STUDIES OF PEAT SWAMPS IN SARAWAK WITH PARTICULAR REFERENCE TO SOIL - FOREST RELATIONSHIPS AND DEVELOPMENT OF DOME - SHAPED STRUCTURES

TIE YIU-LIONG

B. Sc. (Hons.), M. Sc.

STUDIES OF PEAT SWAMPS IN SARAWAK WITH PARTICULAR REFERENCE TO SOIL-FOREST RELATIONSHIPS AND DEVELOPMENT OF DOME-SHAPED STRUCTURES

By

TIE YIU-LIONG

B.Sc.(Hons.); M.Sc.

(University of Reading)

A dissertation submitted to the Council for National Academic Awards, London in partial fulfillment of the requirements for the degree of Doctor of Philosophy

DEPARTMENT OF GEOGRAPHY

POLYTECHNIC OF NORTH LONDON

London, U.K.

November,1990

CONTENTS

CONTENTS

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

STUDIES OF PEAT SWAMPS IN SARAWAK WITH PARTICULAR REFERENCE TO SOIL-FOREST RELATIONSHIPS AND DEVELOPMENT OF DOME-SHAPED STRUCTURES

TIE YIU-LIONG
November,1990

The main objectives of the study are to investigate the soil-forest relationships and to examine the development of the dome-shaped morphology of the peat swamps in Sarawak.

Chapters 2 and 3 contain some background materials. Chapter 4 comprises the literature review which focuses on research work done on tropical peats.

Data collection, executed in two phases, is described in Chapter 5. Physical constraints confined sampling to only 11 transects with 58 cases. The study also involved radio-carbon dating, and monitoring of litterfall, decomposition rate and water-table fluctuation. Chapter 6 describes the structure and vegetation of the peat swamps studied.

Chapter 7 examines the vertical changes of soil properties with depth. The degree of decomposition and levels of most nutrient elements show a decreasing trend down the profile. The trend is reversed as the mineral substratum is approached.

Chapter 8 shows that the change from the floristically rich, high volume forest of PC 1 to the low stature, floristically poor forest of PC 6 is reflected by the decreasing trend of most nutrient elements in the surface peats. In Chapter 9, multivariate statistical techniques are used to isolate the most significant edaphic factors. Discriminant analyses show that the forest zonation across the peat dome is mainly associated with the variations in particle density, pyrophosphate colour index, total calcium, and total iron of surface peat (15-30cm), and total copper, total nitrogen and exchangeable potassium of subsurface peat (30-150 cm).

Chapters 10 and 11 discuss the development of the dome-shaped morphology. The initial formation of lowland peats in Sarawak had taken place under a low-lying, poorly drained but largely terrestrial condition rather than the aquatic situation with a permanent water body. As successive layers of peat in the shape of an inverted saucer were accumulated, the deposit grew vertically and laterally. The basin-shaped foundation also evolved simultaneously. Data collected seem to support the hypothesis that as the peat at the centre gets thicker, the rate of growth decreases as a result of lower biomass production, thus allowing the adjacent areas to catch up and form the flat-topped structure. At the same time, the periphery steepens because the net rate of growth at the very edge also decreases due to a higher rate of decomposition.

ACKNOWLEDGEMENTS

Acknowledgements are owed to a large number of people in Sarawak, Britain and USA. Special thanks are due to the following:

The State Secretary, Sarawak and the Director of Agriculture Department, Sarawak who gave official permission for me to pursue this study.

Dr.I.C.Baillie, my Director of Studies, for his unwavering support and invaluable advice. I would also like to mention specifically that he helped me run some of the statistical analyses after I left PNL.

Mr. Lim Chin Pang, one of the Advisors, for his assistance, advice and encouragement. It was Mr. Lim who introduced me to the subject of peat soils when I first joined the Soils Division, DOA, Sarawak in 1976. He was also responsible for talking me into this project and got me started, even before my registration with CNAA.

Dr. J.A.R.Anderson for his encouragement and assistance. It was his extensive research work on Sarawak peats that formed the basis of the present study. He also took valuable time off from his consultancy work in Brunei to help me collect some of the vegetation data.

Dr.R.H.Bryant, my Second Supervisor, for his advice.

Dr.J.S.Esterle who, as a post-graduate student from the University of Kentucky, USA, worked with me on one of the transects at Tanjung Upar. It was through her persistence that we managed to get some of carbon-14 dating done in USA.

For the field work, I would like to acknowledge the support given by the Soils Division, DOA, Sarawak. I wish to mention in particular the assistance given by Haji Rosli Sahari, Lai Poh Luk, Chai Kok Ing, Jemain Pauzi, Wan Laeng and Wong Sing Jong. Without their hard work, the field programmes would not have been completed. I am also grateful for their companionship and friendship during the time spent in the field.

In the laboratory, thanks are due to the Staffs of Chemistry Division and Soils Division, DOA, Sarawak, particularly Patricia Sim, Chin Siew Phin, Siaw Foh Khoo and Noralwi Pauzi for helping me in the analyses of innumerable samples.

Other Staff Members of Soils Division who assisted me in drafting some of the figures and maps, typing the thesis, and getting the field gears organized are also gratefully acknowledged.

Last but not least, I would like to acknowledge the encouragement given to me by my family, particularly my wife, Lucy and children Tony and Bibiana.

ABBREVIATIONS AND LOCAL TERMS

(a). Abbreviations

ARC	Agriculture Research Centre,Semongok,Sarawak.
CNAA	Council for National Academic Awards,London
DID	Drainage and Irrigation Department,Sarawak.
DOA	Department of Agriculture, Sarawak.
FAO	Food and Agriculture Organization.
FAR	Fibre (content) after rubbing.
IPS	International Peat Society.
J	Journal.
KL	Kuala Lumpur.
MDF	Mixed Dipterocarp Forest.
o.d.	Oven-dried (basis).
PC	Phasic Community (of peat swamp forest).
PCI	Pyrophosphate colour index.
PNL	Polytechnic of North London.
PS	Peat swamp.
PSF	Peat swamp forest.
SD	Soils Division, Sarawak (formerly SSD).
SSD	Soil Survey Division, Sarawak.
UK	United Kingdom.
USA	United States of America.
USDA	United States Department of Agriculture.
USSR	Union of Soviet Socialist Republics (Russia).
yBP	Years before present.

(b). Local Terms

Batang (Btg.)	Main river.
Gunung	Mountain or hill.
Kampung (Kg/Kpg)	Village.
Kuala (K.)	River mouth.
Lubok (Lbk.)	Deep water, usually at large meander.
Rintis (R.)	Cut-line or transect.
Sungai (S./Sg.)	Small river or tributary.
Tanjung (Tg/Tj.)	Cape or river meander.

CHAPTER 1 INTRODUCTION TO THE PRESENT STUDY

Sarawak is the largest state in the Federation of Malaysia. It lies within the tropical monsoon belt between latitude 0^{o} 50' and 5^{o} 00' North, and longitude 109^{o} 30' and 115^{o} 40' East. Covering an area of 124,450 km^2 on the north-west coast of Borneo, it is sparsely populated with a multi-racial population of only 1.3 million (1980 census).The latest estimate for the area of organic soils in Sarawak is 16,600 km^2. These soils are mainly associated with lowland peat swamps (PS) occurring along the lower stretches of the rivers. The peat swamps are further characterized by dome-shaped morphology and distinctive zonation of forest types.

The most extensive and systematic studies of the peat swamps in Sarawak have been those of Anderson (1961, 1963 and 1964a; see Section 4.3.1 for review). His emphasis was on the distribution and ecology of the natural forest. With some subsidiary sampling of soils, he hypothesized that the regular concentric zonation of forest types on the peat domes is mainly due to a decline in soil fertility inward from the periphery though a difference in the drainage regime due to the convexity of the peat domes was also mentioned as an important factor. More detailed studies are required to test this hypothesis.

The bulk of the present study is essentially a pedogenetic one. The patterns of vertical and lateral variation of peat properties within the domed swamps were investigated. The study also involved radio-carbon dating, monitoring of litterfall and decomposition rate, levelling, and peat depth measurement. All these data are used to generate a genetic model for the PS.

The soil data are also used to test Anderson's hypothesis that the concentric zonation of the forest types is due to a decline in soil fertility towards the centre of the swamps. The vertical changes in peat properties are examined to see if the vertical succession within a peat profile is accompanied by a similar decline in the levels of major nutrient elements.

The existence of any marked soil-forest associations may not only be of scientific interest but could have useful applications. In the field of soil survey, the relationships may be used as an aid to the execution of soil surveys, particularly in the interpretation of conventional monochrome aerial photographs which are readily available in Sarawak. From the results of the study of soil-forest relationships, it should be possible to indicate the usefulness, or otherwise, of forest characteristics as an aid to soil survey and evaluation of PS for agricultural uses.

The general objectives can therefore be summarized as : To study the spatial distribution of organic soils across the PS in Sarawak with particular reference to:

(a) The horizontal and vertical variations of the organic soils.
(b) The associations between soil conditions and natural forest types.
(c) The usefulness of forest characteristics as an aid to soil survey and land evaluation in the PS areas.
(d) The formulation of a model of the dynamics of PS development.

CHAPTER 2 GENERAL INTRODUCTION

2.1 PEAT FORMATION AND TERMINOLOGY

Peat is commonly defined as an accumulation of partially decayed plant remains under water or in a poorly drained site where preservation has occurred under anaerobic conditions. Many people consider this mode of accumulation as a geogenic process and the surface layer of a growing deposit as a potential parent material of a soil (e.g. Buol *et al.* 1973; Soil Survey Staff, 1981). When pedogenic processes (chemical, physical and biological) begin to operate, the upper layer alters and the altered layer may then be regarded as a **peaty soil**. The origin of a peaty soil is therefore related to a new genetic sequence, a pedogenic one. For New Zealand peats, Harris (1968) suggested that it is convenient to regard as parent material the layer(s) above the summer water-table and below the surface soil horizon(s); the peat below the summer water-table is then "peat undermass", and below this is the "mineral substratum".

However, it is not easy to decide when, for example, a freshly fallen branch, twig or leaf becomes peat, and when that peat is sufficiently altered through pedogenic processes to call it a peaty soil. The accumulation and the decomposition of freshly deposited plant remains to form peat, and later peaty soil material, can be regarded as one continuous process. Under undisturbed conditions, these so-called geogenic and pedogenic processes usually take place at the same place and time; only with human intervention (eg. reclamation and drainage) would the geogenic process ceases altogether and the pedogenic processes begin to operate more distinctively.

The terms used to designate peat types and natural formations where peat is produced are still highly confused. The reasons for this are evident when one considers the numerous types of peat formed under different conditions of climate, vegetation, water source and balance, chemical composition of the water and human interference. The problem is further complicated by different perceptions and terminologies of the various groups of interested people (geologists, agriculturalists, botanists, chemists, etc). Many terms are the result of different schemes of classification each with different objectives and from different disciplines (e.g. Farnham and Finney, 1965). It must be stressed here that many schemes classify kinds of peatlands rather than types of organic soils. It is not scope of this introductory section to review concepts and nomenclature of the different classification. However, some of the terms which are relevant to the present study are elow.

the past, confusion even existed between the two basic terms: "peat" and "muck". In 1930, 'peat" and "muck" were defined in the pedological sense at the second International f Soil Science held in USSR. Subcommission VI of the Congress recommended that **peat** estricted to organic soils which are at least 0.5 m in depth and 1 ha in areal extent, and eral matter content of less than 35%; where the mineral content ranges from 35 to 65%, soil with similar depth and areal requirements is call **muck**; mineral soils have more than al content (i.e. <35% organic matter or O.M.). However, the confusion did not end here. tempts were made to distinguish between them by designating "peat" as a natural nd "muck" a cultivated peat (Waksman, 1942). Others regarded muck as those soils which igh percentage of plant materials in a well decomposed condition while peat signifies the ic soils.

the revised edition of Soil Survey Manual (Soil Survey staff, 1981), "peat" is described eading of "Parent Material" and is defined as organic material which has accumulated in The principal kinds of peat, according to origin, are "sedimentary peat", "moss peat", s peat" and "woody peat". It is added in the same section that: "In describing organic soils, l is called **peat** if virtually all of the organic remains are sufficiently fresh and intact to tification of plant forms. It is called **muck** if virtually all of the material has undergone lecomposition that the plant parts cannot be recognized. It is called **mucky peat** if a part of the material can be recognized and a significant part cannot" (p.4-18). Under the "Soil Texture", the terms "peat", "muck" and "mucky peat" are similarly defined, and m "mucky" is introduced to modify mineral soil texture when the soil material is essentially t contains enough organic matter to have some properties of muck. Such definitions of nuck in terms of the degree of decomposition therefore contravene the 1930 lation of the International Congress of Soil Science which differentiates the two terms on the mineral content.

Soil Taxonomy (Soil Survey Staff, 1975), however, does not make use of the terms like "peat" and "muck". Although this new system admits that classification of organic soils needs more testing, it introduces a completely new set of terms like **"Histosol"**, **"organic soil materials"**, **"fibric"**, **"hemic"** and **"sapric"** which are quantitatively defined. This does away with much confusion and misunderstanding, but it omits a sub-division within the "organic soil materials" based on the mineral content as recommended by the International Congress of Soil Science in 1930. This omission is perpetuated all the way down to the family level, and for Histosols, Soil Taxonomy does not really discuss specific differentiae which can be used at series and phase levels. The cut-off point at 35 percent mineral content may be debated, but the differentiation between "peat" and "muck" based on this criterion is very relevant and useful in certain situations. In Sarawak, for example, the presence of "muck" (35-65% mineral content) in the surface 50 cm of deep organic soils means that the land, otherwise unsuitable, can be used satisfactorily for wet padi cultivation; its presence anywhere in the profile also indicates alluvial (flooding) influence.

The Canadian system of soil classification (Clayton et.al. 1977) treats the organic soils in a similar fashion to Soil Taxonomy. However, some of the names are different; **"mesic"** and **"humic"**, for examples, are used instead of "hemic" and "sapric". Moreover, the Canadian system has more diagnostic criteria, particularly at subgroup level. The **"cumulo"** layer introduced by the Canadians does identify some cases of flooding effect when distinct interlayering of organic and alluvial materials occurs. The system again ignores the situation when the organic and mineral materials are well mixed to form "muck".

The legend of the Soil Map of the World (FAO, 1974) defines Histosols along the same lines as Soil Taxonomy. However, it separates Histosols into three sub-units (**"Eutric"**, **"Dystric"** and **"Gelic"**) based on pH and presence or absence of permafrost. Soil Taxonomy (Soil Survey Staff, 1975), on the other hand, recommends the use of pH at family level (**"Euic"** and **"Dysic"**); permafrost is taken into account at subgroup level (**"pergelic"**).

FAO's "Eutric" and "Dystric" sub-units, and the "Euic" and "Dysic" families of Soil Taxonomy follow closely the three categories of peats described by Weber (1903), namely **"eutrophic"** (rich in lime), **"mesotrophic"** (intermediate) and **"oligotrophic"** (poor in lime).

Other terms which need to be mentioned here include "**topogenous**" and "**ombrogenous**". Peats which have accumulated in areas where the waterlogged conditions are due to their topographic positions are often referred to as "topogenous" peats. Because topogenous peats derive water and nutrients from surrounding land or mineral soil, they have also been variously regarded as "rheophilous" (Moore and Bellamy, 1974), "minerotrophic" (Sjors, 1961), or "soligenous" (Heinselman, 1963). They have also been named after the general landform of their locations, such as depressional peats, basin peats, valley peats and low moor. "Ombrogenous" peats, either occurring on high ground or are raised above the surrounding land through their own growth, obtain their water only from precipitation. They are also referred to as "ombrophilous" (Moore and Bellamy, 1974) and "ombrotrophic" (Sjors, 1961). Due to the landforms they are associated with, they have also been called blanket peats, raised peats, upland peats, and high moor.

In Sarawak, many terms have also been introduced by various scientists to describe the low-lying, poorly drained areas where peat soils occur. Anderson (1961) pointed out that the two terms "freshwater swamp" and "peat swamp" should be used differently because they have different forest type, both in structure and floristic composition. He commented that Van Steenis' (1958) definitions of "freshwater swamp forest" as developed on mineral or non-mineral soils and independent of climate, and of "peat swamp forest" as developed on peat and restricted to an "ombrogenous climate" are very imprecise. Anderson asserted that the most important factors differentiating these two habitats are the surface structure of the swamp and the degree of flooding. He therefore proposed to define Sarawak swamps as:

(a) **Freshwater swamp** - regularly or seasonally flooded; has peat or muck soils (N.B. no mineral soils allowed) with a pH generally higher than 4.0 (oligotrophic to mesotrophic), or loss of ignition below 75%; level or barely convex surfaces.

(b) **Peat swamp** - not subject to flooding; has peat soils with a pH value of less than 4.0 (oligotrophic), a loss of ignition above 75%; surfaces markedly convex.

With an emphasis on pedology rather than ecology, Andriesse (1974) broadly divided the peat swamps in Sarawak on the basis of topography and terrain morphology into:

(a) **Basin peat swamps** - found on coastal plains; dome-shaped surface; underlying mineral surface generally dips down towards the centre; probable flooding at periphery.

(b) **Valley peat swamps** - found in valleys existing in a low dissected hilly landscape; not dome-shaped; flooding is common; organic soils generally have a higher mineral matter content.

As far as the soils are concerned, Coulter (1950) proposed for Malaya the term **"bog soils"** to include in one group both the muck soils and peats. In Sarawak, Dames (1962) also classified "the soils of the peat swamp areas covered by swamp forests of different types as **"bog soils"** too. However, this term did not stick and in the first comprehensive classification of the soils of Sarawak (Soil Survey Staff, 1966), the term **"peat soils"** was introduced and defined as organic soils in which: (a) the O horizon consists of peat (>65% O.M.) or muck (35-65% O.M.) and is more than 25 cm deep; and (b) the groundwater conductivity does not exceed 500 uS/cm at 25^{0}C at any time of the year.

Subsequently, the second criterion was dropped (Scott, 1973; Lim, 1975) and saline phases of "peat soils" were identified and mapped. As more information on Sarawak's soils was gathered, there were some major changes in the classification system (Tie, 1982). Since the original "peat soils" include both peats and mucks, the term **"organic soils"** was adopted. The definition of **"organic soils material"** was brought in line with that of Soil Taxonomy (Soil Survey Staff, 1975), but the depth requirement was fixed at 50 cm (rather than floating between 40 and 60 cm as in Soil Taxonomy). The local distinction between shallow and deep organic soils at family level was also changed from 100 to 150 cm.

In the rest of this study, the terms "peat" and "muck" are used in the pedological sense as defined by the International Congress of Soil Science in 1930. "Peat soils", "organic soils", and "Histosols" are regarded as synonymous and the terms are used interchangeably. Although organic soils of Sarawak (Tie, 1982) are not defined exactly as the Histosols of Soil Taxonomy, they are close enough to be regarded as equivalents. Other terms, used in association with these soils (e.g. "fibric", "hemic" and "sapric") also carry the same meanings as defined in Soil Taxonomy. The term "peat swamp" (PS) is used for that low-lying, poorly drained physiographic unit associated with organic soils. It therefore includes all of Anderson's (1961) "peat swamp" and some of the "freshwater swamp" although his proposed criteria on the pH and loss on ignition may no longer be binding.

2.2 GLOBAL DISTRIBUTION OF PEATLANDS

Although peatlands are most typical of the boreal and arctic regions of the northern hemisphere, they are found in most climatic zones. Estimates of the world's peat resources have been compiled by many authors but the figures seldom tally. Usually the amounts reported are the exploitable reserves for fuel and horticultural sales, thereby underestimating the total areas classified as Histosols. Table 2.1 reports some estimates presented by Lucas (1982) and Driessen (1977); data from Malaysia, Thailand and Indonesia have been updated by more recent figures (Tie and Kueh, 1979; Hashim,1984; Wiraatmadja, 1987; Eiumnoh, 1987).

It can be seen from Table 2.1 that the most extensive peatlands are in USSR and Canada, accounting for nearly three-quarters of the world's total area. Approximately 90% of the world's peat resources are found in five countries, namely USSR, Canada, Indonesia, USA and Finland.

Tropical and subtropical peat deposits are far more extensive than what were realized earlier. Indonesia has the largest area of tropical peats (26.2 million ha). USA also has some subtropical peat deposits which are mainly found in Florida (1.2 million ha). China may have some subtropical peats but the distribution there has not been very clearly reported. Venezuela, with about 3.0 million ha, probably has the second largest area of tropical peatlands. This is followed closely by Malaysia which has about 2.6 million ha of organic soils.

TABLE 2.1 GLOBAL ORGANIC SOILS' RESOURCES

COUNTRY (mainly Temperate)	AREA (in '000 ha)	COUNTRY (Tropical)	AREA (in '000 ha)
USSR	150,000 (42.0%) +	Indonesia	26,200 (7.3%)
Canada	112,000 (31.4%)	Venezuela	3,000
USA	21,000 (5.9%)	Malaysia	2,560
Finland	10,000 (2.8%)	Vietnam	1,500
Sweden	7,000	Brazil	1,000
China	3,500	Zaire	1,000
Norway	3,000	Guianas*	500
UK	1,582	Papua New Guinea	500
Argentina	1,500	Kenya/Uganda	500
Poland	1,500	Colombia	350
West Germany	1,129	Cuba	200
Iceland	1,000	Thailand	80
Others	6,110	Brunei	10
		Total	**356,721**

SOURCES : Lucas(1982); Driessen(1977); Hashim(1984); Tie & Kueh (1979); Wiraatmadja(1987); Eiumnoh(1987).

* : Guyana,Surinam and French Guiana.

\+ : Figures in Brackets are % of global total area.

2.3 UTILIZATION OF PEAT/ORGANIC SOILS

Peats consist largely of vegetative material in various stages of decomposition. Their unique physical and chemical properties have resulted in a distinct pattern of human exploitation.

Peats have a high potential thermal energy content. Their utilization as a domestic fuel is of considerable antiquity in Europe. This usage is declining but still persists in some remoter areas. However, the use of milled peat in driving power stations to produce electricity is still widely practised in USSR and Ireland. USSR, for example, used 70% of the harvested peat in this manner (Moore and Bellamy, 1974). In Ireland, more than one-fifth of the steam generated electricity comes from peat fuel (Maher,1980).

Apart from USSR and Ireland, the major use of peats or organic soils is in agriculture and horticulture. Here their virtue lie mainly in their high organic matter content, water-holding capacity and cation exchange capacity. Excavated peat has been used as a soil conditioner to improve the physical properties of mineral soils. They can be used for composting or as a mulch. In horticulture, they may be used as a medium of growth. For propagation (to germinate seeds and start cuttings), fibre pots made of compressed peat are widely used in horticulture because they do not need to be removed while transplanting.

Organic soils have also been widely used *in-situ* for general agriculture and horticulture. In some temperate countries, they form some of the most productive soils for vegetables and field crops. Potatoes and onions are frequent crops in USSR. Bulbs are an important enterprise on reclaimed peats in the Netherlands and East Anglia, UK. In Japan, rice is grown extensively on peatlands after improvement by adding a thin layer of clay and silt. In Malaysia, pineapple has been successfully grown on organic soils and large-scale oil palm cultivation is now expanding onto this soil type (Kamal, 1987; Chan and Purba, 1987). Reclaimed peatlands have also been utilized as pastureland. As a medium of growth, however, forestry is probably the most important usage of peatlands in the world. In the temperate regions, various conifer species are commonly grown on organic soils. In the tropics, natural peat swamp forests usually provide an important source of valuable timbers like "ramin" (*Gonystylus bancanus*), "belian" (*Eusideroxylon zwageri*) and "meranti" (*Shorea spp.*).

Peats with their absorbent and deodorizing properties have been used as a litter for cattle and poultry sheds. Having a large specific area, excellent ion exchange properties and a high affinity for heavy metals, peats can also be used as an effective medium for domestic and industrial waste water treatments in both natural peatlands and constructed peat systems (Mclellan and Rock, 1986; Viraraghaven and Rana, 1987).

In fertilizer industry, harvested peats have been utilized in the preparation of mixed fertilizers to add bulk and to reduce stickiness and caking. Other industrial applications include the manufacture of hardboards, peat coke, cardboard, roofing papers, filling materials and activated charcoal. In the chemical industries, many chemical constituents of peats and their derivatives can be extracted; these included furfural, alcohols, acids, waxes, bitumens, resins and oils.

Thus, peat and peatlands have been exploited for various purposes in different countries. In some countries, the harvesting of peat as a fuel and for horticultural and industrial purposes is economically significant. In others, the reclamation of peatlands for agriculture and forestry is essential. This reclamation for agriculture and forestry in particular will become more important as the world population increases and the shortage of land in general becomes more acute.

CHAPTER 3 THE PEAT SWAMPS OF SARAWAK

3.1 OCCURRENCE AND DISTRIBUTION

Sarawak is the largest state in the Federation of Malaysia, covering an area of 124,450 km^2 on the north-west coast of Borneo . It lies between latitude 0^o 50' and 5^o 00' North, and longitude 109^o 30' and 115^o 40' East. Figure 3.1 is a map of Sarawak depicting the locations of various places, rivers, trunk road and administrative Divisions mentioned in this thesis.

Planimetric measurement of the latest series of 1:250,000 land-use maps of Sarawak (1979-1983) shows that PSF cover an area of 13,190 km^2 (Maas *et al.*, 1986). Anderson (1964), however, reported that PS in Sarawak cover 14,660 km^2. Apart from the inherent errors in the determinations of these figures, the difference is probably due to the conversion of some areas of PSF, particularly at the fringes, into other forms of land use since Anderson made his estimate. These figures are also different from the reported acreage of organic soils, the latest figure of which is about 16,600 km^2 (Tie and Kueh, 1979). The latter is probably a better estimate of the real extent of peatlands in Sarawak because pattern of land use (and therefore the forest types) is a less permanent feature than soil types. Based on this figure, it can be calculated that PS account for about 13% of the total land area in Sarawak.

The distribution of organic soils in Sarawak is shown in Figure 3.2. and Table 3.1. Deep organic soils (organic soil materials deeper than 150 cm) are far more extensive than the shallow ones (50-150 cm), accounting for about 90% of the total acreage of organic soils.

