentation products having bad smell are produced in and on the roots (The bad smell of affected roots was similar in any plant species). The reason for this decay of the roots is not yet clearly understood.

When the pits were reexamined 11 days later, the bad smell was much more obvious. This was especially true for soils where the bad smell was not so noticeable in the first examination. On the contrary, the bad smell could not be detected in the reexamination of pits dug in the soil of the normal series but the dipyridyl reaction became more marked. The strengthening of the bad smell may be caused by the enhanced reduction of the soils in pits of the abnormal series. The enhanced reduction of the soils, in turn, may be caused by water which comes from reduced parts of the lower horizons of the neighboring soils through non-capillary pores, and which fills the pits. Water culture of seedlings of mangrove trees using this reducing water may throw some light on this problem. Stagnancy of water and low buffering capacity of a soil against changes in the oxidation-reduction state are considered to be responsible for making the soil especially unsuitable for mangrove trees.

The soils of the abnormal series were not favourable for all mangrove trees except *Nipa*. More attention should be paid to these soils. Further detailed investigation is necessary to elucidate the cause of the production of the bad smell from the roots.

8) Oxidation of the soil and lowering of the soil pH

In the poorly aerated soils, oxidation was recognized only in the uppermost layer (oxidized layer) and tunnel walls of burrowing animals. In the well-oxidized soils, not only almost all walls of non-capillary pores showed an oxidized color, but also the soil matrix did not contain Fe^{2+}. Lobster mounds appeared to be the most well oxidized and often had yellow mottlings, which appeared to be jarosite.

The well-oxidized soils were slightly more acid than the poorly aerated soils. Oxidation of ferrous salts, FeS and FeS_2, which are formed in the reduced soil, are known to release H^+. Oxidation of iron sulfides is more effective than oxidation of ferrous salts in lowering soil pH. The H^+ thus formed may be completely neutralized by carbonates in sea water or partially removed from the soil by sea water when the soil is submerged at high tide and drained at low tide. Surface horizons usually contained small amount of pyrite. The lobster mound was an exception because it was made of pyritic material from lower horizons and only foot of the mound was submerged at high tide. This may be the reason for the slight lowering of pH in the well-aerated soils and the marked pH decrease in the lobster mound.

9) Quality of canal water and its effects on mangrove area

On the basis of water quality of the two canals at both low and high tide, it was concluded that a small river flew into the large canal and formed a salt wedge. However, the small tributary was not connected with any river. At low tide, water in the large canal was affected by the river up to about sites Nos. 4–5 (Fig. 1). At high tide, all the canal weter became similar in concentration to the sea water, except very near to the river itself ($\boxed{\text{No. 0}}$ in Fig. 1). In these upper streams, the growth of mangrove trees was bad and weeds (*Scripus sp.* which was similar to *Scripus wichurae*) grew on the bank of the delta. This was observed until about sites Nos. 2–4. The presence of the weeds may also indicate that these areas are not favourable for mangrove trees.

Since the canal water in the upper streams was sufficiently saline, especially at high tide when the soils were submerged, the bad growth of mangrove trees may not be caused by too low a salinity of the soil but by the infertility of the soil. Tin mining was active in these upper streams and large amounts of mineral particles were added to the river from these sites. Most of the coarse mineral particles may sediment near the tin mining sites (Fig. 2). The mineral particles derived from tin mining may be poor in clay, nutrients, active Fe and active Mn. It is noteworthy that all the soils of the abnormal series, except one, are situated on the left side of the upper streams of the large canal, where tin mining are expected to have the most serious effcts on the mineralogical composition of the soil. This fact suggests that the mineralogical composition is important in maintaining the fertility of mangrove soil or a high buffering capacity against rapid change in the oxidation-reduction state.

10) Mechanical properties of the delta and plant growth

Formation and destruction of the delta was actively proceeding in Phangnga. The uppermost stream of the large canal was a pond 25 years ago, but now deltas were present and mangrove trees grew on these deltas. This rapid formation of the deltas was caused by tin mining.

The deltas with a high elevation (probably an old formation) were eroded at their banks. The shape of the banks was considered to change from convex to concave according to the age of the delta. Sometimes erosion was so serious that trees growing near the bank fell into