Organic soils generally occur between the lower courses of the main rivers like Batang Saribas, Batang Lupar, Batang Rajang and its distributaries and Batang Baram. These lowland peats are usually bounded by sandy ridges on the seaward side or they merge into muddy coastal flats. Along the river they are normally flanked by low levees. Where the levee or the coastline has been eroded, peat can be found exposed along the river banks or sea shore. On the highly developed

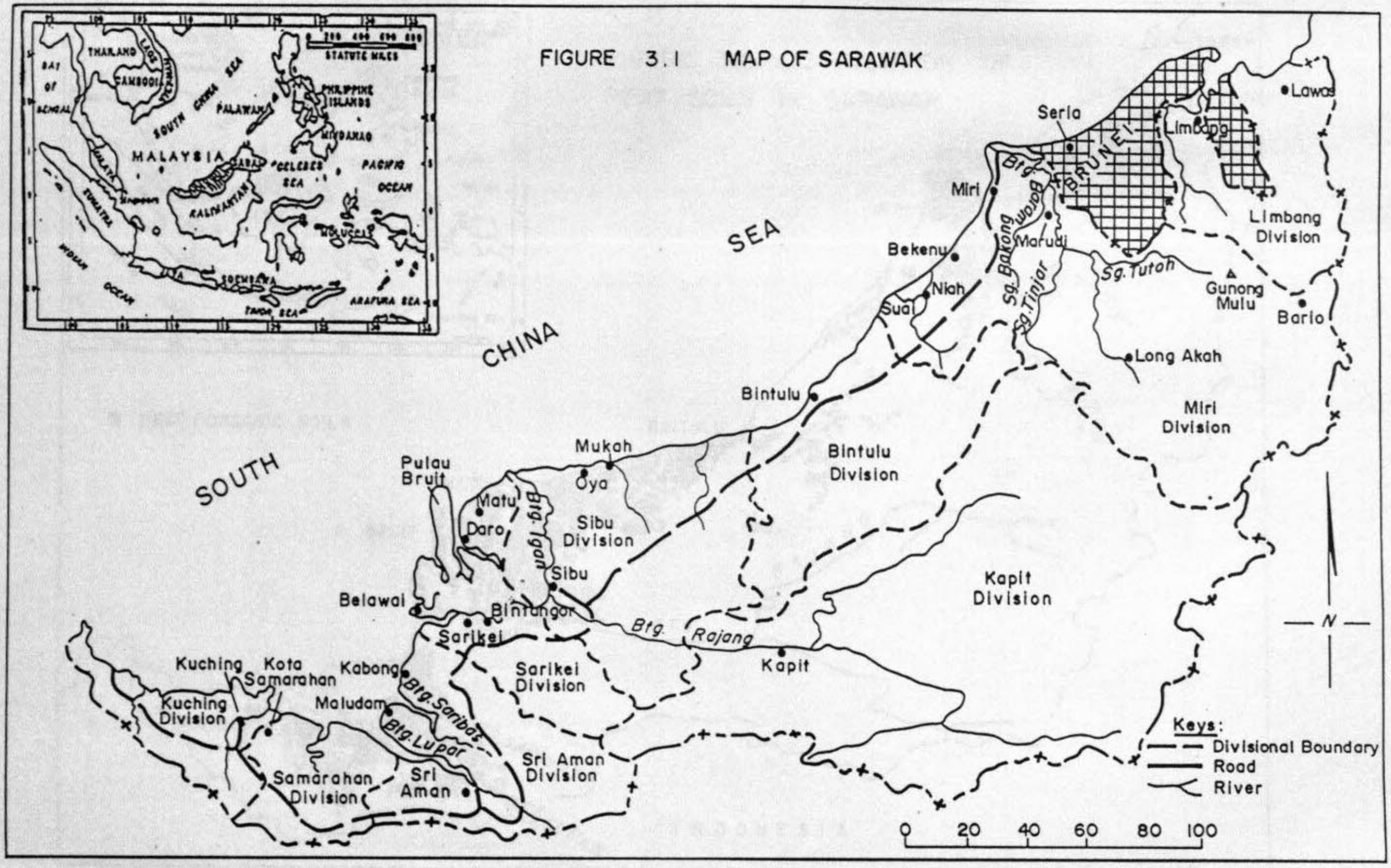


FIGURE 3.1 MAP OF SARAWAK

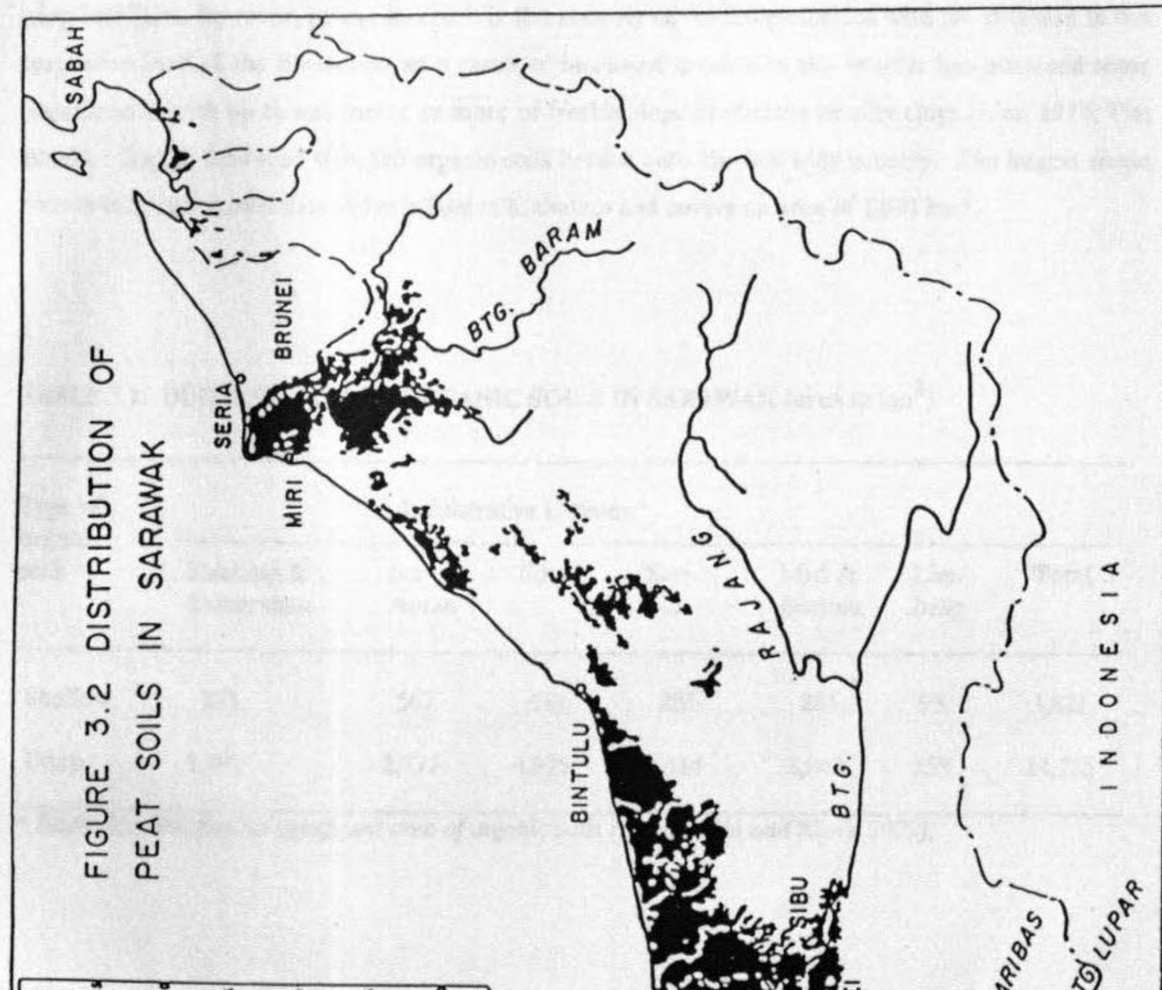


FIGURE 3.2 DISTRIBUTION OF PEAT SOILS IN SARAWAK

swamps further inland, the levee may be very narrow or absent altogether. At some other more low-lying localities, however, recent increase in the severity of flooding coupled with an increase in the suspended load of the floodwater as a result of increased erosion in the interior has plastered some organic soils with up to one metre or more of freshly deposited clays or silty clays (Lim, 1972; Tie; 1988b). On the landward side, the organic soils border onto the low hilly country. The largest single swamp in Sarawak stretches 64 km inland at Maludam and covers an area of 1,070 km^2.

TABLE 3.1. DISTRIBUTION OF ORGANIC SOILS IN SARAWAK (area in km^2)

Type of organic soils	Administrative Division*						
	Kuching & Samarahan	Sri Aman	Sibu	Sari-kei	Miri & Bintulu	Lim-bang	Total
Shallow	153	567	433	285	285	98	1,821
Deep	1,492	2,777	4,975	1,414	3,942	155	14,755

** Kapit Division has no significant area of organic soils (Source: Tie and Kueh, 1979).*

Organic soils in Sarawak are most extensive in the coastal floodplain areas. Small pockets of lowland organic soils are found in interior valleys where drainage is very poor. Some organic soils also occur at high elevation (more than 1000 m above sea level); they are found mainly in the floodplain areas on the Bario Highland (Eilers and Loi, 1982). Organic soils formed largely from mossy materials have also been mapped on the main peak of Gunung Mulu above 1800 m (Tie *et al.*, 1979). However, the present study does not cover these minor categories of organic soils; the emphasis is on the basin organic soils found on the coastal floodplain.

3.2 CLIMATE OF SARAWAK

Sarawak, situated just north of the equator, has a typical climate of the humid tropics. In general, the climate is characterized by high, even temperatures and heavy rainfall without a distinct dry season. It therefore qualifies for the hot and wet extreme of most global or regional climatic classification systems: the "Afa-tropical rainy climate, continuously moist" of Koppen, the "Group I" of Mohr et al.(1972), the "Type A Climate" of Schmidt and Ferguson (1951) and the "Equatorial Monsoon Climate" of Miller (1953).

The seasonal fluctuation of temperature is negligible. Air temperature changes more diurnally, with a range of 6-13^{o}C, the higher range being more commonly recorded in periods of dry, clear weather during the southwest monsoon. The mean daily air temperature in the lowlands is about 26-29^{o}C and the variation in the monthly mean is less than 2^{o}C. Under high forest, the diurnal range is only about 5^{o}C at ground level because of lower maximum temperatures, as the minimum temperatures are virtually the same under the forest canopy as in the open (Walsh, 1982). Soil temperatures at 122-cm depth remain virtually constant at about 29^{o}C throughout the year (Todorov, 1980). Records at 30-cm depth show a more irregular pattern but they rarely differ from those at 122-cm depth by more than 0.5^{o}C. The soil temperature regime in the lowland can therefore be classified as "isohyperthermic" in the nomenclature of Soil Taxonomy (Soil Survey staff, 1975).

The mean annual rainfall is high, varying from about 2500 to over 5000 mm. Its spatial distribution is shown in Figure 3.3. The variation is considerable; due to rain shadow effects, some localities like the Bario area receive less than 2500 mm of rain annually whilst it is more than 5500 mm around Long Akah area not far away.

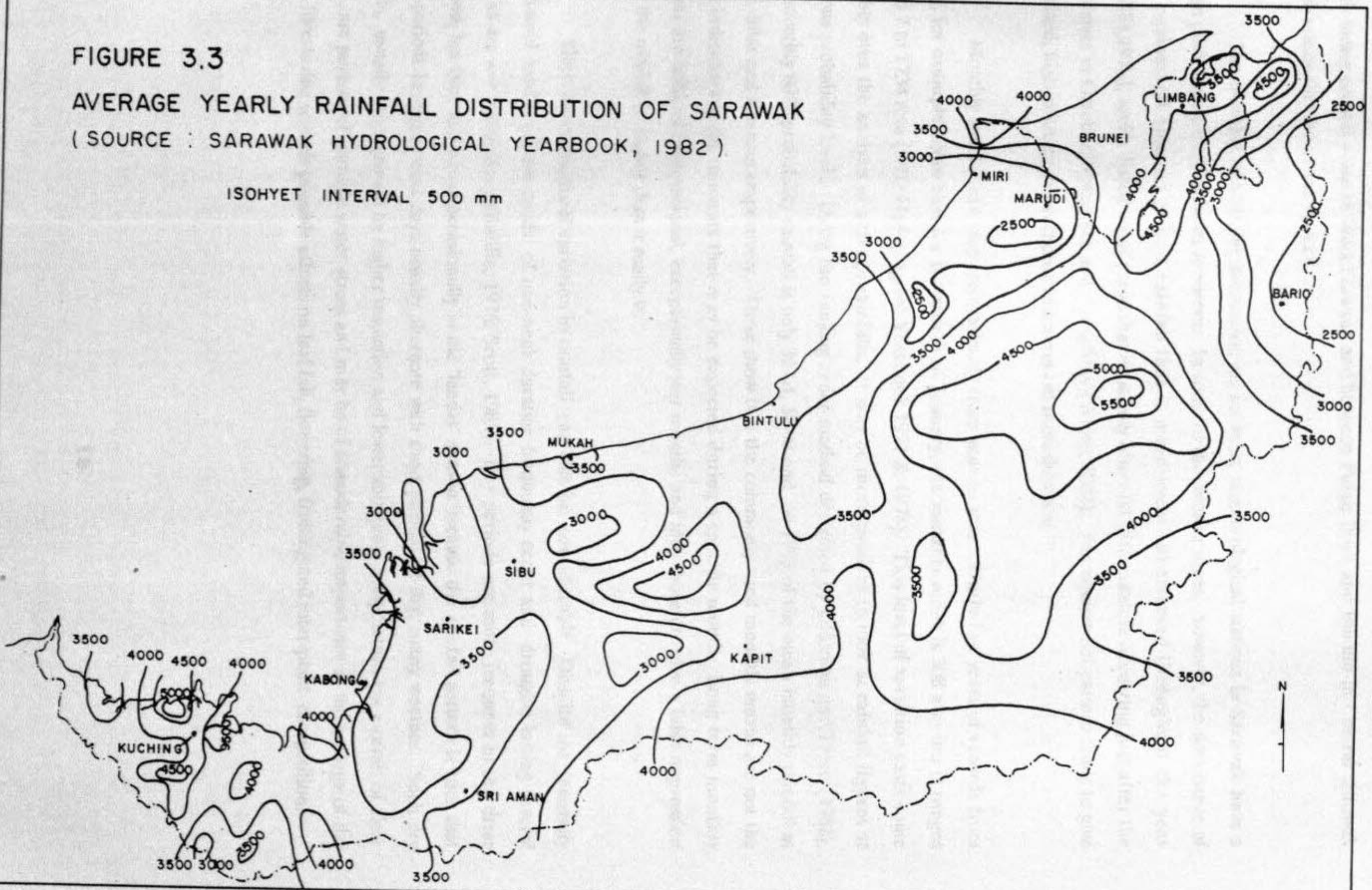
Although the rainfall seldom falls below 100 mm within any month, the monsoonal effect does give a seasonal pattern to the temporal distribution of rainfall. During the Northeast Monsoon from October to February, the rainfall is higher than average. The mid-year Southwest Monsoon season is drier because the mountain ranges along the border with Indonesia have a slight rain shadow effect. For most of Sarawak, the so-called "wet" ("landas") and "dry" seasons are not very distinct; the ratio of the mean rainfalls of the wettest to the driest month is generally less than 2. Only in some

FIGURE 3.3

AVERAGE YEARLY RAINFALL DISTRIBUTION OF SARAWAK

(SOURCE : SARAWAK HYDROLOGICAL YEARBOOK, 1982)

ISOHYET INTERVAL 500 mm



north-facing coastal areas in West Sarawak and between Pulau Bruit and Bintulu in Central Sarawak is the seasonality more pronounced.

The monthly rainfall distribution curves for most meteorological stations in Sarawak have a single peak during the Northeast Monsoon. In some of the interior areas, however, the dominance of the equinoctial element gives a rainfall that is more evenly distributed throughout the year (Baillie,1978), and a distribution curve that is usually bimodal with maxima occurring just after the equinoxes in October/November and April/May (Walsh, 1982). The equinoctial pattern tends to give localized, high intensity convectional rainstorms of short duration.

Monthly rainfall can vary tremendously from year to year. Thirty-five years of records from Miri, for example, show that for the month of January, the monthly mean is 308 mm but it ranges from 7 to 1734 mm (DID Hydrological Yearbook 1977 & 1978). This level of variation casts some doubts over the analysis of average rainfalls. It may be more prudent to look at rainfall figures at various probability levels. Using the ranking order method described by Oldeman and Frere (1982), the monthly 80% probability rainfall is only 39-64, 52-76 and 54-79% of the mean monthly rainfall at Miri, Sibu and Kuching respectively. These show that the commonly used monthly means are not the best indicators of the amounts that may be expected during a specific month. Long-term monthly means are inflated by occasional, exceptionally wet months and may therefore give a false impression that the rainfall is higher than it really is.

Short-term temporal variation in rainfall can also be considerable. Despite the generally perhumid conditions, dry spells of one-week duration frequently occur and droughts lasting several weeks are not uncommon (Baillie, 1976; Scott, 1985). Dry periods are more frequent in the drier season, but they also occur occasionally in the "landas" season because the rainfall pattern is such that wet periods lasting several days usually alternate with short periods of dry, sunny weather. Such dry spells, usually accompanied by higher insolation and lower minimum temperature (as a result of clear sky), are periods of possible water stress and may be of considerable importance in the ecology of the rain forests due to their possible effects on leaf fall, flowering, fruiting and inter-plant competition.

Potential evaporation as measured from an open water surface (Class A evaporation pan) shows less variation than rainfall. Evaporation tends to decrease during wetter months and in areas of higher annual rainfall, probably because of concomitant increase in cloudiness and decrease in insolation. Thus, mean annual evaporation at Kuching (1539 mm) is well below the 1737 mm recorded at Miri (Source: Sarawak Hydrological Yearbook, 1981 & 1982); the mean annual rainfalls are 4101 and 2908 mm respectively. Monthly evaporation usually has a maximum in April/May and a minimum in January/February. Mean daily values range from 4.0 to 4.8 mm. Because of the relative constancy in evaporation, the occurrence of moisture deficit is largely determined by variations in rainfall. Baillie (1976) showed that periods of plant moisture stress occur more frequently in coastal areas with more pronounced seasonality than in the interior with more even distribution of rainfall.

Mean monthly evaporation is almost always exceeded by mean monthly rainfall in all stations in Sarawak. As mentioned above, mean monthly rainfall may be misleading due to the large year-to-year variation. Recent comparisons by the author between mean monthly evaporation and monthly 80% probability rainfall show that moisture deficit may occur during July in Kuching and February to September in Miri. Under the terminology of Soil Taxonomy (Soil Survey staff, 1975), the general soil moisture regime could therefore be classed as either "udic" or "perudic" depending on the region and perhaps the nature of the soil. At poorly drained sites, the soil moisture regime is "aquic".

Totals of actual sunshine hours in the humid equatorial region are usually lower than expected as a result of the cloudiness. The daily mean for the year is 5.74 hours at the coast and 5.43 hours in the interior of Sarawak (Scott, 1985). Calculations of bright sunshine hours as a percentage of day length give a range of 30-53 at Stapok Station, Kuching and 41-58 at Paya Selanyau Station near Miri (Source: Annual Report of Research Branch, DOA for the year 1986), the higher values generally occur in the drier season in the middle of the year.

Relative humidity is high. Mean hourly values usually drop during the day to a minimum of only 55.9% at the coast and 58.0% in the interior, and consistently rise to 95.2 and 99.8% respectively during the night (Scott, 1985). Values of 100% at dawn are common. Monthly means at 0700 hours range from 98-100% under forest canopy (Walsh, 1982).

Overall run-of-wind is low, and flat calm accounts for more than 50% of all records at inland stations. Land and sea breezes reduce flat calms to about 20% at the coast. The higher frequency of breezes in coastal areas tends to increase the evapotranspiration and therefore the occurrence of moisture stress. Readings of winds velocity in excess of 18 km/hr account for less than 5% of the total (Baillie, 1978). However, the occurrence of short-lived, high gusts of wind (45-56 km/hr and above) in association with local convectional rain-storm is not uncommon. Ground evidence of wind damage is fairly widespread in the PSF (Anderson, 1964 b). This is ecologically significant in the formation of gaps in the upper canopy by crown damage or tree-fall, and in the disturbance of soil by up-rooting of trees.

Lightning is another localized event which has an ecological importance in creating canopy gaps. Lightning damage is of frequent occurrence in PSF, particularly in forest dominated by *Shorea albida* (Anderson, 1964b; Brunig, 1964). Anderson concluded that in tropical rain forest where thunderstorms are frequent lightning is one of the most important factors causing mortality among dominants.

3.3 ECONOMIC IMPORTANCE OF PSF

Until now, the prime importance of the peat swamps in Sarawak has been in timber production. Before World War II, the forests had little economic value. It was not until two years after the Japanese Occupation that the importance of PS began to be appreciated when the value of "ramin" (*Gonystylus bancanus*) as a timber was discovered (Anderson, 1961). After the immediate problems of borers and fungal "blue stain" had been solved, the "ramin" export trade blossomed rapidly. Within a short period of time, the timber exports as a whole increased dramatically. The tonnage (in Hoppus round tons) exported shot up from 5,699 in 1947 to 308,616 in 1957 of which "ramin" accounted for about 80% (Anderson, 1961). It was estimated that at least 95% of the timber industry was operating in the PSF during the 1950s. Apart from the value of "ramin" and other peat swamp species, this situation could also be partially attributed to the relative ease with which swamp timber could be extracted. The almost level surface of the swamps and the readily accessible rivers and deltaic channels on the margins simplify logging operations. Rail line extraction routes are constructed and the forest on either side is worked in blocks by the "Kuda-Kuda" method of hand logging to a normal depth of 360 m (18 chains).

In the last few years, however, more and more logging in Sarawak has been done in the upland areas and loggers are moving further inland. As a result, the production of logs and sawn timber from the hill forests has increased tremendously. Even so, the output from the PSF is still considerable. From 1979 to 1982, the production of logs from the swamp forests had remained fairly constant at about 2 million m^3 per annum (Ann. Rep. of Forest Dept., Sarawak, 1979-1982). However, the State output of logs increased from 6.05 to 9.20 million m^3. As a result, the contribution from the swamp forests declined from 36 to 21%.

Out of a total production of 12.3 X 10^6 m^3 of sawn logs and hewn timber in 1985, the PSF still contributed about 23% of the total (Ann. Rep. of Forest Dept., Sarawak, 1985). About 90% of the logs from the swamp forests, worth about 270 million ringgits (M$) F.O.B., were exported. In the same year, timber industry was the second export earner after petroleum and netted slightly over 1,515 million ringgits for the state of Sarawak.

At present, very little of the peatlands has been used for agricultural development. Areas cleared and reclaimed are usually confined to the fringes of the PS where the organic soils are shallower. These developments are generally undertaken on an *ad hoc* basis by the smallholders, mainly for the cultivation of wet padi and sago (*Metroxylon spp.*). A few Government drainage and irrigation schemes have encroached onto the PS. These schemes have so far encountered many problems, particularly with the construction of infrastructure such as drains and bunds. The largest area of peatland which has been exploited for agricultural purpose is between Sibu and Sarikei. Along both sides of Batang Rajang, about 31,000 ha of PS were cleared and drained for the planting of rubber at the turn of the century. The rubber boom in the early 1900s led to the development of this region and the growth of towns like Sibu, Bintangor (formerly Binatang) and Sarikei. However, the generally poor rubber price in the last two decades and the communist insurgency in the 1960s have resulted in the abandonment of most of these rubber gardens.

With the steady rise in population and the scarcity of good agricultural land in Sarawak, pressure for land has increased in recent years. Although the organic soils in Sarawak are not particularly good for agriculture they possess certain qualities which are worth considering. Due to their extensive area, favourably flat terrain (compared to the steep, rugged terrain of most areas with mineral soils) and proximity to the population centres, the organic soils constitute an important part of the land resources of Sarawak. The state government has embarked on a sago plantation project in a deep peat area near Mukah; the initial phase will plant up an area of 2,278 ha but a total of 16,188 ha is planned for development within ten years (Kueh *et al.*,1987). Another proposal for a 250-ha pilot project for large-scale feasibility study of coconut/cocoa and tapioca (cassava) cropping systems, and soil/water management research near Kuching is still being considered by the Government (Kueh and Wong, 1983). It is envisaged that demand for developing peatlands will steadily increase in the near future.

CHAPTER 4. LITERATURE REVIEW

4.1 INTRODUCTION

Until 1895, it was generally accepted in the scientific circles that the high temperature of the tropics, and consequently the rapid decomposition of organic materials, would prevent the accumulation of tropical peat. Early reports like those by John Anderson in 1794 and Bernelot Moens in 1863/64 (cited by Soepraptohardjo and Driessen, 1976) on the occurrence of coastal peat on both sides of the Strait of Malacca were largely ignored. At about the same time (1865-68), Beccari (1904) discovered and wrote about the "black waters" and the build-up of "carbonic material" (he did not call it peat) in the Kapuas Lakes in Borneo. From this observation, Beccari considered that some of the coal deposits in Borneo were lacustrine in origin. In 1895, Koorders, who was a member of the Ijzerman Expedition across Sumatra, described the extensive occurrence of tropical peat forests; later, a German coal chemist Potonie confirmed that the samples sent by Koorders were true peat (Potonie and Koorders, 1909). They defined the peat as a low moor, topogenous formation.

Since then, many occurrences of peat have been reported from tropical and sub-tropical areas. By the turn of the century, C.E.A. Wichman (cited by Soepraptohardjo and Driessen, 1976) already suspected that peats might cover an area of more than one million hectares in Indonesia. Sewandono (1938) described a "high peat moor" in areas of Bengkalis, Sumatra and Veen (1938) wrote about the conversion of peat soils in Besuki, Indonesia into good tobacco soils by "washing out excess sulphur". During the same period, the occurrence of peat was reported in India (Pillai and Subrahmanyan, 1931), Puerto Rico (Dachnowski-Stokes and Roberts, 1934), Brazil (Guinazu, 1934), Florida (Davis, 1946) and Palestine (Reifenberg and Moshiky, 1941). In Sarawak itself, Miller (1949) also wrote about the occurrence and utilization of peat swamps. By 1950, it was therefore well established that organic soils are extensively found throughout the tropics and sub-tropics.

Some of the earliest detailed investigations of tropical peat soils were made by Polak in Indonesia during 1930-1950. In Malaysia, the early studies were done by Coulter (1950; 1955; 1956;

1957) and Anderson (1961; 1963; 1964a; 1964b). All these are reviewed in more detail in the following sections.

In the last few years, there has been a tremendous amount of interest on the uses of tropical and sub-tropical peatlands. Out of a total of 116 papers presented in the second International Peat Congress (IPC) held at Leningrad in 1963 (Taylor, 1964), for example, there was not even a single paper which dealt directly with tropical or sub-tropical peats. In the third IPC (Quebec, Canada; 1968), 38 papers were discussed; once again, they were all about temperate peats. The situation improved slightly in the fourth IPC (Otaneimi, Finland; 1972) during which four papers on tropical and sub-tropical peat soils were presented; notably, two from Malaysia were included (Tay, 1972; Wee, 1972). During the sixth IPC (Duluth, Minnesota, USA; 1980), one paper on Jamaican peat and five papers on the sub-tropical organic soils in USA were discussed. This finally culminated in the staging of a full-fledged international symposium on "Tropical Peat and Peatlands for Development" in 1987. The symposium was jointly organized by the International Peat Society, Gadjah Mada University, and Agency For The Assessment And Application of Technology of Indonesia. The venue was appropriately at Jogyakarta, Indonesia - the country with the largest area of tropical peatlands (see Section 2.2). During the symposium, nearly 90 papers on tropical peat and peatlands were presented. The emphasis was on the development of peatlands for agriculture and forestry, but other uses like the utilization of peat as a fuel were also covered.

4.2 TROPICAL PEATS AND PEATLANDS

4.2.1 Earlier Studies

The most fundamental and some the earliest studies of tropical peat soils were made by Polak in 1930-50. Her main contribution was to describe the structure, hydrology and chemical composition of the peatlands in Indonesia. From her studies (Polak, 1941; 1946; 1950) on the lowland peats, Polak divided them into two types: the ombrogenous and the topogenous peats. The lowland ombrogenous moor, as Polak (1950) pointed out, is situated above the normal groundwater level because of its dome-shaped morphology; topogenous peat, deposited in topographic depressions, occurs in the lowlands and at high altitudes in the mountains. Both Richards (1952) and Van Steenis (1950) stated that the topogenous peats occupied a greater area than the ombrogenous. However, when Van Steenis (1958) compiled his Vegetation Map of Malaysia, he did not differentiate between the two types of peat. Nowadays, it is generally recognized that most of the lowland peats in Indonesia (Pons and Driessen, 1976) and in Sarawak are ombrogenous although probably all of them have started out as topogenous peat.

Polak (1950) observed that the peat was built up by the debris of former forest generations, decayed into a brown mash and held together by a frame of undecomposed tree branches and stems. The ombrogenous peat was extremely oligotrophic with the content of ash ranging from 1 to 3%, that of total phosphate from 0.01 to 0.09%, potash from 0.02 to 0.20%, and lime never exceeding 0.5%. She also wrote that the topogenous peats were more fertile with 9-11% ash, 0.1% phosphate, 0.15% potash and 2% lime.

During the same period, some agronomic trials were also carried out. Ehrencron (1949) concluded that satisfactory crop yield could only be ensured by the application of lime and NPK fertilizer.

In the 1950s, Coulter (1950; 1955; 1956; 1957) made intensive investigations on the PS in Malaya in order to assess their agricultural capability. He estimated that there were about 8100 km^2 (two million acres) of peat (Coulter, 1957), and he used the term "Bog soils" to cover all swamp deposits in Malaya. Chemical examination showed that lowland peats of Malaya are more like the high-moor or oligotrophic peats of temperate countries than low-moor or fen peats. Fractionation showed that lignin makes up a large proportion of the organic matter. Level surveys showed that the convex surface formation is present in the Kuala Langat Forest Reserve (Coulter, 1956), but absent in the Trans-Perak swamp (Coulter et al., 1956). Generally, the peats are relatively shallow; depths over 5.5 m (18 ft) are rare. Field and pot experiments led him to make the following recommendations:

(a) Shallow (1.1-1.2 m) peat is only third class padi soil; on deeper peat, the cultivation of padi would be uneconomic;

(b) Where drainage by gravity is possible, the growth of pineapple on deep peat, and coffee and oil palm on shallow peat is suggested; and

(c) Areas of peat soils with sandy subsoils, or where drainage is difficult, are best left for forestry.

Coulter (1957) also advocated that where possible, the peat deposits should be completely disposed of by removal, burning and/or natural oxidation so that the underlying "fertile alluvium" could be utilized for agricultural purposes.

In Borneo, Van Wijk (1951) briefly studied the PS of Kalimantan in connection with their agricultural possibilities. In 1953, Fitch (1953) wrote about the testing of the fuel value of peat from the 800-ha swamp near Papar, Sabah; the geologists were then interested in using peat as a fuel for railway locomotives in the place of wood or coal. Blackburn and Baker (1958) also found large areas of deep acid PS occupying most of the lowland in Brunei.

In Sarawak itself, the most comprehensive studies to date were done by Anderson (1961, 1963, 1964a). The results and information generated from this series of investigations are reviewed in more detail in section 4.3 together with other studies done on the organic soils and PS of Sarawak.

Further afield in India, Pillai and Subrahmayan (1931) investigated the origin and nature of the peaty soils of Travancore. Subramoney (1951) concluded that these acid peats ("Kari") were infertile, low-lying and cover 207 km^2. In tropical America and Africa, the nature of the peat swamps had also been briefly studied during the same period up to 1960. Chenery (1953) investigated the papyrus peat swamps in Uganda and suggested flooding, leaching and heavy liming as measures to reclaim "dead peats". Ripado (1954) wrote about the properties of peat soils of Mozambique and recommended, contrary to Coulter's (1957) suggestion for Malayan peats discussed above, that rapid decomposition of the organic matter should be avoided upon reclamation. Aubert (1954) singled out the peat soils from the rest of the hydromorphic soils of French West Africa on the basis of complete and permanent waterlogging. Clayton (1958) studied the remnants of a shallow raised bog in Nigeria where peat had developed with an average annual rainfall of only 1300 mm. In British Guiana, Paul (1953) reported on the chemical characteristics and trace element contents of virgin and cropped peat soils, indicating that the nutrients were rapidly depleted by continuous cropping with sugar cane.

4.2.2 The Vegetation

Prior to Anderson's studies (see section 4.3), information on the floristic composition or ecology of the PSF of the Malesia was not comprehensive. Endert (1920) recorded *Campnosperma macrophyllum* as forming almost pure forests on the Moesi delta in Sumatra; in the centre of the swamps in southern Sumatra and Eastern Borneo, *Tristania obovata* and *Ploiarium alternifolium* were dominant. In describing the peat areas of Bengkalis in Sumatra, Sewandono (1938) estimated that there were less than a hundred tree species in the PSF. Polak (1941) dealt only briefly with the vegetation but she had observed the concentric zonation of vegetation in the swamps of Paneh Peninsula in Sumatra. The forest on deep peat consisted of four zones, namely: (a) the outer forest with a thick undergrowth of *Licuala* and *Zalacca* (now *Eleodoxa*) palms; (b) the second zone of dense forest; (c) the high forest of thin stemmed trees mixed with dwarf trees; and (d) the central area of dwarf forest dominated by *Tristania*. In a brief account of PSF in Malesiana, Van Steenis (1950) provided a list of the principal genera but only mentioned three species by name. The list of genera was not very useful because most of them were not exclusive to the PSF.

Durgnat (1952) gave a brief account of a PSF in Lower Perak, Malaya where the peat was about 3.7 m deep and the principal dominants were *Shorea rugosa* , *Campnosperma spp*. and *Cratoxylon arborescens*. Subsequently, a more comprehensive account for all the Malayan PSF was provided by Wyatt-Smith (1959). Many of the common species are also found in Sarawak, including *Blumeodendron tokbrai, Gonystylus bancanus, Palaquium ridleyi, Shorea rugosa*, and *Shorea teysmanniana*. The height of the canopy was about 30 m and the density of the main canopy was less than that in upland rain forest. Emergents were generally absent. Wyatt-Smith also noted distinct variations in the vegetation on very shallow (30-60 cm) peat, deep peat and a peat overlying clay or different substrata; variations consequent of distance from dry land seemed to occur too. Many of the species recorded from Malaya were also listed by Kostermans (1958) for the PSF in Borneo. Compared to those in Sarawak, the PSF in Peninsular Malaysia are more open, with fewer species and probably lower biomass (Anderson, 1983).

Recently, three PS in Riau Province, Sumatra and two in Indonesian Borneo were studied by Anderson (1976). A "catenary sequence" of forest types, with similarities to that found in Sarawak, was also observed. The floristic and structural changes along the "catena" are more marked in

Kalimantan than in Sumatra. Many of the dominant and most abundant species in Borneo are apparently absent in the Sumatran swamps. As revealed by the aerial photographs and satellite imagery, the dense pole-like forest (usually called "Padang") is very extensive in the Sumatran PS. However, most of the principal dominants of Padang Forest in Kalimantan are absent in Sumatra. The swamp forests in Kalimantan also have a consistently larger number of trees per unit area.

4.2.3 Recent Studies in Indonesia

After the initial work done by Polak and a few other scientists, the study of peats in Indonesia was more or less neglected for about 25 years. In the early seventies, studies in the peat areas particularly in the provinces of Riau, Jambi and South Sumatra, and Central and West Kalimantan were resumed. As part of the Netherlands technical cooperation project ATA 106, a series of surveys and studies was initiated with the aims of finding ways to differentiate sub-types in the vast coastal peatlands and of developing guidelines for the optimal utilization of each peat type. Test farms were also started to enable multi-disciplinary study of soils, ecology, agronomy, engineering aspects and social economy. The ATA project itself generated several technical papers which include: (a) Soepraptohardjo and Driessen (1976) who reviewed the background of the study and the problems of reclamation; (b) Driessen and Suhardjo (1976) who reported on the defective grain formation of Sawah rice on peat; (c) observations on the ecology of the five PSF in Sumatra and Kalimantan by Anderson (1976); and (d) an account of the physical properties (Driessen and Rochimah, 1976) and chemical characteristics (Suhardjo and Widjaja-Adhi, 1976) of the lowland peats. Driessen and Sudewo (1977) published another review of the crop performance on Southeast Asian lowland peats.

Following this, the research on peats and peatlands in Indonesia gained momentum and progressed rapidly. During the international symposium on "Tropical Peat and Peatlands for Development" held at Jogyakarta, Indonesia in 1987, 68 papers dealing directly with Indonesian peats and peatlands were presented. It is interesting to note that eleven of these papers dealt with the use of peat as a source of energy. Perhaps this indicates an impending increase in the use of peat as a fuel, both domestic and industrial, in Indonesia. The majority of the papers were on subjects related to agriculture and forestry. Siefermann et al. (1987) wrote about the genesis of peat in the lowlands of

Central Kalimantan, attributing the accumulation of peat to the low base status of the substratum in one case and to the poor drainage in another case where base saturation was high. Sieffermann and Sasitiwarih (1987) reported on the ease of mapping undisturbed peat areas by conventional air-photographs and LANDSAT imagery. Soepardi *et al.* (1987) found that most of the inland peats in Central Kalimantan are underlain by quartz sand and are extremely infertile; getting a good crop is not possible unless mixing with imported alluvial soils and complete fertilization are undertaken. Hardjowigeno and Selari (1987) rated most of the peat soils in Jambi as moderately to marginally suitable for agriculture, while in Riau province many are marginal to unsuitable. In forestry, the main interest now seems to lie in the use of peat as a growth medium for seedlings of trees in the reforestation programme (e.g. Sinaga, 1987). The need for national land-use planning and conservation was also echoed by several authors such as Atmawidjaja *et al.* (1987) and Haeruman (1987).

4.2.4 Recent Studies in Peninsular Malaysia

In Peninsular Malaysia, research on peat soils after 1960 was concentrated in the field of agriculture. This is understandable because of the increasing pressure to develop peatlands for agricultural purposes. With the establishment of the Peat Research Station in Jalan Kebun, Klang in the early sixties, many experiments were conducted on various crops to find out their potential and requirements. The Malaysian Agricultural Research and Development Institute (MARDI) took over Jalan Kebun Station in 1970 and established another Integrated Peat Research Station near Pontian, Johore. Pineapple had earlier been found to grow well on peat soils (Coulter,1956; Tay and Wee, 1972), producing high quality fruits for the canning industry in Johore. A large number of annual crops were later found to be suitable; these include tapioca, sweet potato and vegetables (Chew, 1970; 1977; Chew and Yeong, 1974). Joseph *et al.* (1974) recommended groundnut-sorghum-tapioca as the best crop rotation on peat soils. Of the perennial crops, coffee seems to do well and rubber and coconut are grown on shallow organic soils (Hashim, 1984). The greatest potential, however, is shown by the performance of oil palm on both shallow and deep peats (Kanapathy, 1978; Yim *et al.* 1984; Kamal *et al.* 1987); more and more oil palm are being currently planted on reclaimed peatlands in Peninsular Malaysia.

There has also been research on mechanization and water management. Work done by MARDI has shown that rubber-tracked transporters are promising, and a type of mini-excavator is suitable for land clearing of shrubs and undecomposed wood and for field drain construction and maintenance (Ooi, 1985a; 1985b).

Hewitt (1967) wrote about the origin of lowland peat in Malaya but his stages of formation seem to have been transferred directly from Anderson's (1964) work in Sarawak. More detailed studies on their properties and characteristics (e.g. Ismail, 1984) have shown that the lowland organic soils in Peninsular Malaysia are quite variable; differences between East Coast and West Coast's peats are particularly evident in characteristics like peat depth, ash content and nature of substratum. These differences suggest that the genesis, distribution, physical and chemical properties, and classification of organic soils need to be investigated. All this basic information will have strong implications in the development and management of peatlands for agriculture, forestry, conservation or other uses.

4.2.5 Recent Studies in other Tropical Areas

Peats in other tropical areas have received much less attention than those in Indonesia and Malaysia. During the first international symposium on tropical peats and peatlands held in 1987 in Indonesia, only eight papers out of 90 were directly related to tropical peats outside Indonesia and Malaysia. Perusal of literature generally reveals that technical papers and reports on tropical peats and peatlands are fairly scarce.

In Africa and Central and South Americas, the main interest seems to be the utilization of peats as a fuel. Thus, Korpijaakko (1987) wrote about the development of a remote sensing mapping procedure to detect mangrove peat deposits overlain by mineral soils in Senegal, and the testing of such peats as a source of domestic fuel. Ramirez *et al.* (1987) highlighted the potential usage of peats in Panama for the generation of electricity; it was estimated that a 82 km^2 peat bog could support a 30-MW power plant for 360 years. Wade and Blackwood (1987) reported on the potential of peats in Jamaica for power generation and as a domestic fuel; they, however, also mentioned that other uses of peats and peatlands as a horticultural growing medium and for agriculture, aquaculture and natural reserves have been considered.

The usefulness of peats in Sri Lanka as a fuel for power generation was reported by Lappalainen (1987). Eiumnoh (1987) wrote about the genesis and characteristics of peatlands in Southern Thailand; he believed that the peats there had developed under lagoonal conditions between sandy beach ridges. The net primary production of *Melaleuca leucadendron* stands in the swamp forest of Southern Thailand was studied by Charin Samati (1987) who found that the total aboveground biomass was approximately 32.1 t/ha and the net primary production was 9.27 t/ha/yr.

In the Philippines, the utilization of peat soils for the cultivation of wet padi (*Oryza sativa*) was investigated. Quijano and Nene (1987) reported the varietal selection trials done at the International Rice Research Institute; out of 2,500 rice varieties tested, they found 200 which were tolerant of peat soil conditions. Ottow *et al.* (1987) highlighted the problem of iron toxicity in wet padi growing on peaty soils of Asia and Africa. The problem was found to be largely alleviated by P and K fertilization; Zn should also be supplied before transplanting.

4.3 PREVIOUS STUDIES ON THE PS OF SARAWAK

4.3.1 Peat Swamp Forests (PSF)

In Sarawak, the extraction and marketing of timber are undertaken by licensed private enterprises. The silvicultural management, including reservation of forests, control of exploitation and preparation of felling and working plans is carried out by the Forest Department. Development of sound silvicultural system requires a considerable knowledge of the floristics, structure and dynamics of the forest. When research work was first initiated by Forest Department, it was therefore natural that the early work was concentrated on the ecology and silviculture of the then economically important PSF.

In 1948, little was known about the ecology of the PSF in Sarawak. Even the botanical identity of the principal dominants was obscure. It was only as a result of enumeration surveys in the Rajang Delta in 1949-50, combined with the interpretation of air-photographs, that zonation of PSF was first discerned (Smythies, 1950; 1951). Three forest types were recognized, namely Mixed Swamp Forest, Alan Forest (dominated by *Shorea albida*) and Padang Medang Forest,which was renamed as Padang Paya Forest in the land-use map of 1957. In a paper on Kerangas Forests of Sarawak, Brown (1952) wrongly hypothesized that the zonation of the PSF was caused by subsidence of the coastline and that the original vegetation consisted of conifers and *Shorea albida* on Kerangas soils.

The most comprehensive study on the ecology of PSF, which spanned over a period of almost ten years in the 1950s, was undertaken by Anderson (1961; 1963; 1983). Anderson recorded 253 tree species (including 40 small trees which rarely exceed 5-10 m in height) in the PSF. In one forest type alone, as many as 75 tree species are found on an area of 0.4 ha (one acre). Many of these species are also found in other forest types outside the PS. It is significant to point out that many species which are largely confined to the periphery of PSF also occur in the lowland dipterocarp forest. On the other hand, the species that are present in the forest types in the centre of the swamps are mainly those that are also found on poorer soils, frequently podzols, of the heath forest (Anderson 1963: p.140).

The flora of the PSF of Rajang Delta is richer than those of other PS in Sarawak. In general, it has been found that upper storey species tend to have a more widespread distribution than species of the lower storey. Understorey trees are frequently very localized. *Shorea albida*, for example, occurs in PS from the Sadong river in the southwest to the Badas swamps of Brunei; it is however absent further north in Lawas where it is replaced by a conifer, *Dacrydium pectinatum* and *Casuarina* sp. nov. ("Rhu Ronang"). Palynological evidence has indicated that many of the species have been present in the PS of Borneo for at least 7 million years (Anderson, 1983). Anderson (1963) suggested that the recent changes in sea level during the Pleistocene with consequent erosion and deposition along the coasts may have been an important factor in determining the geographical distribution of PS species. He concluded at that time that more information was required for a better understanding of the phytogeography of these species.

The PSF show conspicuous changes in vegetation types from the periphery to the centre of each dome-shaped PS. Anderson (1961) had used the term "Phasic Community" (PC) to designate a vegetation type. Six PC were recognized on the basis of floristic composition and structure of the vegetation (see Table 4.1). They were numbered PC 1 at the periphery to PC 6 in the centre of the PS. The main changes that characterize the concentric zonation which can easily be seen on aerial photographs are :-

(a) An almost complete change in the floristic composition. *Dactylocladus stenostachys* is the only tree species found in all six types. Amongst the ground flora, only the sedge *Thorachostachyum bancanum* has a similar distribution.

(b) A reduction in the number of tree species per unit area and the total number of species recorded from the edge to the centre. In PC 1 and 2, 30-55 tree species (>30-cm girth) are found in 0.2 ha, PC 3 and 4 have about 12-25 species and finally in PC 6 less than five occur.

(c) A general increase in the number of stems (more than 30-cm girth) per unit area. In PC 1, it varies between 600 and 700 per ha, whereas in PC 4, 650-850 stems usually occur and in the low, dense forest of PC 5 the number is increased to 1200-1350. PC 3 is the exception with only 350-600 stems per ha, and in the open, stunted forest of PC 6, relatively very few stems are found.

(d) A decrease in the average size of a species. *D. stenostachys*, for example, may attain a girth of up to 6 m and a height of 30 m in PC 1 but in PC 6, it occurs as no more than a small tree, usually less than 4 m in height. *S. albida* also decreases in size from a girth of up to 8 m and a height of 60 m in PC 2 to pole-like trees in PC 4 where they are usually 60-120 cm in girth.

Anderson (1961) hypothesized that the "catenary sequence" represents ecological changes involving adaptation to more limiting conditions towards the centre. Though deeper peat soils are normally found towards the centre of individual swamp, Anderson contended that depth *per se* has probably little influence once it exceeded 1.5-2.0 m and the roots can no longer ramify into the mineral subsoil. PC 1 has been found on peats exceeding 15 m in depth while PC 4 may occur on peats of less than 5 m. He suggested that the drainage regime in relation to the PS structure may be a contributing factor: PC 1 and 2 occur on the periphery where the gradient is greatest and the drainage conditions better; on the central, flat bog plain, lateral movement of water is more restricted and the surface peat soil probably more anaerobic during the wetter months. Anderson also mentioned that the availability of nutrients may be a further and probably more critical factor, especially in PC 4 to 6.

TABLE 4.1. CHARACTERISTICS OF THE SIX PHASIC COMMUNITIES (after Anderson 1961,1963,1983)

PC	NAME	MAIN TREE SPECIES	
		UPPER STOREY	MIDDLE - UNDERSTOREY
1	Gonystylus-Dactylocladus -Neoscortechinia Association (Mixed Swamp Forest)	*Gonystylus bacanus*(Ramin) *Dactylocladus stenostachys* (Jongkong), *Shorea* spp., *Copaifera palutris*	*Neoscortechinia kingii* *Alangium havilandii*
2	Shorea albida-Gonystylus -Stemonurus Association (Alan Forest)	*Shorea albida*, *Gonystylus bacanus*	*Stemonurus umbellatus*
3	Shorea albida Consociation (Alan Bunga Forest)	*Shorea albida*	*Tetractomia holttumii*, *Cephalomappa paludicola* *Ganua curtisii*
4	Shorea albida-Litsea -Parastemon Association (Padang Alan Forest)	*Shorea albida*, *Litsea crassifolia*	*Parastemon spicatum*
5	Tristania-Parastemon-Palaquium Association	*Tristania obovata*, *Parastemon spicatum*, *Palaquium cochlearifolium*	Saplings of bigger trees
6	Combretocarpus-Dactylocladus Association (Padang Paya Forest)	*Combretocarpus rotundatus*	*D.stenostachys* *Litsea crassifolia*, *Garcinia cuneifolia*

(...continue on next page)

TABLE 4.1. (Cont.)

PC	Emergent height(m)	Girth	Stems* per ha	Species+ per 0.2ha	Canopy	Other features of trees and ground flora	Occurrence
1	40-50	n.a.#	600-700	30-55	Uneven; multi-storeyed.	Structure and physiognomy similar to MDF on mineral soils; many species with pneumatophores, stilt roots and buttresses; *Zalacca conferta* may form dense thickets esp. on shallow peats.	Periphery zone of swamps, esp. Rajang Delta and near the coast.
2	up to 60	2-4 m, few up to 7m	n.a.	40-45	Uneven; multi-storeyed.	Similar to PC 1 but with scattered very large *S. albida* trees; large trees usually hollow and with stag-headed crowns; *Nepenthes bicalcarata* and *Pandanus andersonii* frequent.	Common; extensive in Rajang Delta.
3	45-60	1-3 m	350-600	10-20, usually <15	Even.	Middle storey sparse; lower storey moderately dense; cauliflower-like crowns of *S. albida* distinctive on air-photo; large trees heavily buttressed; *P. andersonii* frequent.	Extensive in Lupar-Saribas and Baram swamps, largely absent in Rajang Delta.
4	30-40	60-120 cm	650-850	10-25	Mainly even; dense.	Very slender stems giving pole-like aspect; dense understorey 3-6 m high; *Nepenthes spp.* quite frequent.	Common in central areas of swamps in Rajang Delta and as transition zones in Baram.
5	15-20	mostly <60 cm	1200-1350	11-18	Even; dense.	Understorey sparse; herbaceous plants largely absent; some pitcher plants.	As transition zones in Baram & Brunei swamps.
6	Few >12	45 cm, few 75-90 cm	Few	<5	Open; shrub-like.	Stunted, xeromorphic, with pneumatophores; *Myrmecophytes* and *Nepenthes spp.* numerous; sedge, *Thorachostachyum bancanum* and *P. ridleyi* abundant; sphagnum moss also occurs.	Only in central areas of swamps along middle reaches of Baram River.

* Stems with 30 cm girth or larger; + Tree species with 30 cm girth or larger; # (information) not available.

In particular, easily soluble phosphorus and potassium of surface peats had been found to show a decrease along a transect towards the centre of a highly developed swamp near Marudi (Anderson,1961, Chapter 4).

The xeromorphic characteristics of Padang Paya Forest (PC 6) and its resemblance to the Kerangas Forest on humus podzols are particularly interesting. Whitmore (1975) suggested that periodic water stress may be an important factor in these forest types. Brunig (1971) cited a review by Loetschert on the relation between xeromorphy and nitrogen nutrition of peat bog plants; the latter concluded that the more xeromorphic plants were also less well supplied with nitrogen. A general association between xeromorphic-sclerophyll development and nutrition, particularly that of phosphorus and nitrogen, has also been described in Australia (Webb,1968).

The surface aerodynamic roughness, the height of the stand canopy and the heat load estimator decrease along the gradient from better drained perimeter to water-logged centre of deltaic PS much like the gradient from MDF on deep hill soils to Kerangas Forests on shallow podzols (Brunig, 1971). All these characteristics plus the smaller leaf size and the xeromorphic features of Padang Paya Forests help to reduce transpiration. Brunig (1974) mentioned that low transpiration rates may be essential to avoid excessive uptake of toxic solutes from the highly acidic phenol-rich groundwater common to both of them.