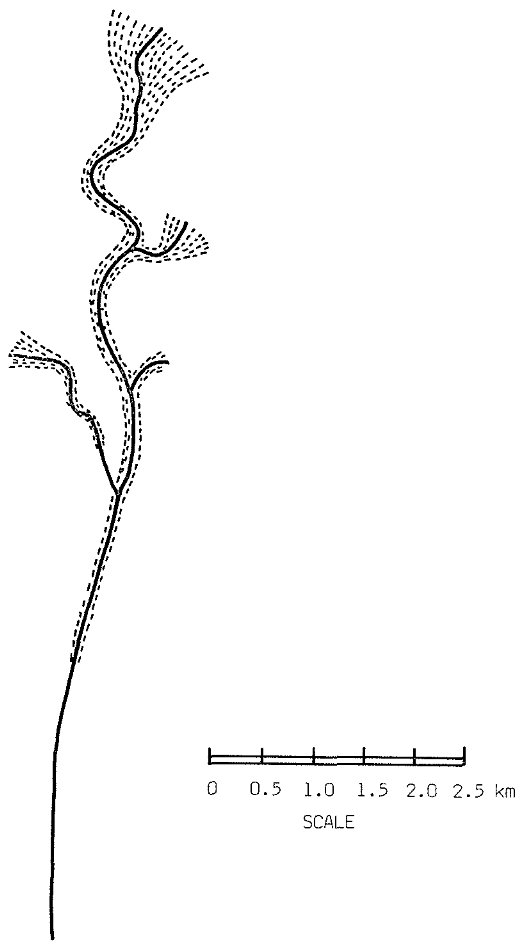


Fig. 2 Turbidity of canal water at low tide.

the canals. At the same time, new deltas were being formed at places where the stream flow was slow. Destruction of the delta by erosion appeared to be enhanced by waves which were formed by boats moving through the canals.

From a mechanical viewpoint, a relationship may be expected between the bearing capacity of the soil and the pressure which plants apply to the soil. This pressure is usually determined by the weight of the aboveground part of the tree and the shape and the distribution pattern of the roots. For instance, *Sonneratia* and *Avicennia* are small trees with extended roots, which should result in low pressure to the soil. This may be a reason why *Sonneratia* and *Avicennia* can grow in soil with a low-bearing capacity. *Rhizophora* are big trees and their pressure upon the soil seems to be higher than that of *Sonneratia* and *Avicennia* and may be suited to soils with higher bearing capacities. In addition, the entangled root system of *Rhizophora* may protect the bank of the delta aginst erosion.

The slope of the bank of the delta appeared to change according to the species of plants growing there. A forest consisting solely of *Sonneratia* was established on the newly formed low delta with a flat bank (site No. 16). *Avicennia* was spread at the front of the higher delta with a slightly convexed bank (site No. 15). Disturbance by canal water waves may be minimal in the *Sonneratia* areas, and slightly more serious in the areas where *Avicennia* grows. That is, *Sonneratia* seems to prefer minimum disturbance by waves and *Avicennia* seems to be more tolerant. If this consideration is tenable, we can say that mechanical disturbance by waves is another controlling factor in the growth of mangrove trees. In this respect, we can imagine that *Rhizophora*, which may be able to protect the bank of the delta against erosion, can grow where the bank is more convex and be more tolerant to mechanical disturbance by waves than *Avicennia*.

11) Effects of human activities

The effects of tree cutting, tin mining, road construction and boat crusing on mangroves have already been pointed out. In addition to these, people were influencing mangrove forests by the careless disposal of their garbage. Plastic material was scattered near the village and was accumulating in the deltas. This material may inhibit root growth, animal activities and movement of water inside the soil.

12) Classification of mangrove soils

Mangrove soils are completely different from common terrestrial soils and rather similar to paddy soils. Both mangrove soils and paddy soils are affected by alternation of submergence and drainage. The main differences between these two soils are as follows:

1. The period of alternating submergence and drainage is far shorter in mangrove than in paddy soils.
2. Water in mangrove soils is saline, while water in paddy soils is usually not.
3. Animal activities (formation of tunnels by burrowing animals and faunal pedoturbation) are far more marked in mangrove soils than in paddy soils.

All soils supporting mangroves have been classified as Aquents. However, it may be more appropriate to say that Aquents include the poorly aerated and consequently strongly reduced soils with low bearing capacity and that Aquepts include the well aerated and more or less oxidative soils with high bearing capacity, because the poorly aerated soils were quite different from the well aerated soils in many respects. In addition, the weakly reduced soils may be classified as intergrades between Aquents and Aquepts.

13) Concluding remarks

Plant-soil-water relationships in mangrove areas have been considered[4,5] to be extremely complicated because many factors are operating at the same time. We must solve this complicated problem carefully by investigating each factor one by one, in the same way as Jenny[6] when he elucidated the factors in soil formation.

In the area we studied, salinity of the water (and consequently, salinity of the soil) was rather uniform and most of the soil was clayey and deep. Accordingly, in our present research, the effects of difference in salinity, soil texture, and soil depth on the plant-soil-water relationships have been minimal. The situation was rather fortuitous for us. We could pay our attention to a limited number of factors. If further research is done in the area upon varying salinity, soil texture and soil depth, we hope that recognizing the effects of these factors and combining the results of the investigations of several limited areas, where a few factors are studied, we may attain a complete understanding of the plant-soil-water relationships of mangroves.

The results of our investigations in Phangnga are schematically illustrated in Table 4.

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