Brunig (1971) also found that the very high albedo and the peculiar crown and canopy structure (dense cauliflower crown shape, and dense and smooth canopy surface) of *Shorea albida* would compensate for the effect of larger leaf size as far as transpiration rates are concerned. The dominance of this species on interior PS sites may also be partly related to efficient avoidance of toxic substances in the peat water through low transpiration rates and its association with low fertility in PS may be indirect.

The palynology of samples taken from a 13-m core collected in PC 6 near Marudi had also been examined (Anderson, 1961; Anderson and Muller, 1975). The study showed that the basal clay at 11.5-13.0 m below the present surface was rich in *Rhizophora*, *Nypa*, *Oncosperma* and *Acrostichum* pollen, clearly indicative of a former zone of mangrove vegetation. A sharp boundary between 10 and 11 m with a decrease in mangrove pollen and a sharp increase in peat pollen types, particularly those of *Campnosperma*, indicated the former presence of *Campnosperma - Crytostachys - Zalacca* sub-association. This is found in the transition zone between current mangrove and PSF in some of the coastal areas. Above 10.5 m, the pollen was almost entirely that of the PSF. It was also evident that there was a temporal succession on the site sampled, with similarities to the present spatial "catenary sequence" of forest types with PC 1 occurring first and PC 6 only developing at the end of the sequence. Comparison with a Miocene coal from Berakas, Brunei, situated about 115 km northeast of the location of Marudi core, showed that the Holocene and Miocene PS vegetation, separated by about seven million years, has probably seen little changes. The earlier PS had a composition similar to that of present-day PC 1 and had probably never developed into a raised bog.

On the basis of these ecological studies, one of the first management plans was prepared for Bintulu PSF in 1961 (Brunig, 1961).Despite the intensive logging of PSF and its great potential as an economic resource, forestry research was very much reduced when Anderson turned his attention to limestone forests. However, a few silvicultural plots were maintained and assessed intermittently as part of a continuing investigation on the regeneration of logged-over PSF (Clark, 1968; Lee, 1972).

4.3.2 Structure and Development of PS

Anderson (1961) also studied the structure of the PS in Sarawak by means of level surveys and borings to the substratum. Similar results from the Geological Survey Department and from the consultant studies done by White et al. (1956; 1957a; 1957b) were also considered by Anderson (1964a). The PS are usually bordered by a narrow levee of mineral soils which may be liable to flooding. On the land-ward side of highly developed swamps, the levee may be absent or very narrow. On the seaward side, the swamps may grade into mudflats or be bordered by sandy beach deposits.

There is a general rise in elevation in a convex form from the river or coast into the PS. The absolute rise and the convexity at the periphery become more pronounced with distance from the sea. The maximum rise of 9.3 m was recorded at Naman Forest Reserve near Sibu and the most pronounced convexity of the swamp surface at Tanjung Pasir swamp near Marudi. The central bog plain is almost flat with a rise of less than half a metre per kilometre. With the rise in surface elevation, there is a corresponding fall in the level of the basal mineral materials, usually clays or silty clays, from the river-bank or coast into the swamp centre. This gives the peat deposit a lenticular cross-section. Peat depth therefore normally increases from the periphery to the centre. Both small rises and old river channels may, however, be buried under the peat. In such cases, the depth of peat becomes highly irregular. The partially drowned landscape typical of the hill-swamp transition zone around Sibu area is a good example, and it is near here that Anderson (1983) recorded peat depth up to 17 m at a point which probably represents an old river channel. The greatest depth of peat recorded is 21 m in a swamp at the apex of Rajang Delta (Anderson, 1973). The peat mantle also tends to thicken on the landward side as a result of more prolonged development. It has been found that the substratum level is mainly below the present normal river level, but rarely below the mean sea level except in the Rajang Delta.

In Sarawak, the wide meanders of the lower river courses may cut through the levees and expose and erode the peat itself. This may also occur on the seaward fringe due to a change in marine currents. An organic soil formed entirely from peat which was eroded and then redeposited has been found in the Pulau Bruit area (Scott, 1985).

The domed surface of the PS restricts flooding to the periphery where mineral soils at the levees usually grade into muck soils before true peats are encountered. The water table throughout the PS is normally at or close to the surface. As the ground surface is domed, the water table is therefore stilted. Preliminary investigation by Anderson (1961) indicated that the seasonal variation in water table level in the peripheral zone may be about 10 cm, whereas a slightly greater variation of about 20 cm occurs in the centre of a swamp. The maximum range of variation had not been recorded because observations were only taken for seven months. Nevertheless, he suggested that this slight difference in the drainage condition may be one of the factors contributing to the zonation of forest types in the PS of Sarawak (see 4.3.1 above).

Groundwater flow in the PS is apparently confined to the top 1-2 m. The presence of well preserved woody material in the peat deposit below the surface indicates cessation of decomposition and suggests complete stagnation of sub-surface water.

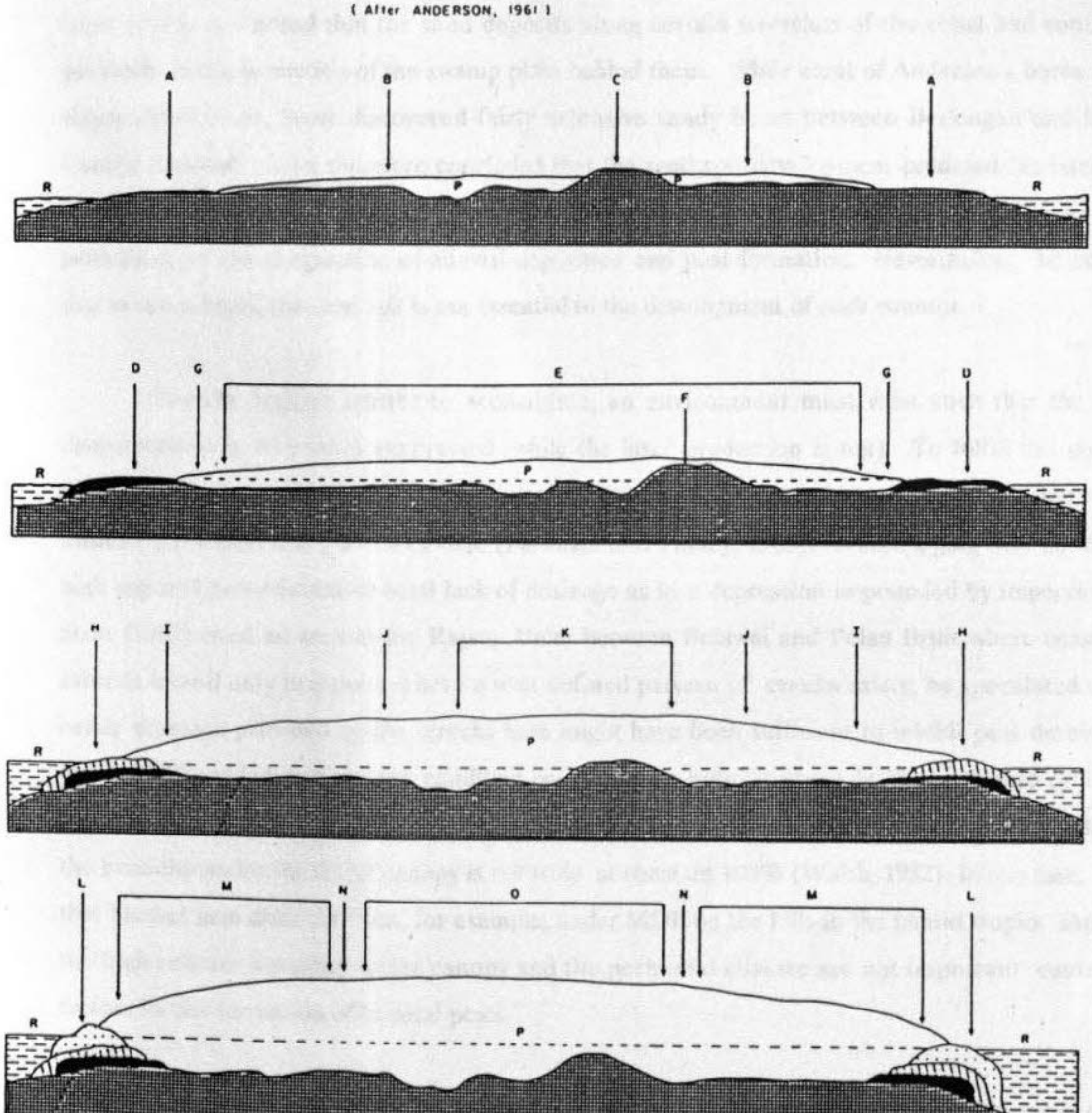
The low level beach deposits on the interior swamp margins indicate that the coastline had probably followed the present hill-swamp boundary about 5,000-5,500 yBP. Around 5200-5400 yBP, the sea level was probably about 6 m higher than the present; from about 5000 yBP, there was a slight fall in sea-level (Zuraina, 1982). Following this slight recession, sea level has been relatively stable at the present datum (Scott,1985) and this condition has, amongst other things, allowed the development of a wide plain of PS in Sarawak. Radio-carbon dating of peat samples from a highly developed PS near Marudi has indicated that peat accumulation at that site began at about 4,000-4,500 yBP (Wilford, 1961). The overall rate of surface elevation since its initial formation has been about 2.81 mm per year. However, the rate has not been constant; it has decreased from an average of 4.76 mm per year at the early stage to 3.14 at the intermediate phase, and further to 2.22 in the later stage. The differences would have been greater if allowances for increased compaction of peat masses at the lower depths have been taken into account. From this, Anderson (1964a) suggested that the decrease in the rate of peat accumulation as the vegetation communities in the succession advances could account for the gradual flattening of the swamp surface. This process continued until the almost flat bog plain with a highly convex perimeter is formed.

From palynological evidence, Anderson (1961) considered that the initial phase of PS development was the build-up of marine clay plain in sheltered embayments on which mangrove became established. Progressive deposition offshore allowed the seaward migration of mangrove but in the poorly drained flats behind the advancing shoreline a shallow peat was formed and mangrove communities were gradually replaced by PSF associations (see Fig. 4.1). Anderson suggested that this process was able to continue as long as the offshore current and wave conditions were conducive to the build-up of alluvium offshore. To support this, he cited three relatively sheltered embayments (between Miri and Seria and north of Marudi, between Bintulu and Sarikei, and between Tanjung Po and Nyabor) as examples which account for the main regions of PS in Sarawak (see Fig.3.1,p.15). As the distance of the original swamp from the sea increased, rivers tended to back up and deposit alluvium along their banks, which were raised above the level of the original swamp subsoils. This is how the characteristic saucer-shaped mineral foundations of PS evolved. As the peat got deeper, especially in the centre, the rate of accumulation diminished and a typical flattened bog plain slowly evolved. In some more highly developed PS, this had continued and the plain had extended laterally.

Although Anderson (1961) has written about the formation of a peat bog dominated by *Shorea albida* behind a sand spit at Seria,he has found little evidence in Sarawak and Brunei to support the hypothesis of Wyatt-Smith (UNESCO, 1958) that estuarine PS in Malaysia are always

Figure 4.1 DEVELOPMENT OF RAISED BOG FORMATIONS

(After ANDERSON, 1961)



A - Mangrove on tidal mudflat

B - Transitional phase on shallow peat with Campnosperma - Crytostachys-Zalacca association

C - Small island of higher land with dryland forest

D - Further deposition of alluvium, probably with nipah

E - Peat swamp develops shallow convex shape and entirely covered with PC 1.

F - Higher land & irregularities obliterated by peat deposit

G - Transitional zone

H - Further deposition of alluvium, probably with riparian forest

I - PC 1 on periphery zone with steeper gradient

J - PC 2 on margin of bog plain.

K - Bog plain dominated by <u>Shorea albida</u>.

L - Further deposition of alluvium

M - Very constricted PC 1, 2, 3 and 4.

N - Narrow zone of PC 5.

O - PC 6 on central bog plain which has extended laterally.

P - Peat.

R - River / tidal creek.

associated with coastal sites at which a sandbank on the seaward side has held up drainage. However, Scott (1985) has noted that the sand deposits along certain stretches of the coast had contributed positively to the formation of the swamp plain behind them. While most of Anderson's bores found a clayey substratum, Scott discovered fairly extensive sandy bases between Bedengan and Matu in Central Sarawak. Scott therefore concluded that the sand spit development predated the later stages of peat accumulation nearer to the present coastline, and that the offshore sandbars had given protection for the progression of alluvial deposition and peat formation. Nevertheless, he conceded that in some areas, the sand spit is not essential to the development of such swamps.

For the organic matter to accumulate, an environment must exist such that the rate of decomposition is very much suppressed (while the litter production is not). To fulfill this condition, the most important requirement, particularly in the tropical lowlands, is anaerobiosis due to water saturation for extended periods of time (Farnham and Finney, 1965). Waterlogging may be due to a high regional groundwater or local lack of drainage as in a depression impounded by impervious clay. Scott (1985) cited an area at the Rajang Delta between Belawai and Pulau Bruit where coastal peat extends inland only to a point where a well-defined pattern of creeks exists; he speculated that the better drainage provided by the creeks here might have been sufficient to inhibit peat development. Polak (1950) added that the wet condition could also be brought about by the perhumid climate and the "almost constant 100% humidity" of the air under the closed canopy of the tropical PSF. However, the humidity under the forest canopy is not truly at constant 100% (Walsh, 1982). In any case, the fact that blanket peat does not form, for example, under MDF on the hills in the humid tropics shows that the high relative humidity under canopy and the perhumid climate are not important contributing factors for the formation of tropical peats.

Adequate moisture to induce anaerobic condition is generally necessary in every climatic zone, but Bailey (1950) postulated that an additional requirement for the formation of peat in the tropics is low pH. This is not necessarily true because it is well understood now that the basal clays would have a near neutral pH under the natural reduced condition (Ponnamperuma, 1972). Other factors such as microbial toxins (Mohr et al.,1972), high sulphur and salt contents (Anderson, 1964a) and low nutrient status (Andriesse, 1972) have been suggested. These may play a role in the formation of peat in the tropics, but they are probably of minor importance.

Andriesse (1974) argued that the slow accumulation of mineral deposits in the basins due to the small mineral loads of the rivers had allowed the peat to be deposited instead. Similarly, Scott (1985) explained that the Rajang Delta between Pulau Bruit and Nyabor is dominated by mineral alluvium because of the large volumes of silt brought down by the Rajang River which has a large catchment area. However, Scott's interpretation raises inconsistency as to why the so-called "Sibu Bay" area further upstream was infilled by peat rather than alluvium in the earlier stages. The explanation would be more convincing if he could prove that either the mineral load of Rajang River had increased or the pattern of flow and deposition had changed over the years.

4.3.3 Organic Soils

While Anderson was doing his studies on the ecology of the PSF, data on organic soils of the PS were gradually amassed by the Department of Agriculture, Sarawak. This was mainly undertaken as part of a systematic soil survey programme.

Miller (1949) reported that deep and poorly drained peats in Sarawak were planted with sago (*Metroxylon spp.*), whereas swamp padi was cultivated on shallow (less than 90 cm) peats with controlled drainage. In 1954-56, a firm of irrigation engineers was engaged to survey three PS areas and assess their suitability for rice cultivation (White, 1956; 1957a; 1957b). Though the conclusions of these studies were not very positive, the surveys provided valuable information on the structure of these swamps (see section 4.3.2). In the first attempt to classify the soils of Sarawak Dames (1962) identified ten major soil types. He classified "the soil of the peat swamp areas covered by swamp forests of different types as Bog Soils". Apart from the determinations of peat depth and texture of mineral subsoil, no further studies were made. Dames concluded that "Bog Soils" were ombrogenous and oligotrophic, and that those deeper than 150 cm were not suitable for agriculture.

The main tasks of the Soil Survey Division are to systematically survey the whole state of Sarawak at a reconnaissance level, and to survey potential and development areas in more detail. From these surveys, numerous reports and more comprehensive soil memoirs (Andriesse, 1972; Eilers and Loi, 1982; Scott, 1985) have been released. Most of these reports, particularly the memoirs, have brief discussion on the classification, distribution, properties and agricultural potential of the peat soils in their respective areas. Although there were no specific efforts made to study the organic soils, these survey data provided some information on the range of properties and the distribution of organic soils in Sarawak.

In a detailed appraisal of the soils in Bekenu-Niah-Suai area, Wall (1966) emphasized on the recognition of the "peat photo-association" as an aid to mapping peat areas from aerial photographs. Like other soil survey reports, though with more details, he also dealt with the classification, distribution and agricultural value of the peat soils. Summarizing his experience in Sarawak and information collated from work done in neighbouring countries, Andriesse (1974) wrote a review paper on tropical lowland peats in South-East Asia, covering a range of topics including characteristics of the peats, their agricultural potential and reclamation problems. Subsequently, similar attempts were made to review the contemporary knowledge of the organic soils in Sarawak. Based on data gleaned from various soil survey reports, the properties, distribution and importance of organic soils in Sarawak were discussed with particular reference to sago cultivation (Tie and Lim, 1976) and to water management (Tie, 1977). All this information on Sarawak peats plus the results from local agronomic research were updated and put together as a single review paper by Tie and Kueh in 1979.

From these various soil survey reports and reviews, the following generalizations can be made about the properties and characteristics of organic soils in Sarawak :

(a) The peats are reddish brown to very dark brown in colour.

(b) They are raw and woody consisting of hemic to sapric material in the top and fibric in the lower tiers. Well preserved tree trunks, branches and roots are abundant.

(c) Bulk densities (o.d. at 105°C) of peats in the top 1-2 m range from 0.084 to 0.150 g/cm^3 depending on the degree of decomposition and the mineral matter content.

(d) Unless artificially drained, organic soils are water- logged for most of the year.

(e) Deep peat soils mostly show very high losses on ignition of 83-99%. Shallow organic soils at the fringes of the PS and Histosols occurring in narrow valleys generally have higher content of mineral matter.

(f) Although there is a trend towards slightly higher pH values in shallower peats, they usually all have very low pH of less than 4.0.

(g) Total N content is mostly greater than 1%, but the C:N ratio is higher than 20.

(h) Total P content ranges from 400 to 1,000 ppm and the levels normally decrease with depth and with distance from the sea.

(i) CEC at pH 7.0 usually ranges from 70 to 100 meq per 100 g soil (o.d.). Exchangeable K, Ca and Mg are usually less than 1.0, 0.5-5.0 and 1.0-10.0 meq/100g(o.d.) respectively.

(j) Morgan-extractable Cu is practically nil while Zn, Fe and Mn do not exceed 5, 35 and 50 ppm respectively.

It has been established that the properties in general are very much influenced by the depth to, and the nature of, the mineral substratum and by the degree of flooding. However, the information available thus far is still scanty and incomplete.

In Sarawak, agronomic research work on peats was not started until a research station was established at Stapok, Kuching in 1966. Initial efforts were aimed at screening a very wide range of crops and crop cultivars to see which of them were suitable for cultivation on drained organic soils. This work was subsequently expanded with the setting-up of three more research stations on peats : one at Sessang near Saratok to investigate basin peats nearer to the sea; one at Sungai Mauh near Sibu to look into deep peat areas under old rubber; and the other at Sungai Talau near Mukah for research on sago (*Mextroxylon spp.*) and other wetland crops. Based on the results obtained so far, the most promising crops under properly drained conditions include pineapple (*Ananas comosus*), tapioca (*Manihot esculenta*) and oil palm (*Elaesis guineensis*)(Tie and Kueh, 1979). Under undrained conditions, sago (*Metroxylon spp.*) may be cultivated; wetland rice (*Oryza sativa*) can only grow and produce satisfactorily on shallow organic soils,or deep ones with mineral lenses or high mineral content at the surface.

Tropical organic soils are noted for their extremely low chemical fertility. Organic soils in Sarawak are no exception and they require, amongst other things, adequate fertilization for satisfactory crop growth. Ahmed and Ng (1973) using maize as the indicator plant in a pot experiment found responses to N, K, S, Cu, B and Mo. These have been partially confirmed in field trials where responses of various crops to N, P, K, Cu, Fe and B have been consistently obtained (Tie and Kueh, 1979). Some crops like pineapple and sago do not need liming, but most of the other crops require about 5-10 t/ha of dolomite or limestone.

The studies conducted at the various peat research stations have been (and still are) mostly confined to the agronomic aspects. Facilities and personnel are not available for studying soil and water management problems. Consequently, the scope of research activities have not provide sufficient confidence in developing and managing large areas of deep peats. It was therefore proposed in 1983 that a pilot project should be started at Asajaya (formerly Nonok) area to carry out soil-water management studies and to work out the economic feasibility of a few promising cropping systems (Kueh and Wong, 1983). It is envisaged that as the pressure for agricultural land increases, the Government will accord higher priority to more integrated studies which will hopefully pave the way for successful utilization of the organic soils, particularly the deep peats.

4.4 SIMILAR STUDIES ON SITE-FOREST RELATIONSHIPS WITH PARTICULAR REFERENCE TO SARAWAK AND BRUNEI

Although site-forest relationships are an aspect to be covered in the present study, this section does not intend to review in detail the voluminous literature available on such relationships in other types of forests. The site-forest relationships of the tropical rain forests in Sarawak and Brunei will be considered first. It will then examine a few other studies which have a similar approach or which are relevant in other ways. Brunei is included here because much of the work done in Sarawak had stemmed directly from the earlier studies in Brunei.

Since the early phytogeographical studies done at the turn of the century (Schimper, 1903), there has been a general consensus that the main subdivisions of tropical rain forests are determined by climatic seasonality and altitude. Except for the Montane Forest, all the forest types in Sarawak are variants of the evergreen forests of equatorial lowlands. In the tropical lowlands, variations in elements of the climate such as temperature or moisture are ecologically less important than at high altitudes and latitudes; however, similar kinds of edaphic limitation have been observed to give rise to structurally and ecophysiologically similar forest types throughout the humid tropics (Baillie, 1978).

Some of the earlier studies on site-forest relationships in Brunei and Sarawak were done by Ashton (1964; 1973) on Mixed Dipterocarp Forests (MDF). Initially with a restricted range of parent materials, he found that local topography and the associated edaphic changes are major forest determinants. When a wider range of forests with a wider range of soils and rock types were sampled, Ashton discovered that the differential role played by soil parent material and the associated differences in chemical fertility became more important than that of topography. He also suggested that the single most important nutrient is P, which appeared to be critical at reserve levels below 150 ppm; above this, P apparently declined in importance and other nutrients or possibly some non-chemical factors might become more influential. Ashton and his co-workers later reinvestigated the site in Brunei. When the topographic effects were removed by treating alluvial, hill and ridge sites separately, they found that the floristic groupings of alluvial sites based on association analysis corresponded to the first principal soil component which described a gradient of sandiness and mineral nutrients (Austin *et al.*, 1972). Similar analyses for hill and ridge sites indicated that differences in the flora were associated with a soil leaching gradient.

Investigation into soil-forest relationships in the MDF was continued and the scope enlarged by Baillie (1978) in the late sixties and early seventies. Using factor and discriminant analyses, Baillie found that there are generally marked site effects on the distribution of floristically defined variants of MDF and of many of the commoner species like *Dryobalanops oblongifolia* and *Shorea quadrinervis*. Chemical characteristics related to the soil parent material, particularly reserve levels of P and Mg are the most influential on species distributions; soil reaction and possibly exchangeable Al are important in some species. Baillie also discovered that hollow decay is more affected than species distributions by more variable site characteristics such as soil depth, organic matter levels and exchangeable base status; decay levels tend to be higher on less fertile sites.

Apart from Ashton and Baillie's work, there have been no other major systematic plant ecological studies in the MDF of Sarawak and Brunei. Other forest ecologists have studied the role of edaphic factors in determining the distribution of the main forest types in Sarawak (e.g. Richards, 1961; Ashton, 1971; Brunig, 1974; Whitmore, 1975; Chai,1982; Newbery and Proctor, 1984). In his ecological studies on the Kerangas Forests (heath forest), Brunig (1974) concluded that the structure and physiognomy of the forests are largely influenced by moisture availability but soil fertility and small biomass turnover may also be contributing factors. He further mentioned that the various adaptations of the plant communities in the Kerangas Forests to reduce transpiration rates may be essential to avoid uptake of toxins from highly acidic, phenol-rich soil solution. The studies on Kerangas Forests are particularly interesting because of their structural resemblance to the Padang Paya Forests (PC 6) in the centre of the peat domes (see Section 4.3).

In the mangrove forests, vegetation zonation is being found to be closely related to the frequency of tidal inundation and the associated differences in soil and groundwater characteristics such as salinity, and levels of Ca, Na and C1 (Chai, 1982). Chai also proposed that species colonization, succession and zonation in this forest type are controlled by the differential abilities of the various species to adapt to the different conditions of the environment.

Proctor *et al.* (1983a) studied four contrasting lowland rain forests in Gunung Mulu National Park, namely alluvial forest (AF), MDF, heath forest (HF) and forest over limestone (LF). Using polythetic agglomerative, monothetic divisive and polythetic divisive classification techniques to subdivide each site into two or three vegetation classes and principal component analysis to reduce the soil variables to two components, they found that the vegetation classes on the AF and HF were significantly associated with changes in the pH-exchangeable Ca component, and the organic C-CEC component respectively (Newbery and Proctor, 1984). No associations between soils and vegetation were found for MDF and LF. For the MDF, they suggested that probably many factors are involved in controlling the biomass or species richness. As a result, no simple relationship between these attributes and the soil nutrient element concentrations could be found from their studies.

Within the lowland dipterocarp forest of Peninsular Malaysia, earlier workers generally found that edaphic factors have little discernible or significant effect on the local floristic composition (references summarized in Baillie, 1978). Baillie suggested that this could be due to the gentle landscape with relatively gradual soil changes. He also considered these conclusions as being tentative because of the limited environmental data involved. This problem of insufficient data was highlighted by Ashton (1976) when he re-examined some of the study plots in Peninsular Malaysia. With more detailed environmental data, Ashton was able to relate some of the forest variations to site conditions, particularly topography and drainage condition.

In Sabah, Burgess (1961) found distinct floristic and structural differences for three areas of lowland dipterocarp forests on soils with different parent materials, drawing an interesting parallel with the Sarawak findings discussed above (Ashton, 1973). Fox (1971) also considered the distribution of the seven major lowland forest types in Sabah to be strongly influenced by site conditions.

In reviewing the earlier work done on site-forest relationships in tropical rain forests, Baillie (1978) found that there is a considerable range of opinions on the importance of edaphic influences on the variation in the "climatic climax" evergreen forests. Some of the contradictions are explicable if the methodology, data and assumptions of the individual studies are examined. Thus, badly disturbed forests are not likely to show marked edaphic influence. Even in undisturbed forests, biological and chance factors may predominate if site conditions are relatively homogeneous. Where the edaphic influence has been demonstrated, there may be differences over the relative importance of various site factors. If the variation in one aspect of the data is more pronounced than others, that factor will apparently become the major determinant of the forest types. The relative variability of the different factors (Baillie and Ahmed, 1984), the range of samples and the intensity of investigation will therefore affect the outcome of each individual study (Baillie, 1978). Consequently,most of the studies apply only for the specified range of sites and forest conditions.

The condition of the forest at any point in time and space is the result of the interaction of physical and biological processes, current and historical. In Sarawak, soil surveyors generally find that the main forest types are good indicators of major changes in soil conditions (Dames, 1962; Wall, 1966; Andriesse, 1972). Within the most extensive MDF, however, floristic and structural variations are only of limited assistance in delineating soil mapping units (Baillie, 1978). In contrast, the concentric zonation of the different phasic communities of the PSF is easily discernible on conventional aerial photographs (Anderson, 1961; Wall, 1966). Although Anderson had made some preliminary studies on the relationship between this zonation and some edaphic factors (see Section 4.3.1), his conclusion is somewhat tentative and more detailed studies are therefore required.

CHAPTER 5. DATA COLLECTION

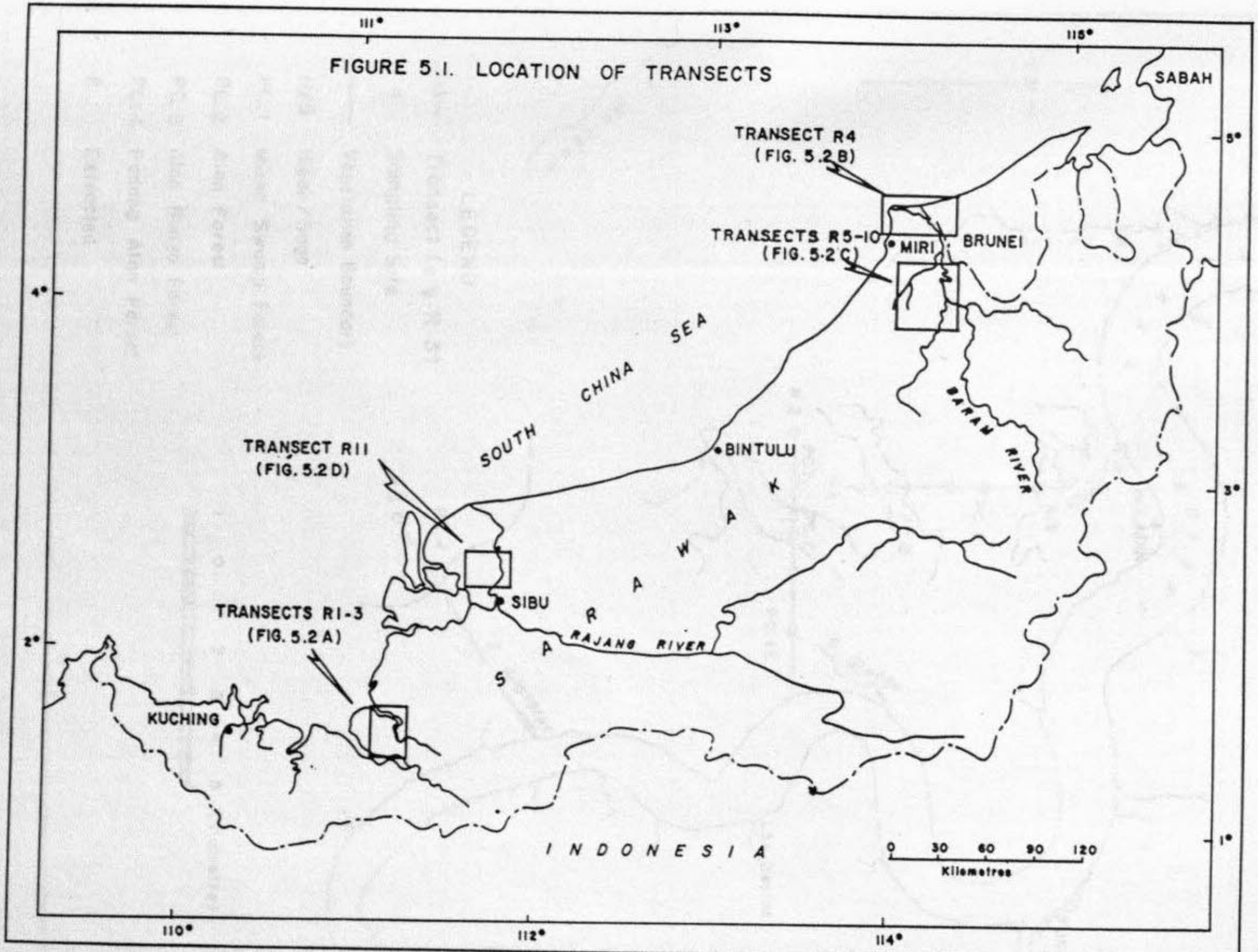
5.1 EXECUTION OF THE STUDY

The data on which this study is based had been collected intermittently over several years. This long time span was partly because the laboratory analyses of the large number of soil samples had been relatively slow and time-consuming. However, the main reason was that the writer has not been able to work on this project on a full-time basis. As a research officer/soil surveyor in the Department of Agriculture, there were many routine soil surveys and other duties to be performed.

Field work for the project began in January 1981 when the first transect at Maludam was traversed, studied and sampled. Pedological studies proceeded rapidly and by the middle of 1981, the work on the four major transects (R1 and R4-R6; see Fig. 5.1 and 5.2 A-D) initially planned were completed. Due to other commitments, the writer was not able to do more field work until 1983. In the meantime, soil samples were prepared and sent to the laboratory at Agricultural Research Centre (ARC), Semongok for analyses. At the beginning of 1983, enumeration survey of the vegetation in 0.2-ha plots (each comprised of five 20x20 m sub-plots) established along these four transects was carried out with botanical guidance and help from Dr. J.A.R. Anderson. With the soil and vegetation data collected thus far, the writer felt that it was timely to proceed with the statistical treatment, and a whole range of statistical analyses was therefore undertaken at the Polytechnic of North London (PNL) in 1984-85. When the author returned to Sarawak in August 1985, a second phase of field work was carried out along transects R.2-3 and R.7-11. In addition, samples were taken for radio-carbon dating, and field experiments were established to monitor litter-fall, water table and decomposition of leaf litter, small wood and large wood in the PSF.

There was no facility either at ARC or PNL to do radio-carbon dating. This was done in collaboration with Joan S. Esterle of the University of Kentucky, USA. She was studying peat as a precursor to coal, and her project involved the domed peat deposits in Sumatra and Sarawak. The

FIGURE 5.1. LOCATION OF TRANSECTS



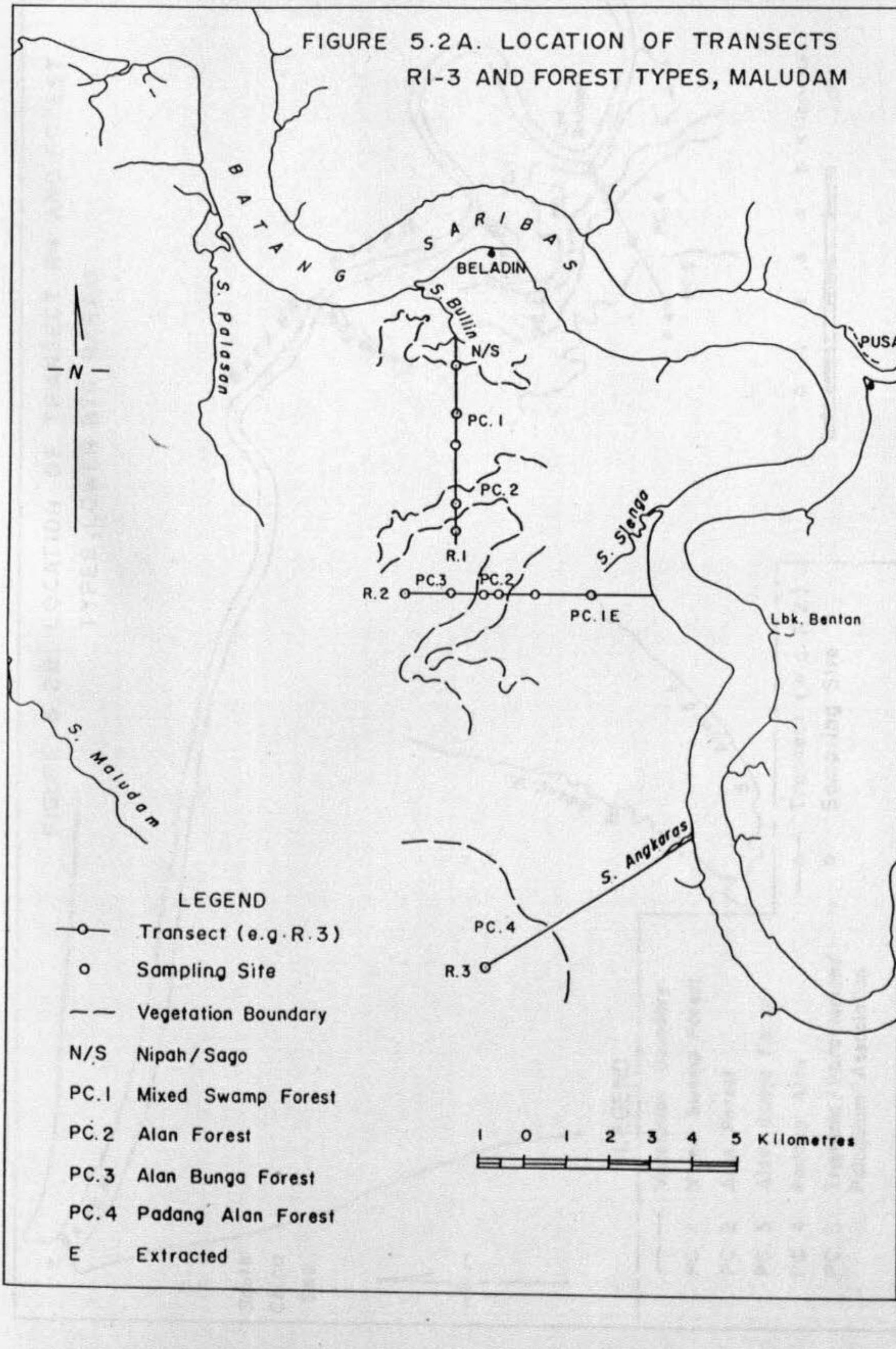


FIGURE 5.2A. LOCATION OF TRANSECTS
R1-3 AND FOREST TYPES, MALUDAM
BATANG SARIBAS
BELADIN
S. Bullin
S. Palasan
N
N/S
PC.1
PC.2
R.1
PC.3
PC.2
R.2
PC.1E
S. Slenga
Lbk. Bentan
PUSA
S. Maludam
S. Angkaras
PC.4
R.3
LEGEND
Transect (e.g. R.3)
Sampling Site
Vegetation Boundary
N/S Nipah/Sago
PC.1 Mixed Swamp Forest
PC.2 Alan Forest
PC.3 Alan Bunga Forest
PC.4 Padang Alan Forest
E Extracted
1 0 1 2 3 4 5 Kilometres

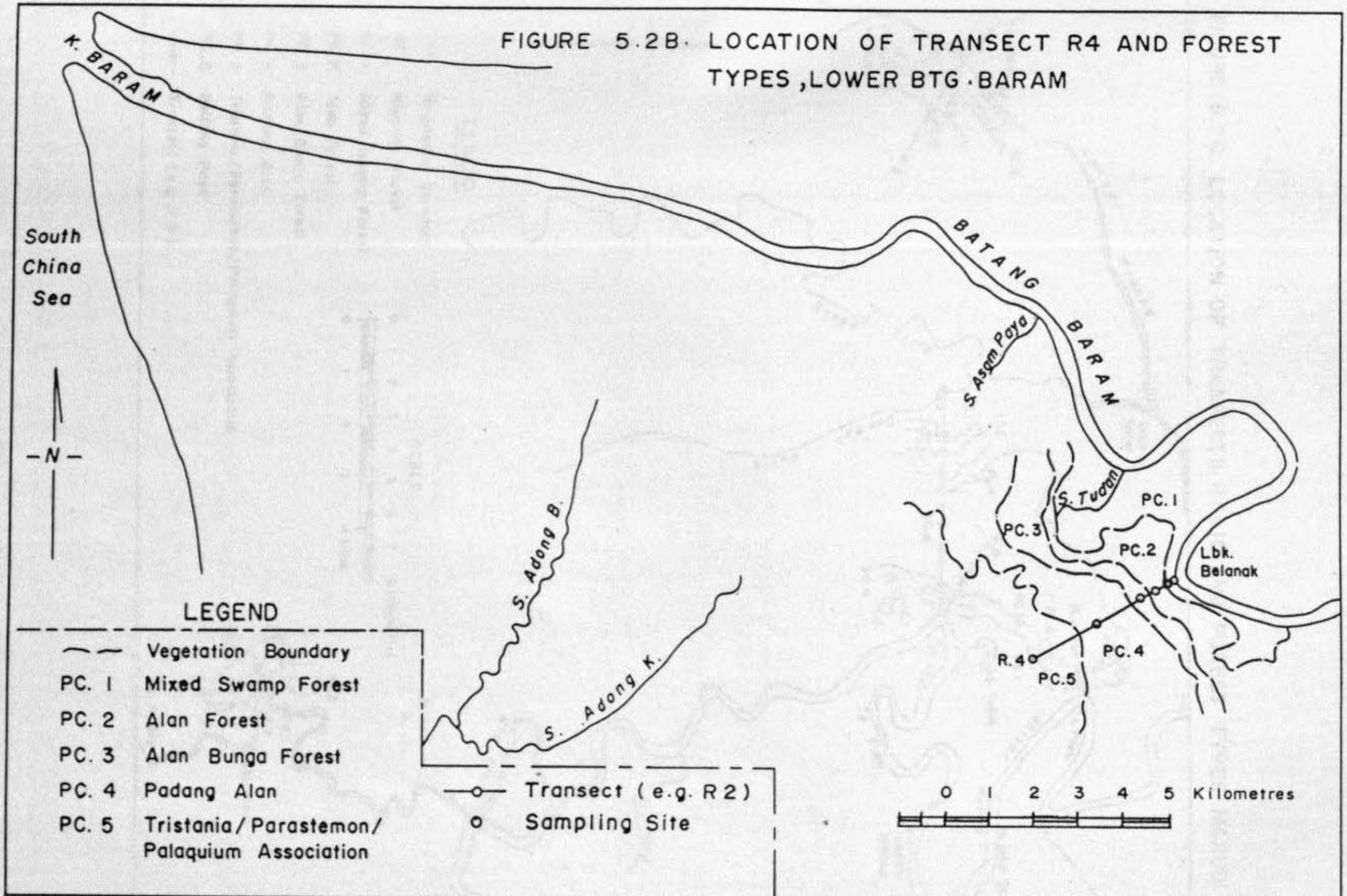
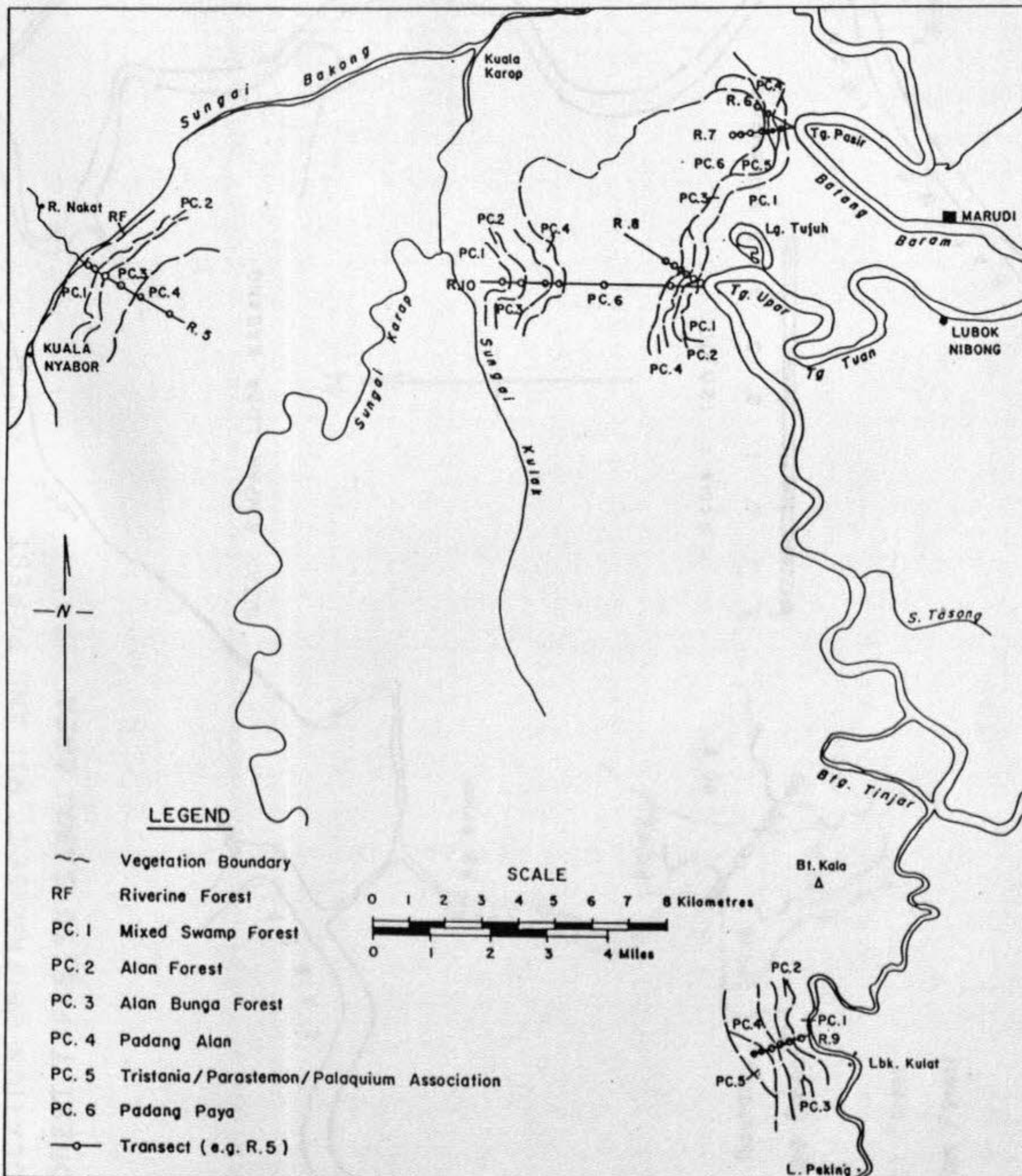


FIGURE 5.2B. LOCATION OF TRANSECT R4 AND FOREST TYPES, LOWER BTG. BARAM

FIGURE 5.2C. LOCATION OF TRANSECTS R5-10 AND FOREST TYPES, MARUDI



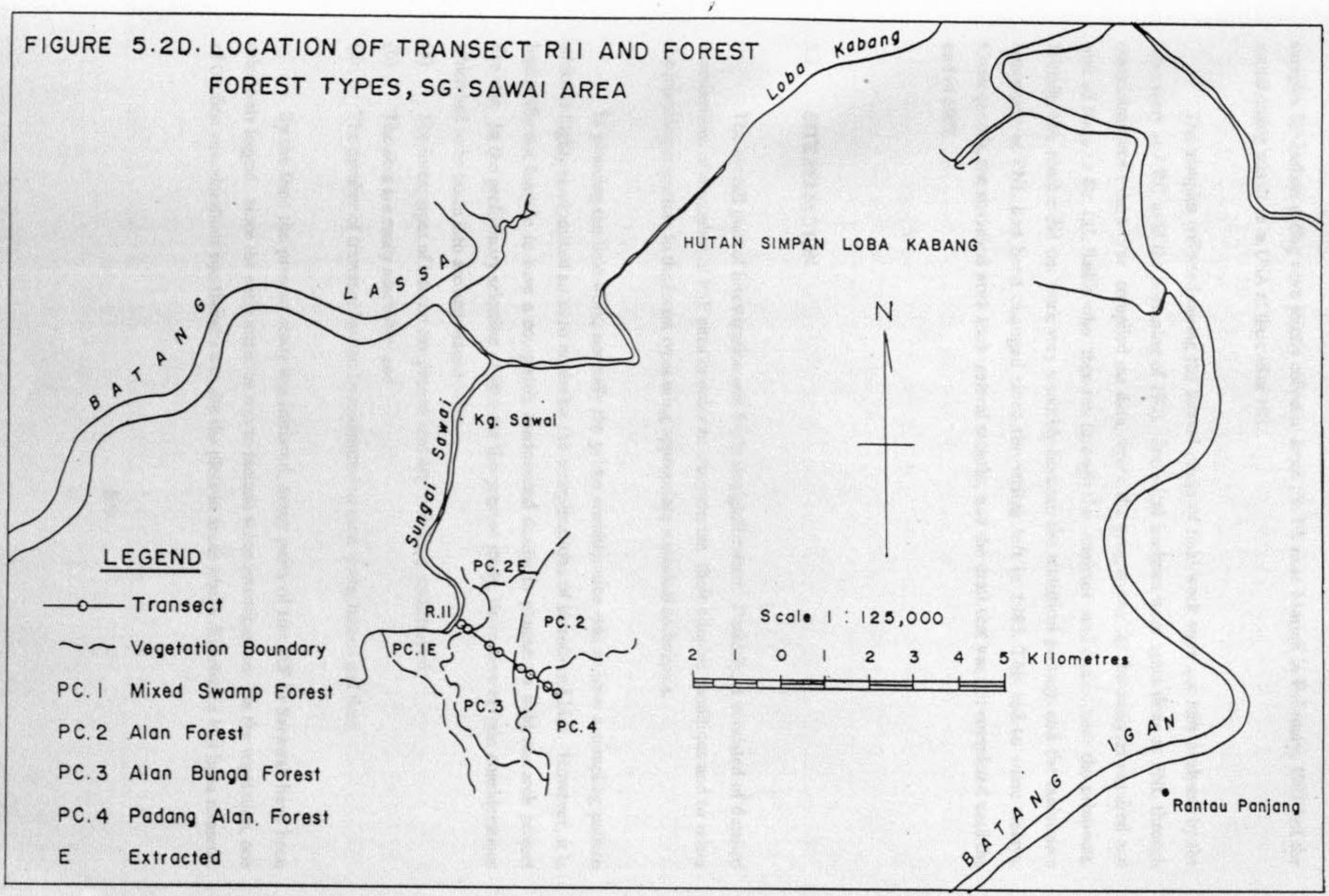


FIGURE 5.2D. LOCATION OF TRANSECT RII AND FOREST FOREST TYPES, SG. SAWAI AREA

samples for carbon dating were jointly collected from the PS near Marudi in February, 1987 but the actual dating was done in USA at the end of 1987.

The samples collected during the second phase of field work were not fully analysed by the laboratory at ARC until the beginning of 1988. Statistical analyses were again done at PNL through correspondence : the writer compiled the data, wrote the programme for the analyses required and sent all these to Dr. I.C. Baillie who then ran through the analyses and mailed back the print-outs. Initially, this routine did not work very smoothly because the statistical package and the mainframe computer at PNL had been changed since the writer left in 1985. This led to some delays. Consequently, the statistical work took several months, and the draft text was not completed until the end of 1989.

5.2 SITE SELECTION

The overall plan of investigation was fairly straightforward. Basically, it consisted of detailed examinations of a number of PSF sites in order to characterize their edaphic conditions and to relate the edaphic parameters to the forest types using appropriate statistical techniques.

In planning the field work, normally the prime consideration was to have a sampling pattern which is highly randomized so as to minimize the complications of introduced bias. However, it is logistically not feasible to have a completely randomized design in planning a field research project like this. In the preliminary selection of sites for the present study, there were certain considerations which had to be taken into account, namely that:

(a) The forest types of interest are present and are relatively undisturbed;

(b) The sites are easily accessible; and

(c) The number of traverses have to be minimized to save costs, labour and time.

By the time the present study was initiated, many parts of the PSF in Sarawak have been selectively logged. Since the early intention was to include some investigations on the vegetation, one of the first considerations was therefore to site the plots in areas where disturbance had been minimal.

Because of this, most of the PS areas in Central Sarawak between Bintulu and Sarikei (see Fig. 3.1) were ruled out; in the end, only one transect, R.11 (see Fig. 5.2D) was sited in this region. The Forest Department of Sarawak has accurate maps showing the forest types and the logging history. These maps were relied upon for the preliminary identification of localities to be included in the present study.

There is practically no road access into any of the PS in Sarawak. Communication from the nearest town or kampung to the edge of a PS has to depend invariably on small boats. From there, line cutting is necessary to penetrate the PS. This is costly, laborious and slow. It is impossible to study plots which have been randomly established in a PS by, for example, selecting pairs of numbers from a table of random numbers and using these as the coordinates of the points on a grid. The transect method with traverses cutting across the concentric zones of forest types was therefore employed. The primary consideration here was to include as many forest types as possible along every cut-line.

Having identified the PS to be included in this study, the starting points of the transects were decided more or less arbitrarily on the basis of accessibility and ease of accurate location. The bearing of the transects was determined by the zonation of the forest types; the idea was to cut nearly orthogonally across the boundaries of the concentric zones. Along each transect, the boundaries between the forest types were marked out with the help of vegetation maps prepared by Forest Department. In the field, the forest types were verified and the transect was measured and pegged at 25-m intervals. Where it was decided to have a single plot within a forest type, the plot was arbitrarily sited at about the mid-point along the portion of the transect which cut across that particular forest type. Where more than one plot were to be established, then the locations were randomly chosen from the tape numbers of the relevant section of the transect.

The method adopted is a highly stratified random sampling procedure (Wang, 1982). There may be objection to the seemingly high concentration of traverses around Marudi area (Figure 5.2C) in the northern part of Sarawak. This was unavoidable because two of the forest types, PC 5 and 6 could only be found in this area. Site selection was also limited by the logging history of the PSF; highly disturbed PSF in Central Sarawak had to be excluded.

In the end, eleven transects were cut (see Fig. 5.1 and 5.2 A-D). R.10 at Tanjung Upar (Fig. 5.2C) was basically used to examine the spatial variations of surface peats across the dome. This site was selected because almost all the phasic communities are represented here and it is sufficiently far inland (about 38 km from the coast) for any coastal effects to be significant. The sampling points along R10 were located at Tape (or Peg) 216 (PC 1), Tape 198 (PC 2), Tape 174 (PC 3), Tape 158 (PC 4) and Tape 110 (PC 6). Only PC 5 was not sampled because it is not well represented along the transect.

From the other ten transects, 58 soil profiles or cores spread over the six PC of PSF were described and sampled (see Table 5.1). Out of these, eight were earmarked to be used as test cases in statistical analyses such as discriminant analysis. Another four profiles along Transect R7 were taken separately in late 1986 for the analyses of total sulphur (TS). Two other sampling sites, R1/T4 and R5/T6 (not shown in Table 5.1), were discarded because the vegetation was found to be transitional between the riparian forest and the mixed peat swamp forest.

5.3 METHODOLOGY

5.3.1 Soil Sampling and Analyses

During the first phase of field work done in 1981-83 (See section 5.1), soil sampling procedure along transects R.1 and R.4-6 was more detailed and more parameters were investigated. At each site, a pit with a depth of about one metre was dug and described. This was not easy because of the high water table; one man had to keep on bailing the water while the pit profile was described and sampled (see Plates 1 and 2).

Field description of soil samples brought up by the peat auger was mainly confined to colour, ash (or mineral) content and the degree of decomposition. Besides these three attributes, description of pit profiles included other characteristics like root distribution and woodiness.In Sarawak, five classes of woodiness in organic soils have been recognized; they are non-woody (<2% wood by volume), low (2-10%), moderate (10-30%), high (30-60%) and very high (>60%). Field estimation of the degree of decomposition was done according to the following criteria:

TABLE 5.1 DISTRIBUTION OF SAMPLING SITES

Transect No. & Location	Forest		Types			
	PC1	PC2	PC3	PC4	PC5	PC6
R.1,Sg.Bulin, Maludam(Fig.5.2A)	3	1	1	-	-	-
R.2,Sg.Slenga, Maludam(Fig.5.2A)	2(1)	2(1)	2(1)	-	-	-
R.3,Sg.Angkaras, Maludam(Fig.5.2A)	-	-	-	1	-	-
R.4,Lbk.Belanak, K.Baram(Fig.5.2B)	2	1	1	1	1	-
R.5,K.Nyabor, Bakong(Fig.5.2C)	2	1	1	2	-	-
R.6,Tj.Pasir, Marudi(Fig.5.2C)	-	-	-	1	-	1
R.7,Tj.Pasir, Marudi(Fig.5.2C)	-	-	1	1	1	4
R.8,Tj.Upar, Btg.Baram(Fig.5.2C)	1	-	1	1	1	2
R.9,Lbk.Kulat, Btg.Tinjar(Fig.5.2C)	1	1(1)	1(1)	1	2	-
R.10,Tj.Upar, Btg.Baram(Fig.5.2C)	1*	1*	1*	1*	-	1*
R.11,Sg.Sawai, Sibu(Fig.5.2D)	1(1)	2	1(1)	1(1)	-	-
Total	12(2) 1*	8(2) 1*	9(3) 1*	9(1) 1*	5 -	7 1*

( ) Test cases for multivariate analyses;
** Cases used only for studying variations across a peat dome.*

(a). **Fibric material**- Raw or undecomposed; organic material is sufficiently fresh and intact to permit identification of plant forms; when squeezed, it acts like a sponge, and less than one-third of the material extrudes between the fingers.

(b). **Hemic material** - Moderately decomposed; a significant part of the material can be recognized and a significant part cannot; when squeezed, it acts more as a paste rather than a sponge, and about one- to two-thirds of the material extrudes between the fingers.

(c). **Sapric material** - Well decomposed; virtually all of the material has undergone such decomposition that plant parts cannot be recognized; when squeezed, it acts as a paste and more than two-thirds of the material extrudes between the fingers; when wet, it is slightly plastic, and when moist, it feels like a loam.

Undisturbed ring or core samples (5cm dia.;100cm^3) were taken in duplicate from the profile face by horizontal insertion for the determinations of bulk density (BD) and shrinkage upon air- and oven-drying. Although there were some minor variations in the profile morphology between sites, sampling was done at fixed depths for ease of comparison. In any case, horizon differentiation below the top well decomposed material was not pronounced. Ring and bulk samples were taken at the following depths: 0-15, 15-30, 30-60 and 60-100 cm. Deeper bulk samples, one every 50-cm depth, were also taken progressively by augering until the mineral substratum was reached. In order to keep the total number of samples within reasonable limits, bulk samples taken for physical and chemical analyses were not replicated. The only exception was the surface (0-15 cm) samples along Transect R10 where five replicates per site, spaced at least 1 m apart, were taken in 1986. For bulk density (BD) determination, most of the profiles were only sampled at three depths down to 60 cm; deeper undisturbed ring samples were difficult to take because of the high groundwater table and the abundance of undecomposed woody materials.

Augering was done manually using the modified Macaulay peat sampler and 1-m extension rods (Plate 3). This was a formidable task because of the abundance of hard and undecomposed coarse woody materials which could not be penetrated by the auger. The sampling of one profile usually took about half a day for three men to complete. It was almost inevitable that one had to try innumerable times for each successful augering. Furthermore, several borings had to done before enough materials were obtained for each bulk sample. The only bonus was that these composite samples taken from several points spaced at least 30 cm apart could be regarded as been more

TABLE 5.2 SUMMARY OF DATA COLLECTED

Site Characteristics	Soil Characteristics at Various Depths*		Groundwater Analyses*
	Morphological/physical	Chemical	
1.Forest type	1.Colour	1.pH (H_2O,KCl & $CaCl_2$)	1.pH
2.Ground level	2.Root content	2.Organic C	2.EC
3.Groundwater table	3.Wood content	3.Loss on ignition	3.N
4.Distance from nearest river	4.Fibre content	4.Total N	4.Ca
5.Distance from sea	5.PCI & PSI	5.Exch.Ca,Mg K & Na	5.Mg
6.Depth of peat	6.Subsoil texture	6.CEC	6.K
	7.Bulk density	7.Avail.P	
	8.Shrinkage upon air-drying, resaturation & oven-drying	8.Total Ca,Mg K,P,Fe,Mn, Zn & Cu	
	9.Particle density		

* *See Appendix I for methods of analyses.*

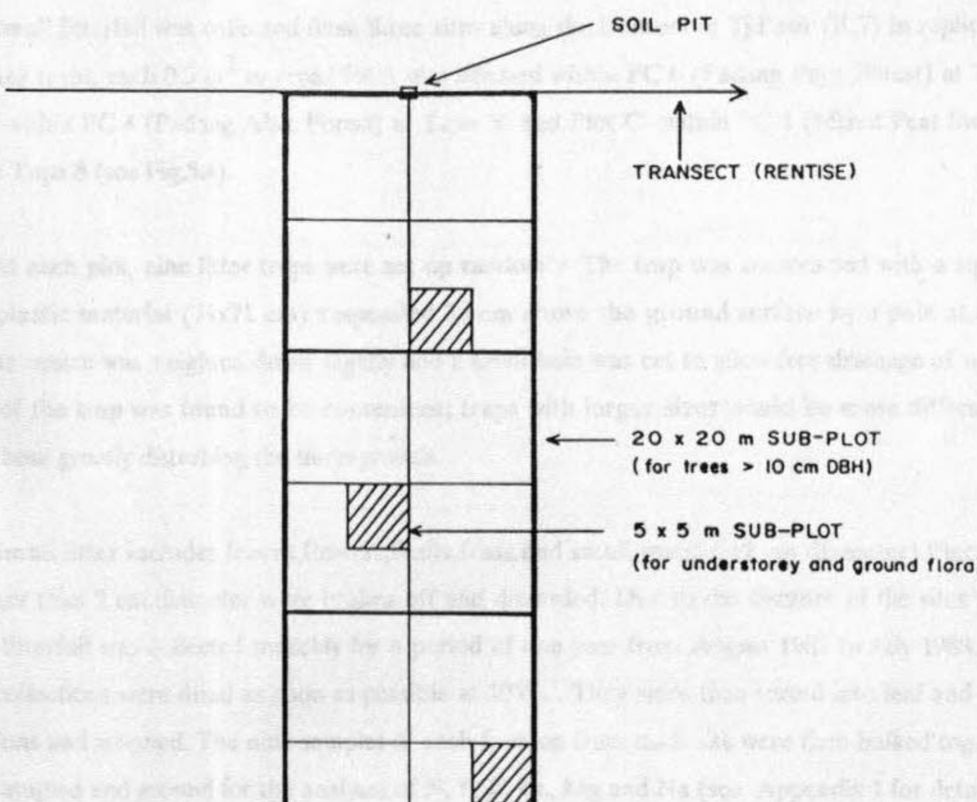
Some attempts were made to reduce the number of variables. Preliminary results obtained from the first phase of field work indicated that some of the parameters were highly inter-correlated and some consistently showed insignificant contributions in any of the multivariate statistical analyses (see Section 9.2.2). During the second phase of sampling undertaken in 1985-86, the procedure was therefore simplified to exclude the sampling of groundwater and peat below a depth of 150 cm, and the determinations of pH(KC1), pH($CaCl_2$) and shrinkage upon drying. No pits were dug and all samples including those for bulk density determination were collected using the modified Macaulay peat sampler. It was found that the peat auger could take undisturbed peat samples in a semi-cylindrical form. Some of these samples were therefore collected separately for oven-drying; the oven-dry weight divided by the volume calculated from the dimensions of the semi-cylindrical samples gave the bulk density.

5.3.2 Site Characterization

The domed-shaped structure of the PS reported by Anderson (1964) is seldom pronounced enough to be apparent during traversing. The ground surface of a few traverses was therefore levelled by using an Abney level. Spot height readings were done at an interval of 50-75 m. Where benchmarks established by Land and Survey Department could be found at a reasonable distance from the transect, the levels were related to these benchmarks and subsequently to the mean sea level. Otherwise, an arbitrary zero was assigned to the starting point of the traverse.

Besides ground surface levelling, general site characterization was mainly confined to a description of the vegetation and measurements of water table and peat depth. Such brief descriptions of the vegetation mainly served to identify the forest type. Along transects R.1, 4 and 5, however, more detailed investigations on the forest types were undertaken with the assistance of Dr. J.A.R. Anderson in 1982-83. An additional site at R.7 Tape 35 was studied by the author in 1987. On each of these sites, a 0.2-ha plot consisting of five adjacent sub-plots each measuring 20x20 m were established orthogonal to the transect (Fig. 5.3). Within each sub-plot, the diameter at breast height (DBH), diameter at first branch, height to first branch and the total height of all trees exceeding 10-cm DBH were measured. As far as possible, tree species were identified in the field. The abundance of understorey (less than 10-cm DBH) including shrubs and herbaceous plants was determined by counting them in smaller 5x5 m sub-plots (see Fig. 5.3).

FIGURE 5·3· LAYOUT OF VEGETATION STUDY PLOT



5.3.3 Litter Production and Decomposition

Small Litter Production

Small litterfall was collected from three sites along the transect at Tj.Pasir (R.7) in replicated square litter traps, each 0.5 m^2 in area.Plot A was situated within PC 6 (Padang Paya Forest) at Tape 42,Plot B within PC 4 (Padang Alan Forest) at Tape 30 and Plot C within PC 1 (Mixed Peat Swamp Forest) at Tape 8 (see Fig.5.4).

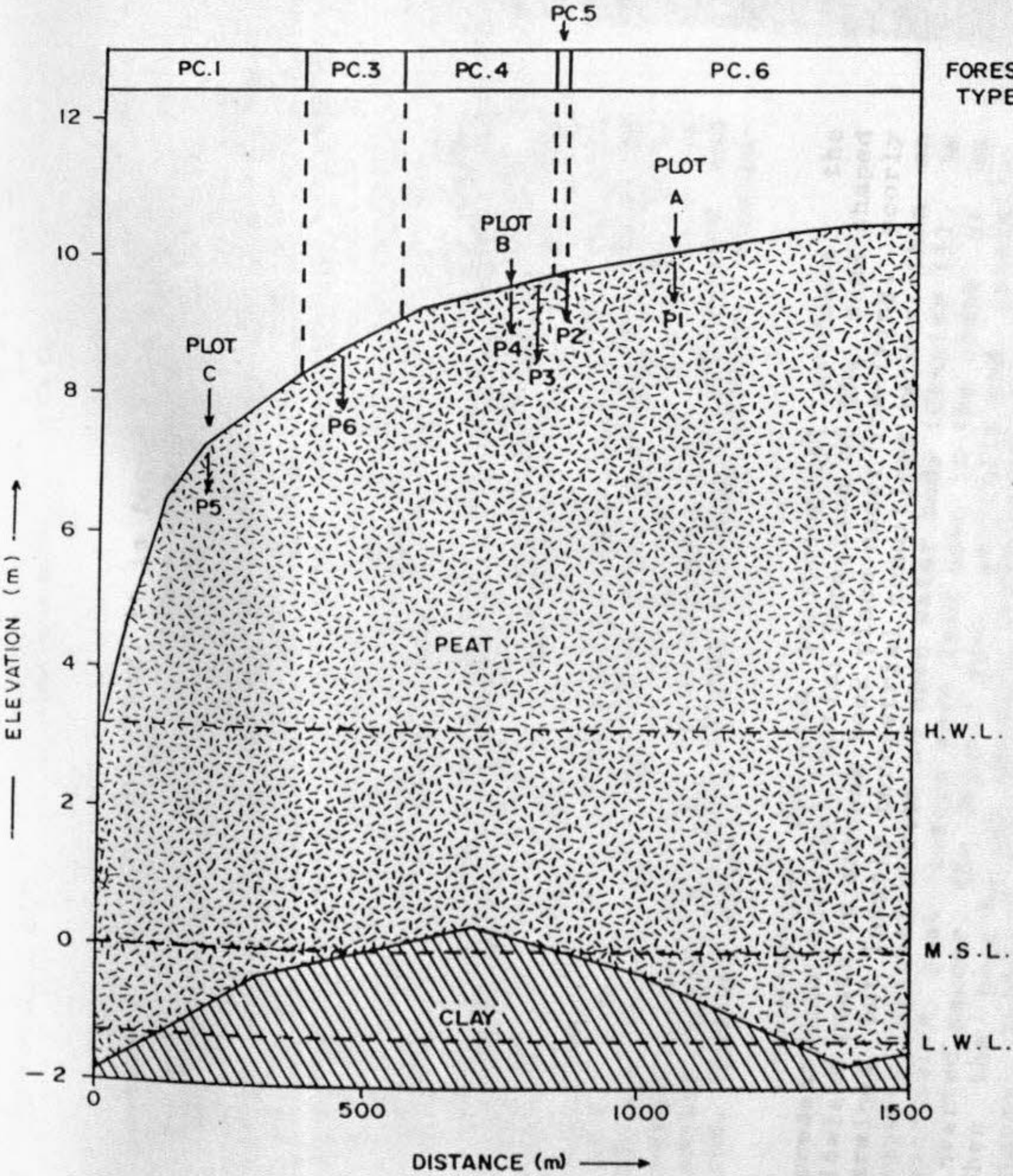
At each plot, nine litter traps were set up randomly. The trap was constructed with a square sheet of plastic material (71x71 cm) suspended 30 cm above the ground surface by a pole at each corner.The centre was weighted down slightly and a small hole was cut to allow free drainage of water. The size of the trap was found to be convenient; traps with larger sizes would be more difficult to install without greatly disturbing the undergrowth.

Small litter includes leaves,flowers,fruits,frass and small wood (<2 cm diameter).Pieces of wood larger than 2 cm diameter were broken off and discarded. Due to the distance of the sites from Kuching, litterfall was collected monthly for a period of one year from August 1987 to July 1988. The monthly collections were dried as soon as possible at 105^{o}C. They were then sorted into leaf and non-leaf fractions and weighed. The nine samples of each fraction from each site were then bulked together and sub-sampled and ground for the analyses of N, P, K, Ca, Mg and Na (see Appendix 1 for details of the analyses).

Leaf Litter and Small Wood Decomposition

For leaf litter decomposition study, litter bags of different mesh sizes are usually used and the rate of decomposition is often correlated with the mesh size. In the present experiment,however,cages were constructed on the ground and the leaf (and small wood) samples were placed on the ground surface enclosed within each cage. It is believed that decomposition taking place under such condition would resemble more closely to the natural situation on the forest floor (Chai,1982).

FIGURE 5.4 LOCATION OF LITTER PRODUCTION AND DECOMPOSITION EXPERIMENTS AND SITES FOR WATER TABLE MONITORING



M.S.L – Mean sea level

H.W.L – Highest water level in Btg. Baram (DID, 1970-78)

L.W.L – Lowest water level in Btg. Baram (DID, 1970-78)

P1 – 6 – Sites for monitoring water table

At each of the three sites along R.7, a rectangular cage measuring 4 m long,0.5 m wide and 0.5 m high was constructed using wire netting with 10-mm mesh size (see Plate 4). Before the cage was constructed, the ground surface was completely cleared of fallen and partially decomposed litter. The ground surface inside the cage was also overlain with wire netting of 25-mm mesh size. These were necessary in order to ensure that the leaves placed inside the cage for the study could be easily identified during sampling and would not be mixed up with soil organic matter. Each cage was divided into eight compartments.The corners and the long sides of the cage were pinned down with the help of jungle rollers.After the leaves and the small wood were put in the cage,the top was covered with nylon netting of 2-mm mesh size to prevent fresh litterfall from getting into the cage; on the other hand,the netting did not prevent the samples from being exposed to the natural elements like rain and sunshine.

At least 600 freshly fallen leaves (mixed litter) which showed no discoloration or signs of animal attack were collected from the ground surface in Plots A,B and C respectively. Each of these was then divided randomly into 12 batches of about 50 leaves each. The fresh weight of these samples were determined in the field using a balance with an accuracy of 0.1 g.Four 50-leaf samples from each site were brought back for drying at 105^{o}C to obtain the oven-dry weight.The purpose was to determine the ratio of dry to fresh weights and to use this ratio to calculate the dry weights of the rest of the samples.

The remaining eight samples at each site were placed separately in the eight compartments of the litter cage.Monthly observation was made until all the samples were sampled.During each observation,two batches were taken back for oven-drying and weighing.The experiments were started in August,1987 and lasted for four months.They were repeated in March,1988 when the first observation was omitted so that another set of observation was possible after a lapse of five months. In the end, there were four replicates for the second, third and fourth observations, but only two for the first and fifth.

While the leaf litter decomposition experiments were taking place,a similar set of experiments involving small wood (<2 cm diameter) was laid down.At each site,small fresh twigs and branches were gathered and cut into lengths of about 20 cm.These were then divided randomly into batches of about 20 pieces each.They were weighed in the field to obtain the fresh weights.Four were then taken back for oven-drying and the rest were spread separately in the eight compartments of the litter cage together with the leaf samples.Similar observation was made on a monthly basis.This set of experiments was repeated in February,1988 and during the repeat,the first observation was omitted to obtain a set of results after a lapse of six months. As in the case of leaf samples, there were only two replicates for the first and last observations while the rest had four.

The results of both leaf litter and small wood experiments were expressed either in percent loss of weight or as percentage of original weight (both on o.d.basis).

Large-wood Decomposition

This set of experiments was also established in August, 1987 within Plots A,B and C.Stems with diameter of 12-15 cm were cut from three or four living trees.As the aim was to have a within-site measurement,the most common tree species of the respective plot was selected : *Combretocarpus rotundatus* for Plot A,*Shorea albida* for Plot B and *Alangium havilandii* for Plot C.Wood from a common source would have been needed for between-site comparison.

After felling the trees,a steel bow-saw was used to cut the stem into sections of 50-cm length.As far as possible, sections with knots were avoided to ensure uniformity in sampling. The fresh weight of each sample, including the bark, was measured in the field using a scale balance of 10 g accuracy.Fifty-four sections were obtained and weighed for each plot.Six were taken back for oven-drying to constant weight at 105^{o}C;the sections were split into smaller pieces in order to speed up the drying process.The mean dry to fresh weight ratio was used to calculate the dry weights of the remaining samples in each respective plots.

The remaining 48 samples for each plot were divided into two batches of 24 each.Each set was then numbered with rust-proof aluminium tags.One set was then buried under the surface peat (see Plate 5) and another set was placed on the ground surface and left to decompose. The samples were examined at two-monthly intervals.During each observation, four buried and four exposed sections from each site were randomly sampled and taken back for oven-drying.The experiments were terminated in August,1988 and six observations were made. Decomposition was measured as percent weight loss on oven-dry basis.

5.3.4 Monitoring of Groundwater Table

Groundwater table at six localities along Transect R.7 at Tanjung Pasir (see Fig.5.4) was monitored over a period of one year from August, 1987 to July,1988. These sites included Plots A (Tape 42; PC 6), B (Tape 30; PC 4) and C (Tape 8; PC 1) where litterfall and decomposition experiments were carried out simultaneously. In addition, three other sites at Tapes 18, 32 and 35 were also investigated. However, the results of the last three sites were later omitted in the discussion because they showed comparable values to those of the plots and the patterns of monthly variation were identical.

At each site, an auger hole was bored to a depth of about 1 m with an Edelman auger. This bore hole was then lined with a 1.5-m plastic pipe (10 cm dia.) which had 4-5 rows of holes (1 cm dia.; 7-8 cm apart) drilled along the length of the pipe (see Plate 6). Measurement of water table was done once a month when the litterfall and decomposition experiments were sampled. As part of the pipe was left protruding above the ground surface, determination of the depth of water table with a dip-stick was very convenient. The depth of water table was expressed in cm below the ground surface. Since this transect was levelled, the final elevations of the ground surface and of the water table were related to the mean sea level (see Fig.10.3).

During the monthly observation, a groundwater sample from each site was also taken and brought back in a tightly sealed plastic bottle. Levels of K, Ca, Mg, Na, Cl and total dissolved solids (TDS) were determined on these water samples after filtering off the suspended particles. Details of these analyses are given in Appendix 1.

5.3.5 C-14 Dating

This part of the study was done in collaboration with Joan S. Esterle of the University of Kentucky, USA. The peat samples for carbon dating were jointly collected from the PS along Batang Baram, two along R.10 at Tj. Upar, three along R.4 at Lubok Belanak and one at the coast near Kuala Baram (see Fig.11.1). The two samples along R.10 were located at Tape 36 (depth 4 m) and 216 (depth 2 m) while those along R.4 were situated at Tape 39 (depth 8.5 m), 78 (depth 7 m) and 142 (depth 3.5 m). The peat sample near the coast was collected just above the basal sand at a depth of about 1 m.

The actual dating was done by Krueger Enterprises Inc., Massachusetts, USA. The sample for carbon dating was dispersed in a large volume of water and the clays and organic matter were eluted away from any sand and silt by sedimentation and decantation. The clay/organic fraction was then treated with hot dilute HCl to remove any carbonates. It was then filtered,washed,dried and roasted in oxygen to recover carbon dioxide from the organic matter for the analysis.The date was based on the Libby half life (5570 years) for C-14. The error stated is $\pm 1\sigma$ as judged by the analytical data alone. The modern standard is 95% of the activity of N.B.S. oxalic acid.

5.4 DATA RECORDING

All field data collected on site were recorded in a small notebook. On returning to the office, these data were quickly transcribed onto standard soil profile cards used routinely by the Soils Division of Agriculture Department. The laboratory data were also copied onto the reverse side of the same cards. An example of these is presented in Figure 5.5.

Before these data were entered into the computer data file, they were transcribed onto the general coding sheet used by the Computer Service of PNL. It was decided at the outset that the data file would be organized in a fixed-column format, allocating five columns for each variable except for the accession number and some notations for locality, sampling site and horizon. Five columns were found to be adequate for a variable after checking through the range of all variables involved. Since

FIGURE 5·5 AN EXAMPLE OF SOIL PROFILE CARD

Soil Group : ORGANIC SOIL Family : ANDERSON Series : Anderson 1 Phase :

Survey Area : Beladin Area Vegetation/Land Use : Mixed Peat Swamp Forest

Profile No : Field No. R403/08 Drainage : Very poor

Location : Rentis B2 tape 23 Permeability : -

Grid : V328,780 1:50,000 sheet No: 1/111/5 Watertable at : Almost at the surface

Parent material Forest peat Flooding : -

Altitude : - Erosion : -

Terrain class : 1A0. Rainfall : -

Topography : Flat Sampled by and date: Tie & Rosli 25/1/81

Slope : - Aspect : Position : Pit/Auger Profile : Pit

Surface features : Uneven Classification (U.S.D.A)

Horizon and Lab. No.	Depth (cm)	Description
	0 – 15	Very dark brown (10YR 2/2) partially decomposed hemic material; wet, non-sticky; many fine to medium roots; few large roots; structureless; non-woody; gradual boundary;
	15 – 30	Very dark brown (10YR 2/2) partially decomposed hemic material; wet, non-sticky; structureless; many medium to large roots; moderate wood content; gradual boundary;
	30 – 60	Black (10YR 2/1) hemic material; wet, non-sticky; structureless; many medium, few fine and large roots; moderate to high wood content; gradual boundary;
	60 – 90	Black (10YR 2/1) hemic material as above except there are fewer roots; gradual boundary.
	90 –120 (auger)	Black (10YR 2/1) peat; clear wavy boundary;
	120 – 140 (auger)	Light grey to grey (10YR 6/1) clay; wet, sticky and plastic.

(SP12)

Ds = 9.81 Km dbh = 18.6 cm

Eo = 0.325 m dFB = 12.9 cm

HFB. = 9.3 m

Tot Ht = 15.4 m

N. Tree = 140.

S1Ø = 41

N9 = 126.

BM. = ~~304~~ 182 t/ha

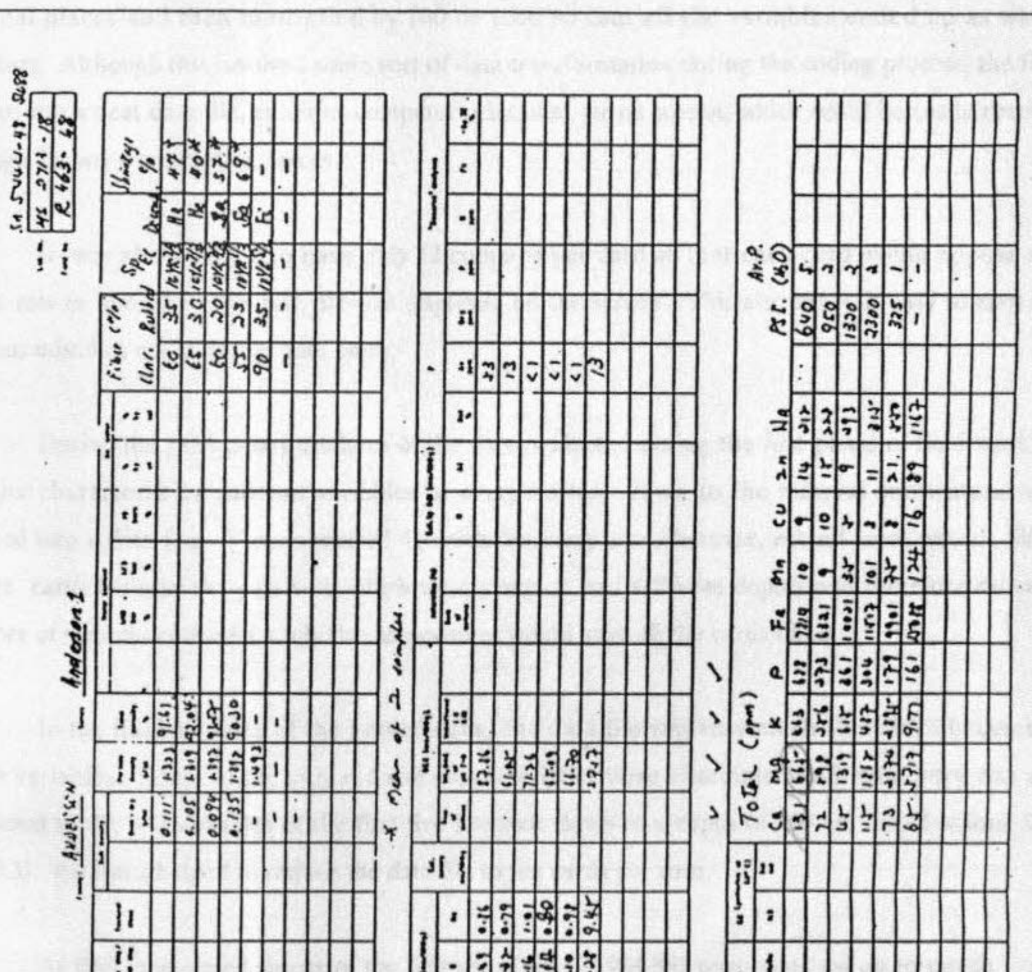


FIGURE 5.5 (CONT.)

most of the original data had decimal points, the figures were rounded off to the second or third decimal places and then multiplied by 100 or 1000 so that all the variables ended up as whole numbers. Although this involved some sort of data transformation during the coding process, the final reward was a neat data file, either as computer printouts or on screen, which could be easily checked through for any transcription errors.

It was also decided to have only 72 columns per card so that each card would appear as a single row or line when the data file was displayed on the screen. This also made it easy to spot any obvious mistakes made during data entry.

During the preliminary analyses of the data collected during the first phase of field work, all the site characteristics and soil variables of every horizon down to the mineral substratum were entered into a data file. These required 41 cards for every case.However, not all cases would fill up all the cards because the peat soils which were sampled had different depths and therefore different number of samples collected. Only the deeper ones would have all the cards filled.

In the final analyses of the pooled data, the data file was very much shortened because of fewer variables. Some of the site and soil characteristics were eliminated and data entry was also restricted to the soil variables of the first five horizons down to a depth of 150 cm (see Sections 5.3.1 and 9.3). All these helped to reduce the data file to ten cards per case.

At PNL, the coded sheets of the first set of data (1984-85) were punched on to punch cards which served as a more permanent record of the data file. The data were finally entered into the computer through these punch cards. This punch card procedure was omitted for the final set of data (1988) which was entered directly into the data file.

As the data had to go through several steps before they were finally stored in a computer data file, some errors were inevitably made during the transcription. Checking was carried out after every step. Several errors were detected and corrected. Final checking involved the comparison of the computer printouts with the original soil profile cards. Descriptive statistics (e.g. means, maximum, minimum, etc) of the variables were also found to be useful in spotting mistakes made in transcription.

CHAPTER 6. SITE CHARACTERISTICS

6.1 INTRODUCTION

During the first phase of the field work, more detailed characterization of the study sites was undertaken. The more important site information collected include the characteristics of the vegetation, and the peat depths and spot heights along the transects (see Section 5.3.2 for methodology).

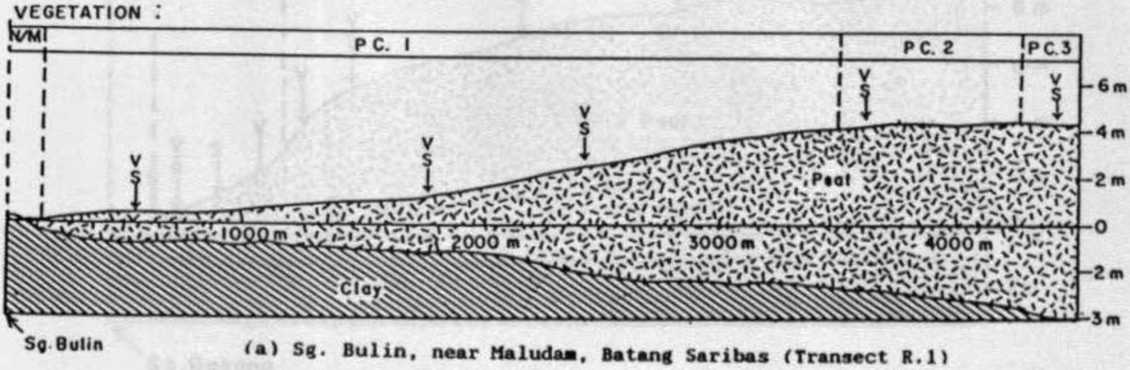
Peat depths and spot heights provide valuable information on the structure and the development of the peat deposits. These are discussed in Section 6.2 and further elaborated in Chapter 11.

Section 6.3 presents the vegetation data. The original intention was to collect detailed vegetation data so that statistical analyses could be performed to test the validity of the PC classification used by Anderson (1961). Having looked at the data collected, it was realized that it would be difficult to find sufficient undisturbed samples of some of the forest types, particularly those of PC 1 and 2 (see discussion below). This part of the study was therefore abandoned during the second phase of the field work (except for one plot in PC 6 which was not included initially). The vegetation data collected are presented below so that readers may gain a better understanding of the types of vegetation that are involved in this study. The edaphic and the ecological aspects of the forests will be discussed further in Chapters 8, 9 and 10.

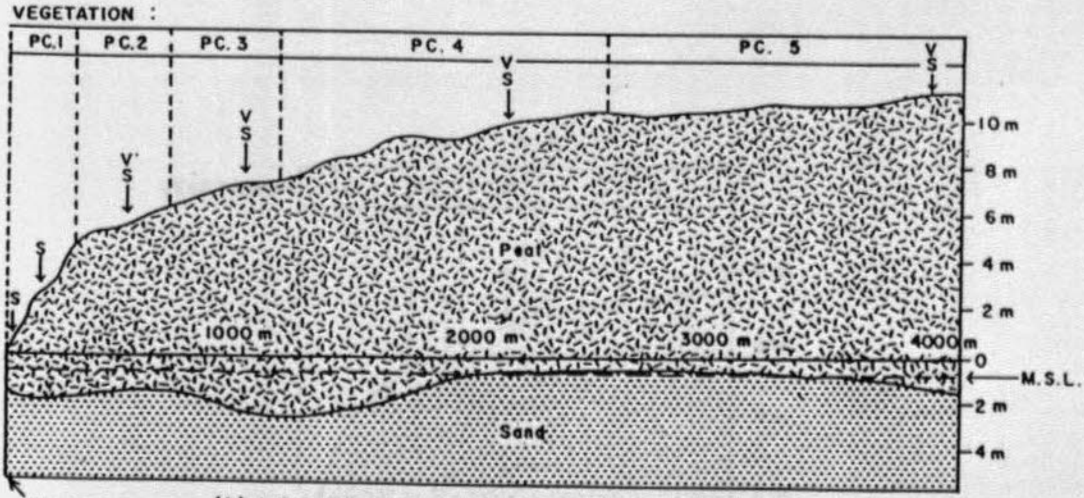
6.2 STRUCTURE OF PEAT SWAMPS

Five transects, R.1, 4, 5, 7 and 10, were levelled with an Abney level. For Transects R.4, 7 and 10, the elevations were related to mean sea level; for the other two transects, this was not possible because there were no benchmarks in the vicinities. The peat depth was determined at regular intervals along each transect with a modified Macaulay peat auger. From these data, the cross-

FIGURE 6.1 CROSS - SECTIONS OF THE TRANSECTS



(a) Sg. Bulin, near Maludam, Batang Saribas (Transect R.1)



(b) Lubok Belanak, Lower Batang Baram. (Transect R. 4)

NOTES / SYMBOLS :

(1) Vertical axis – Elevation in metres above the starting point (arbitrary).

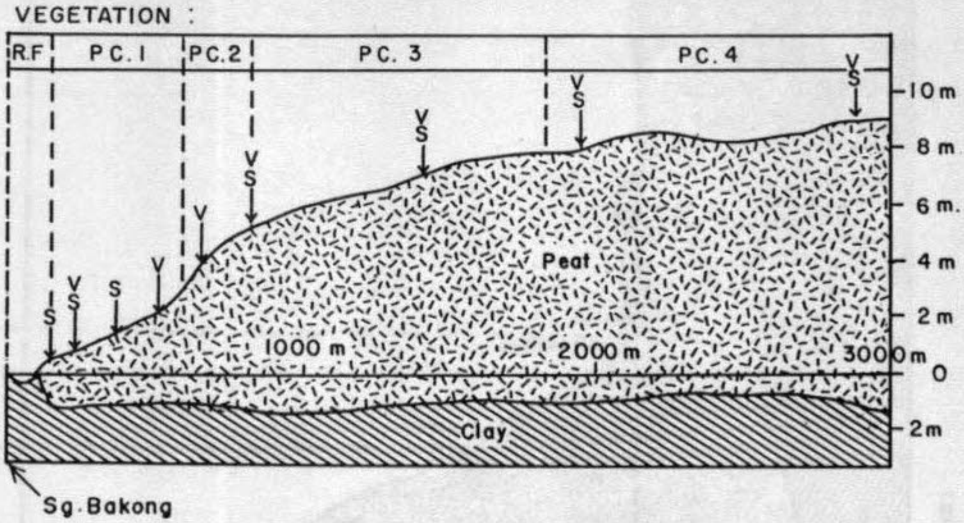
(2) Horizontal axis – Distance in metres from the starting point.

(3) N/M = Nipah / Mangrove ; RF = Riverine Forest ; P C. = Phasic community of Peat Swamp Forest. (1 = Mixed Swamp Forest ; 2 = Alan Forest ; 3 = Alan Bunga ; 4 = Padang Alan ; 5 = Tristania / Parastemon / Palaquium Association; 6 = Padang Paya or Padang Keruntum).

(4) ↓ – Sampling point (S = Soil ; V = Vegetation).

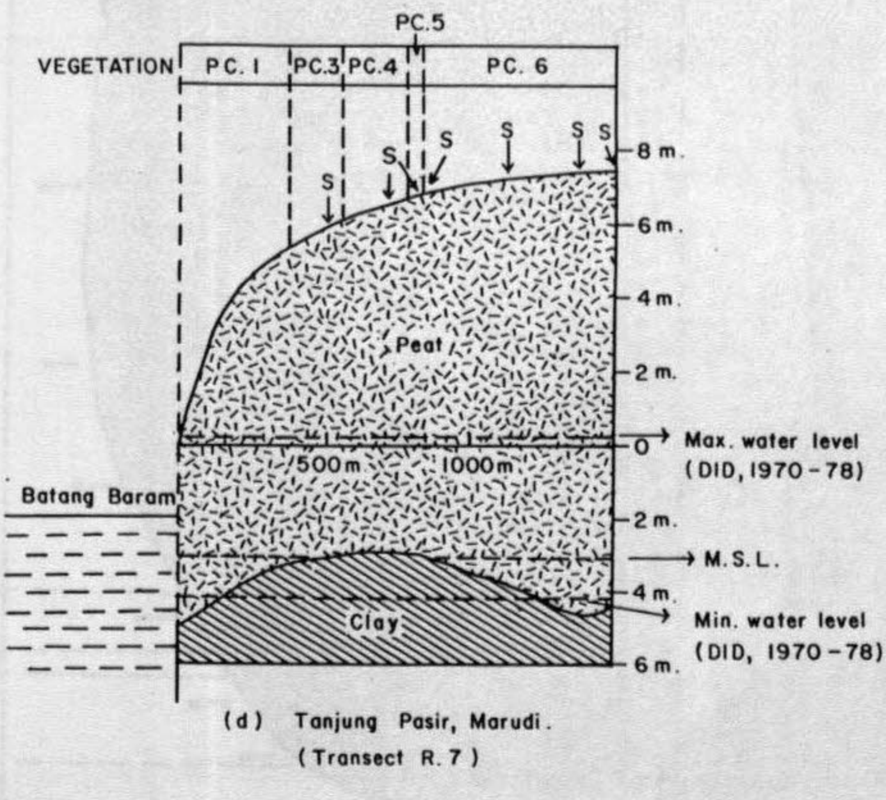
(5) M. S. L. – Mean sea level (where known).

FIGURE 6.1 (CONT.)



(c) Opposite Sg. Nakat, near Kpg. Nyabor, Sg. Bakong.

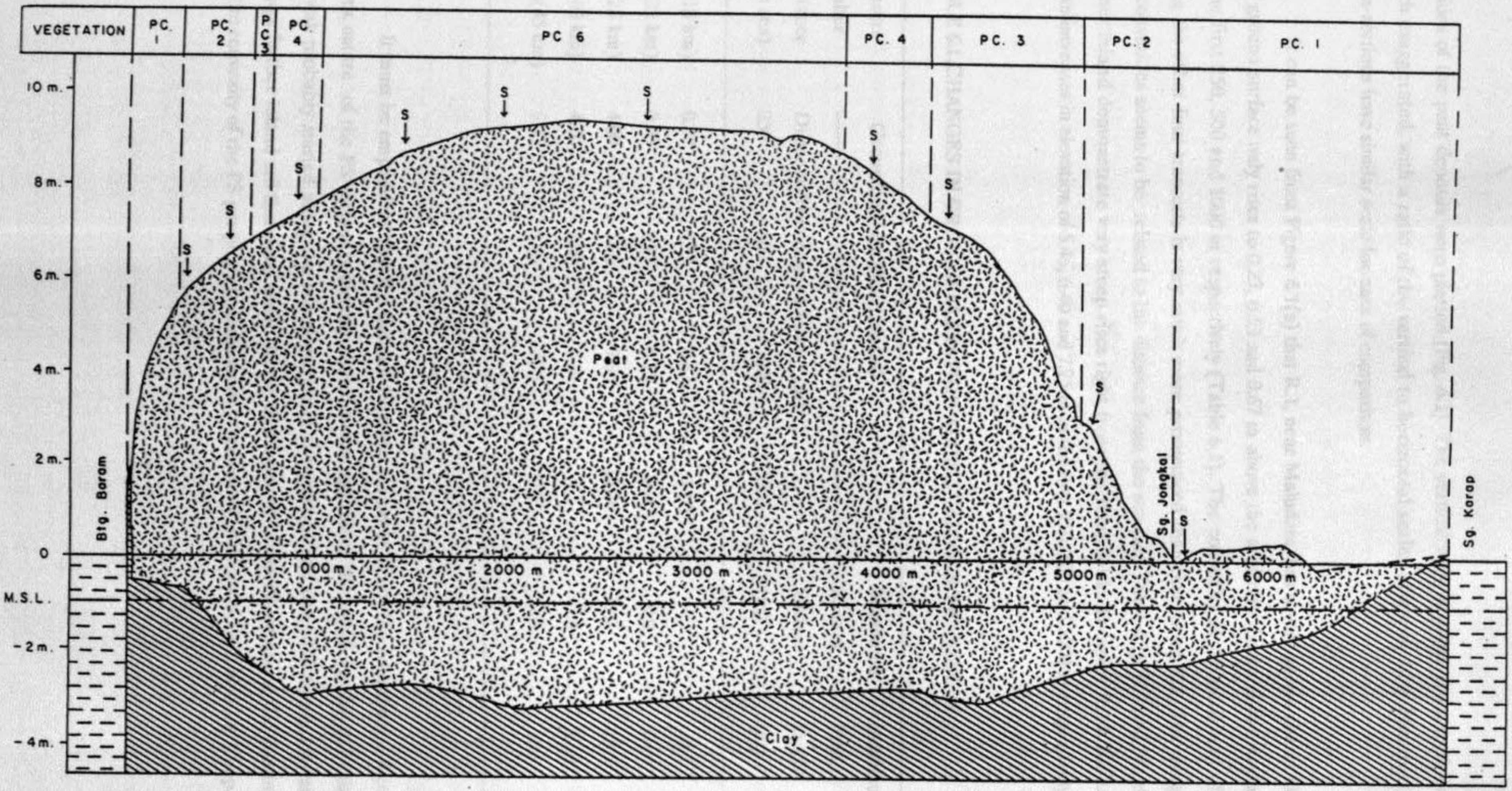
(Transect R. 5)



(d) Tanjung Pasir, Marudi.

(Transect R. 7)

FIGURE 6.1 (CONT.)



(e) Tanjung Upar, Batang Baram (Transect R 10) sections of the peat deposits were plotted (Fig. 6.1). The vertical scale of these cross-sections is very much exaggerated, with a ratio of the vertical to horizontal scales of about 1:90. However, all the cross-sections have similar scale for ease of comparison.

It can be seen from Figure 6.1(a) that R.1, near Maludam, has a very gentle rise in elevation. The ground surface only rises to 0.27, 0.53 and 0.67 m above the arbitrary datum at the starting point in the first 250, 500 and 1000 m respectively (Table 6.1). The convexity at the periphery of the PS along the other four transects is very much more pronounced than that along R.1. The steepness of the convexities seems to be related to the distance from the sea (see Table 6.1). R.7 and 10 which are further inland demonstrate very steep rises right from the river bank. Transect R.10, for example, shows increases in elevation of 5.45, 6.40 and 7.75 m in the first 250, 500 and 1000 m respectively.

TABLE 6.1.CHANGES IN GROUND ELEVATION ALONG VARIOUS TRANSECTS

Transect Number (Distance from sea)	Ground surface elevation (m) — Distance from edge of Swamp (m): 250	500	1000	2000	Maximum Rise of Surface (m)	Maximum Peat Depth (m)
R.1(18 km)	0.27	0.53	0.67	1.60	4.3	8.5
R.5(22 km)	0.93	2.27	6.13	8.40	9.0	10.4
R.4(25 km)	4.00	5.60	7.60	10.00	11.2	12.5
R.7(40 km)	4.70	5.90	7.10	-	7.4	12.0
R.10(45 km)	5.45	6.40	7.75	9.25	9.3	12.5

It must be emphasized that the distance from the sea *per se* is not the contributing factor. The convex nature of the PS surface is directly related to the age. Since the initial formation of the PS in Sarawak probably started along the inland margin of the swamps and extended slowly seawards, the swamps further inland are therefore older. As the development of the PS advances, the doming effect and the convexity of the PS periphery become more pronounced (Anderson,1961; also see Chap. 11).

R.10 at Tj.Upar is located furthest inland and it shows the most dramatic rise in ground elevation at the edge of the swamp. This is closely followed by the nearby transect at Tj.Pasir (R.7). The swamps which show a high convexity at the edges level off very quickly and the central bog plain is almost flat. The central portion of the swamp along R.10 from 1.75 to 3.50 km, for example, rises by only 0.3 m.

These observations substantiate the finding by Anderson (1961) that the convex morphology of the PS becomes more pronounced with increasing distance from the sea. Anderson recorded maximum relative rise of 9.3 m at Naman Forest Reserve near Sibu and the most pronounced convexity at Tj.Pasir swamp near Marudi. In the present study, the maximum rise above the arbitrary datum is 11.2 m recorded along R.4 at Lubok Belanak; R.5, 7 and 10 also show substantial rises of 9.0, 7.4 and 9.3 m respectively, whereas R.1 near the coast has a gentle rise of only 4.3 m above the datum.

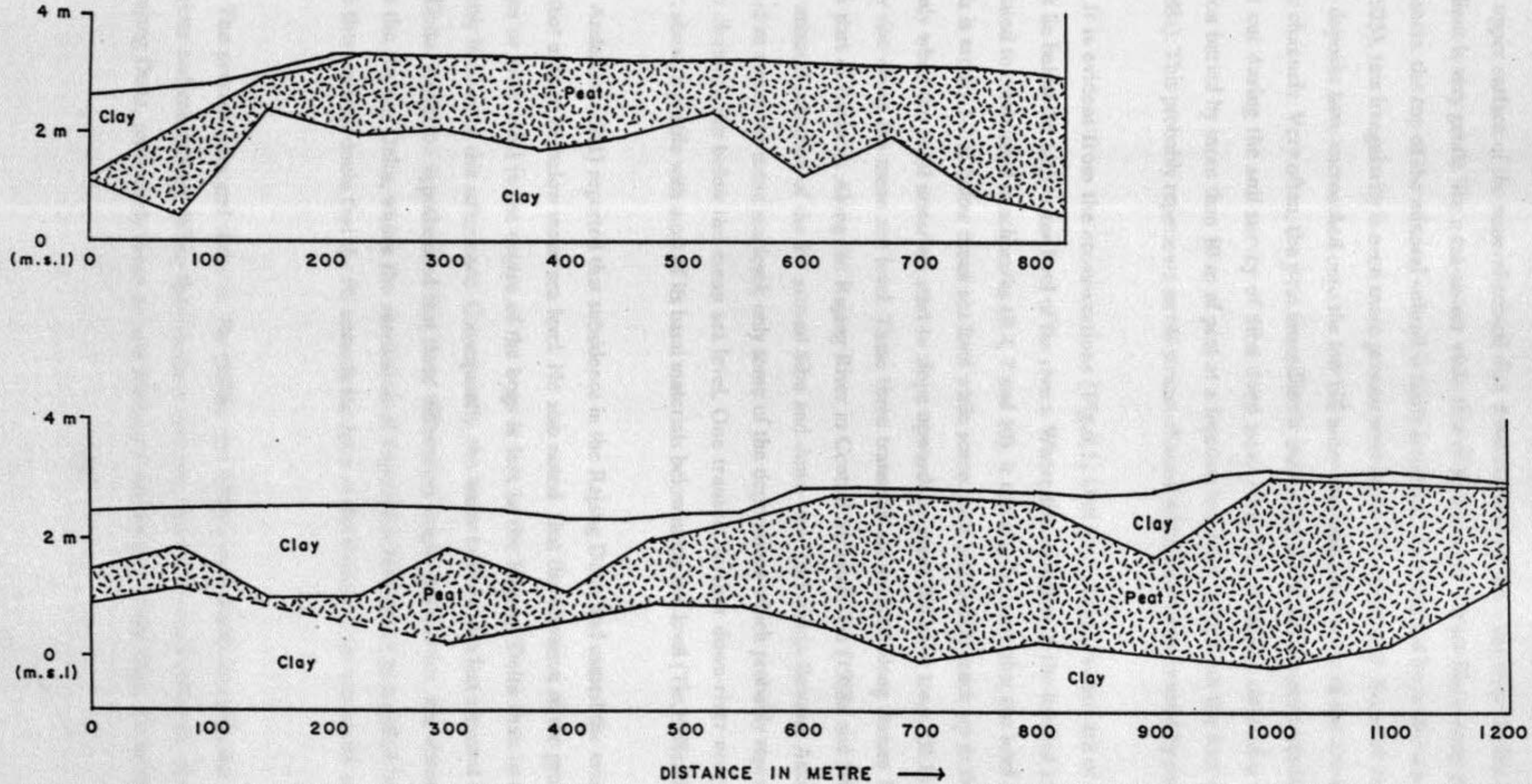
Maximum peat depth also increases with distance from the sea (see Table 6.1). Here again, it is the age of the PS rather than the distance from the coast that is thought to be causally related to the peat depth. Along R.1, the maximum peat depth recorded was 8.5 m while depths in the range of 12.0 to 12.5 m were encountered in the Tj.Upar, Tj.Pasir and Lubok Belanak areas.

Anderson (1961) reported that the subsoils along his transects were invariably a stiff white or yellow clay. This is not always true. Transect R.4 at Lubok Belanak, for example, is almost entirely underlain by a sandy substratum. Scott (1985) also reported fairly extensive areas of peats overlying sandy deposits in the coastal region of Central Sarawak.

It can be seen from the profiles plotted in Figure 6.1 that the river levees along Baram River at the starting points of R.4, 7 and 10 have been eroded and the peat deposit can be found immediately bordering the river. In the case of R.10, the first 25 m of the peat surface had been plastered with a layer of silty clay deposited by floods. This phenomenon is fairly common in Sarawak. During the semi-detailed soil survey of the deep peat area around Sibu (Tie,1988a) and also in the detailed survey of Lebaan-Bawang Assam Drainage Scheme area (Tie,1988b), deposition of flood sediments on top of the peat was seen to be quite extensive (see Fig.6.2). In some cases, the deposition has been intermittent and overlapping with further peat formation, resulting in discrete lenses of mineral soil within the peat.

Along Transects R.1 and 5, the river levee is still intact. It is apparent from these transects

FIGURE 6.2 CROSS-SECTIONS OF PS STRUCTURE AT LEBAAN-BAWANG ASSAM AREA
(Source: Tie, 1988b)



that the upper surface of the mineral subsoil dips downwards away from the river. In the case of R.1, the gradient is very gentle like a tea-saucer while that of R.5 is more abrupt like a soup-plate. For all the transects, the top of the mineral subsoil is fairly irregular. As reported by Anderson (1961) and Scott (1985), this irregularity is even more pronounced in the PS of Central Sarawak region where the peat deposits have encroached onto the low hill areas and blanketed some of the low mounds and old river channels. Very often, the peat immediately bordering a low hill is unexpectedly deep; one transect cut during the soil survey of Sibu deep peat area, for example, showed a trench-like depression buried by more than 10 m of peat at a location less than 50 m from the foot of a low hill (Tie, 1988a). This probably represents an old stream channel which had been covered by peat deposit.

It is evident from the cross-sections (Fig.6.1) that the mineral substrata of all the five transects lie below the high water level of the rivers. Where the elevation of the levelled transects had been related to established benchmarks (R.4, 7 and 10), it can also be seen that the level of the basal materials is mostly 1-2 m below mean sea level while some parts just barely reach up to the mean sea level. Only when the basal materials start to slope upwards to meet the river levee (R.10 - Fig.6.1.e) that they rise above the mean sea level. These three transects are located along Baram River in the northern part of Sarawak. Along the Rajang River in Central Sarawak, Tie (1988a and 1988b) found that the mineral substrata of the PS around Sibu and down-river to Lebaan-Bawang Assam area are mostly 1-2 m above the mean sea level; only some of the depressions which probably represent buried old river channels dip below the mean sea level. One transect further down-river near Bintangor, however, shows a profile with most of its basal materials below mean sea level (Tie,1988a:Fig.3e).

Anderson (1961) reported that subsidence in the Rajang Delta had caused the mineral subsoil level in that area to be below mean sea level. He also noted that the elevation of the ground surface above sea or river level in the centre of the bogs is less in the Rajang Delta than in the Baram, presumably because of this subsidence. Consequently, the water table is also less elevated in the PS of Rajang Delta. Anderson hypothesized that these differences might account for the absence of PC 5 and 6 in the Rajang Delta, where the succession of vegetation had never proceeded beyond PC 4 although there is little doubt that the PS towards the apex of the Rajang Delta are as old as the Baram swamps.

The present data and those in Tie (1988a and 1988b) only partially vindicate Anderson's observations and conclusions. While there is some evidence that the mineral substrata of some of the PS at Rajang Delta, particularly those around Bintangor and further down-river, are below the mean sea level, this is not the case along transects further up-river. On the other hand, information from the Baram area has shown substrata lying generally below the mean sea level. Therefore, the Rajang/Baram difference in vegetation succession may not be due to the subsidence of the Rajang Delta as suggested by Anderson. On the whole, current data suggest that the mineral substrata, except for the deep depressions representing old river channels, are always within 2 m of the mean sea level. The implications of such a situation on the development of PS will be discussed together with radio-carbon dates in Chapter 11.

6.3 PEAT SWAMP FOREST (PSF)

Detailed investigations on the forest types at some of the soil sampling sites along Transects R.1, 4, 5 and 7 were undertaken (see section 5.3.2). The results, summarized in Tables 6.2 - 6.5 and Figure 6.3, are discussed below. In the following discussion, "trees" refers to stems of dbh (diameter at breast height) of 10 cm or more. Following the approximate groupings used by Anderson (1963:p.224-225), trees of the upper storey generally have a dbh of over 50 cm, middle storey 20-50 cm, and lower storey 10-20 cm. The understorey which rarely attains 10 cm dbh is mainly composed of saplings of larger trees.

6.3.1 Brief Descriptions of Forest Types

Transect R.1

Four sites along Transect R.1 at Tapes (or Pegs) 70, 97, 145 and 177 were studied. The forest at T70 can be described as a poor Mixed Swamp Forest (PC 1) where the larger trees with dbh >50 cm are dominantly *Parishia maingayi* ("Upi Paya") (see Table 6.4). In sub-plots 3-5, large trees with dbh >50 cm are conspicuously absent. The canopy is very uneven with dominants attaining 46-52 m in height. The middle and lower storeys are dense and dominated by *Cephalomappa paludicola* ("Arau Paya") with trees mostly in the 10-20 cm dbh class and 10-16 m height class. The understorey is sparse, occurring in patches. Ground herbaceous plants consist primarily of *Thorachostachyum bancanum* sedge. Large lianas and small epiphytes are frequent. There is no significant build-up of roots above the swamp surface.

TABLE 6.2 MEAN CHARACTERISTICS OF TREES WITH DBH $\geq$ 10 cm

Transect/Tape No./PC	DBH* (cm)	Height* (m)	H:D* Ratio	Species /plot+
R1/ 70/1	20.1	17.7	97.9	36
R1/ 97/1	18.8	17.1	100.7	32
R5/ 9/1	23.0	20.8	104.9	28
R5/ 15/1	20.5	17.1	95.9	46
R1/145/2	19.7	15.5	89.3	39
R4/ 21/2	24.7	16.8	77.7	26
R5/ 33/2	27.7	24.2	102.4	26
R1/177/3	25.2	21.6	95.7	16
R4/ 39/3	29.0	24.2	98.2	18
R5/ 56/3	28.7	27.9	101.4	22
R4/ 83/4	30.3	25.2	85.9	12
R5/ 78/4	26.5	29.4	113.9	10
R5/115/4	25.7	26.6	111.5	10
R4/155/5	18.9	18.8	106.3	14
R7/ 35/6	15.2	10.5	72.3	7

** Mean of all trees recorded at each site/plot.*
+ Number of species per 0.2 ha plot.

TABLE 6.3 MEAN£ NUMBER OF TREES AND BASAL AREA PER HECTARE

Transect/ Tape No./ PC	Diameter Class (cm) <10	$\geq$10-20	>20-50	>50	Total $\geq$ 10 cm	Basal Area (m^2)
R1/ 70/1	16,400	400	165	30	595	29.6
R1/ 97/1	18,560	345	125	20	490	20.3
R5/ 9/1	12,480	280	125	45	450	30.4
R5/ 15/1	13,440	410	185	30	625	31.9
R1/145/2	18,000	570	170	45	785	40.0
R4/ 21/2	15,120	320	150	40	510	46.0
R5/ 33/2	12,640	310	90	70	470	53.0
R1/177/3	14,560	325	80	80	485	44.4
R4/ 39/3	17,920	225	50	85	360	40.6
R5/ 56/3	14,160	270	80	115	465	41.6
R4/ 83/4	21,680	235	165	95	495	47.1
R5/ 78/4	19,120	220	390	35	645	42.7
R5/115/4	18,160	200	410	10	620	36.9
R4/155/5	27,120	530	255	5	790	27.5
R7/ 35/6	15,040	225	60	0	285	6.1

£. Mean of 5 sub-plots per site.

ABLE 6.4 FLORISTIC COMPOSITION OF THE STUDY PLOTS

ansect/ ape No./ PC	Dominant Tree Species (>10 cm dbh) ≥10-20 cm dbh (Lower storey)	>20-50 cm dbh (Middle storey)	>50 cm dbh (Upper storey)
/ 70/1	*Cephalomappa paludicola (50%)* *Alangium havilandii (10%)*	*Cephalomappa paludicola (24%)* *Diospyros maingayi (15%)*	*Parishia maingayi (67%)*
/ 97/1	*Cephalomappa paludicola (62%)* *Blumeodendron tokbrai (6%)* *Tetractomia latifolia (6%)*	*Cephalomappa paludicola (36%)*	(Only 4 trees of different species recorded)
/145/2	*Cephalomappa paludicola (18%)* *Tectractomia parviflora (9%)* *Diospyros maingayi (8%)*	*Diospyros evena (15%)* *Lithocarpus andersonii (12%)*	*Shorea albida (44%)*
/177/3	*Tectractomia parviflora (38%)* *Cephalomappa paludicola (15%)*	*Gonystylus bancanus (31%)* *Parastemon spicatum (20%)*	*Shorea albida (100%)*
/ 21/2	*Diospyros evena (19%)* *Ilex hypoglauca (19%)*	*Diospyros evena (63%)*	*Shorea albida (100%)*
/ 39/3	*Diospyros evena (38%)* *Xanthophyllum racemosum (16%)*	*Parastemon spicatum (60%)*	*Shorea albida (100%)*
/ 83/4	*Parastemon spicatum (23%)* *Xanthophyllum racemosum (26%)*	*Shorea albida (79%)* *Combretocarpus rotundatus (12%)*	*Shorea albida (100%)*
/155/5	*Xanthophyllum racemosum (25%)* *Eugenia leucoxylon (13%)* *Shorea albida (9%)*	*Shorea albida (57%)* *C. rotundatus(27%)*	Only 1 *Combretocarpus rotundatus* recorded
/ 35/6	*Dactylocladus stenostachys (61%)* *Tristania obovata (11%)* *Palaquium cochleariifolium (9%)*	*C. rotundatus(100%)*	---
/ 9/1	*Eugenia spp.(11%)* *Ganua coriacea (11%)*	*Copaifera palustris (42%)* *Eugenia spp. (20%)*	*Dryobalanops rappa (44%)* *Parishia maingayi (44%)*
/ 15/1	*Ganua pierrei (23%)* *Dyera polyphylla (9%)* *Xanthophyllum amoenum (9%)*	*Copaifera palustris (43%)*	*Copaifera palustris (50%)* *Dryobalanops rappa (33%)*
/ 33/2	*Tetractomia parviflora (18%)* *Ilex hypoglauca (17%)*	*Gonystylus bancanus (69%)*	*Shorea albida (100%)*
/ 56/3	*Tetractomia parviflora (17%)* *Ganua coriacea (17%)*	*Shorea albida (44%)* *Gonystylus bancanus (25%)*	*Shorea albida (100%)*
/ 78/4	*Palaquium ridleyi (50%)* *Parastemon spicatum (18%)*	*Shorea albida (83%)*	*Shorea albida (100%)*
/115/4	*Shorea albida (38%)* *Palaquium ridleyi (15%)* *Parastemon spicatum (15%)* *C. rotundatus (13%)*	*Shorea albida (94%)*	*Shorea albida (100%)*

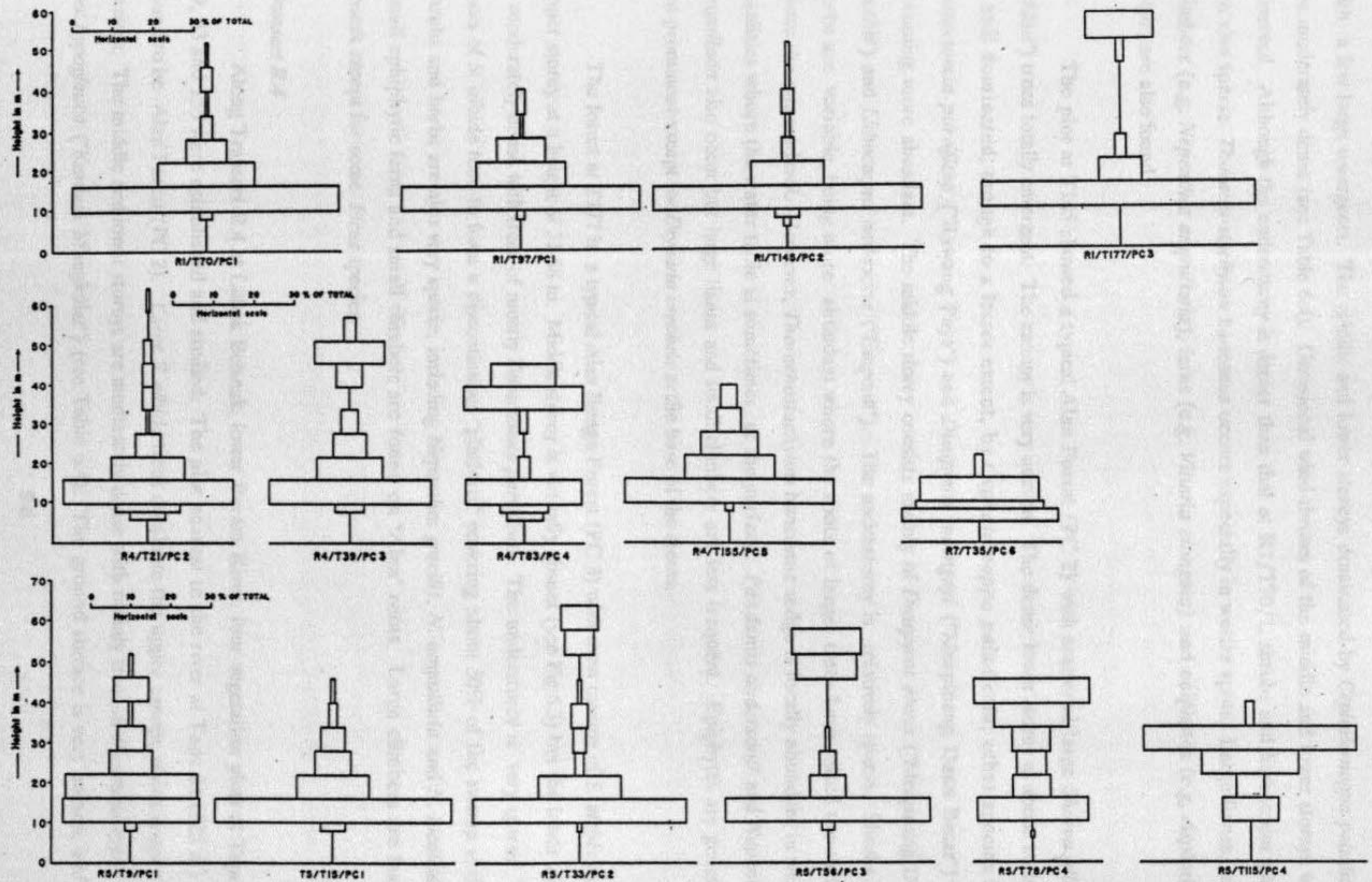
e figures in brackets denote the percentages within that particular diameter class.

TABLE 6.5 MEAN* H:D RATIO OF TREES IN VARIOUS DIAMETER CLASSES

Transect Tape/ PC	Diameter classes (cm) of trees									
	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	≥100
R1/ 70/1	106.9	86.5	76.8	67.8	66.7	-	56.9	53.4	-	-
R1/ 97/1	109.4	92.1	79.1	63.9	53.4	60.9	-	-	39.4	-
R5/ 9/1	120.6	87.5	82.8	74.0	76.5	-	64.8	53.1	53.3	-
R5/ 15/1	106.7	86.1	73.9	61.8	58.8	50.0	-	-	46.7	39.0
R1/145/2	97.4	74.8	70.6	-	53.2	53.7	51.4	45.9	-	42.9
R4/ 21/2	86.6	71.7	63.0	65.0	-	-	57.9	51.7	41.2	42.9
R5/ 33/2	112.8	94.3	95.6	92.5	-	82.6	80.4	70.3	63.6	58.2
R1/177/3	104.3	79.3	69.0	100.2	91.4	84.2	73.6	67.5	61.4	-
R4/ 39/3	110.8	98.0	-	75.0	83.3	76.7	64.8	61.0	55.8	-
R5/ 56/3	105.1	89.7	115.5	116.4	94.6	85.4	77.1	-	-	-
R4/ 83/4	88.0	74.1	99.6	87.8	77.3	68.1	56.0	-	-	-
R5/ 78/4	114.9	123.3	114.7	97.6	82.7	-	-	-	-	-
R5/115/4	133.5	116.3	93.4	79.0	65.6	-	-	-	-	-
R4/155/5	114.6	94.5	86.3	77.3	72.2	-	-	-	-	-

** Mean of all trees recorded at each site. Dash (-) means no tree was recorded in that diameter class.*

FIG. 6.3 RELATIVE FREQUENCIES OF TREES (> 10cm dbh) IN VARIOUS HEIGHT CLASSES



The study plot at T97 is also rather poor Mixed Swamp Forest. The canopy is very uneven with a few large emergents. The middle and lower storeys dominated by *Cephalomappa paludicola* are moderately dense (see Table 6.4). Occasional wind-throws of the middle and lower storeys were observed. Although the understorey is denser than that at R1/T70/1, shrubs and herbaceous plants are also sparse. *Thorachostachyum bancanus* occurs especially in wetter spots. Large lianas, small climbers (e.g. *Nepenthes ampullaria*), ferns (e.g. *Vittaria elongata)* and epiphytes (e.g. *Asplenium nidus*) are also found.

The plot at T145 showed a typical Alan Forest (PC 2) with scattered large *Shorea albida* ("Alan") trees totally emergent. The canopy is very uneven. The dense lower storey at about 10-16 m is still dominated, though to a lesser extent, by *Cephalomappa paludicola*; other species like *Tetractomia parviflora* ("Rawang Paya") and *Diospyros maingayi* ("Merpinang Daun Besar") are becoming more abundant. The middle storey consists mainly of *Diospyros evena* ("Merpinang Daun Kechil") and *Lithocarpus andersonii* ("Empenit"). The understorey is relatively sparse. Shrubs and herbs are variable, being more abundant where the roots of larger trees have raised the surface above the swamp level. However, *Thorachostachyum bancanus* sedge is locally abundant in wetter localities where the water table is sometimes at the surface. *Pandanus andersonii* and *Nepenthes ampullaria* also occur but large lianas and small climbers are less frequent. Epiphytes are generally not prominent except for *Drynaria involuta* at the base of the stems.

The forest at T177 is a typical Alan Bunga Forest (PC 3) with even canopy of *S. albida* in the upper storey at a height of 52-58 m. Middle storey is virtually absent (see Fig.6.3) but the lower storey is moderately dense with trees of mostly *Tetractomia parviflora*. The understorey is very sparse. The roots of *S. albida* tend to form a discontinuous "platform" covering about 50% of the swamp surface. Shrubs and herbs are also very sparse, including *Nepenthes gracilis*, *N. ampullaria* and *N. bicalcarata*. Small ephiphytic ferns and small climbers are found on "Alan" roots. Large climbers are largely absent except for some *Ficus* species.

Transect R.4

Along Transect R.4 at Lubok Belanak, lower Baram River, four vegetation plots at Tape 21, 39, 83 and 155 were established and studied. The plot nearest to the river at Tape 21 (525 m) was found to be Alan Forest (PC 2). Large *S. albida* trees dominate the upper canopy which is open and uneven. The middle and lower storeys are moderately dense with mainly trees of *Diospyros evena* and *Ilex hypoglauca* ("Kerdam Mungkulat") (see Table 6.4). The ground surface is very uneven, and the sparse ground flora comprises mainly ferns (*Asplenium* spp. and *Cyathea glabra*), *Pandanus andersonii* and Nepenthaceae. The forest is fairly typical of Alan Forest in the Baram region.

A typical Alan Bunga Forest (PC 3) was found at T39. The upper storey is composed of a pure, even canopy of *S.albida* which averages 85 trees per ha and reaches a height of 58 m. The middle storey is largely absent while the lower storey to a height of 20 m is sparse with trees of *D. evena* and *Xanthophyllum racemosum* ("Nyalin"). The understorey is moderately dense. The ground surface is very rough with roots of *S. albida* raised above the swamp surface. Shrubs and herbs are sparse with a few *Nepenthes* species, *Alocasia beccarii* and small ferns. There are some small climbers like *Ficus callicarpides* and *Lecananthus erubescens*, and epiphytic ferns like *Asplenium nidus*.

The forest at Tape 83 is possibly intermediate between Alan Bunga (PC 3) and Padang Alan (PC 4) Forests. However, it is more akin to the latter although the trees are generally larger in size than a typical Padang Alan Forest. *S. albida* totally dominates the even, upper storey at heights up to 46 m (see Fig.6.3). *S. albida* is also the dominant species in the middle storey where a few *Combretocarpus rotundatus* ("Keruntum") trees also occur. The lower storey is sparse with trees of mainly *Parastemon spicatum* ("Ngilas Padang") and *Xanthophyllum racemosum*. The understorey is dense. Herbaceous plants are virtually absent and the ground flora in general is very sparse, comprising mainly Nepenthaceae. *Asplenium* ferns and climbers are also rare. The ground surface is uneven and not compacted.

A marked change was observed at Tape 100 along Transect R.4. The ground surface becomes more compacted and more even. The forest at Tape 155 is PC 5. There is a moderately dense canopy at about 20 m, but emergents (mainly *S. albida* and *C. rotundatus*) can attain 30-38 m heights (see Fig.6.3). Trees with 10-19 cm dbh are mainly *Xanthophyllum racemosum*, *Eugenia leucoxylon* ("Ubah") and *S. albida*. The ground flora is very dense with prominent "Pandan" such as *Pandanus andersonii*. There are very few herbs, climbers and epiphytes except for a few terrestrial orchids, some *Thorachostachyum bancanum* and *Nepenthes* species.

Transect R.5

Six ecological plots were established and studied along Transect R.5. The first two at Tape 9 and 15 were found to be Mixed Swamp Forest (MSF), with the one at Tape 15 as the more typical. They both have very uneven canopy with some emergents of *Dryobalanops rappa* ("Kapur Paya"), *Parishia maingayi* and *Copaifera palustris* ("Sepetir Paya") rising to heights of 46-52 m (see Table 6.4

and Fig.6.3). The middle storey is moderately dense with trees dominated by *Copaifera palustris*. The plot at T15 has a dense lower storey with mainly *Ganua pierrei* ("Ketiau Puteh") while the moderately dense lower storey at T9 is dominated by *Eugenia spp.* and *Ganua coriacea* ("Ketiau Merah"). The ground flora is fairly sparse in both plots; *Thorachostachyum bancanum* occurs and is most luxuriant in wetter spots or in more open localities. Climbers like *Uncaria ovalifolia* and *Ficus* species, and epiphytes like *Asplenium nidus* are more frequent in the plot at T15. The ground surface is nearly level in both plots but the plot at T9 is probably subject to flooding at very high water.

Though not very typical, the plot at T33 is essentially Alan Forest (PC 2). The upper, semi-closed canopy at about 60 m is formed by *Shorea albida*. The middle storey is sparse (see Fig.6.3) and is composed of mainly *Gonystylus bancanus* ("Ramin"). The moderately dense lower storey rises to about 20 m, consisting primarily of *Tetractomia parviflora* and *Ilex hypoglauca*. The ground flora is sparse. Nepenthaceae are rare, and there are some small epiphytic ferns on the buttresses and roots of *S. albida* which are raised to about 1.5 m above the swamp surface. Large lianas are largely absent but some medium climbers reach the middle storey and small climbers are frequent in the understorey.

A typical Alan Bunga Forest (PC 3) is present in the plot at T56. The upper storey, reaching a height of about 60 m, is composed of a pure, even canopy of *Shorea albida* with 50-70 cm dbh and which averages 115 trees per ha. The middle storey is very sparse. The lower storey rising to a height of about 16 m is moderately dense and is dominated by *Tetractomia parviflora* and *Ganua coriacea*. The ground flora is sparse with Nepenthaceae, *Pandanus andersonii*, *Vittaria elongata* and *Asplenium* epiphytic ferns. Large lianas are absent but small climbers and epiphytic ferns occur. The ground surface is not entirely covered by the roots of *S. albida* but in some localities, the root "platform" (largely hollow underneath) may reach a height of 1 m above the surface.

The vegetation at T78 is a typical Padang Alan Forest (PC 4) with an even, pure canopy of *Shorea albida* at heights of 40-46 m. Trees are smaller and on average, only 35 stems per ha reach 50 cm dbh or bigger. The lower storey is sparse with mainly *Palaquium ridleyi* ("Nyatoh Terong") and *Parastemon spicatum* ("Ngilas Padang") while the understorey is moderately dense. The ground flora includes mainly Nepenthaceae. Small climbers are fairly frequent in the understorey but large lianas are absent and epiphytes are few. "Platforms" of *S. albida* roots cover about 60-70% of the swamp surface and they are about 0.5-0.7 m high.

The Padang Alan Forest at T115 is basically similar to that at T78. However, it represents a more extreme form, totally dominated by *S. albida* trees which are slightly smaller in dbh and the even upper canopy is about 10 m lower than that at T78. Small trees of *S. albida* also dominate the lower storey but *Palaquium ridleyi* and *Parastemon spicatum* are still numerous (see Table 6.4). *Combretocarpus rotundatus* also becomes fairly significant in the lower storey. The ground flora and the ground surface conditions are similar to those described above for the plot at T78.

Transect R.7

The plot at Tape 35 along Transect R.7 can be described as a typical Padang Paya Forest (PC 6). The vegetation is very stunted with a sparse canopy at 16 m, though a few *C. rotundatus* do attain heights up to 22 m (see Fig.6.3). The trees are very small, with dbh less than 20 cm; they include mainly *Dactylocladus stenostachys* ("Jongkong"), *Tristania obovata* ("Selunsor"), and *Palaquium cochleariifolium* ("Nyatoh Jelutong"). The understorey is fairly sparse. Herbaceous plants on the ground surface are dominated by *Thorachostachyum bancanum* and *Pandanus ridleyi*. Myrmecophytes and Nepenthaceae are numerous. The ground surface is uneven, and *Sphagnum* moss is found in depressions where water collects (during wetter months).

6.3.2. SUMMARY AND DISCUSSION

The floristic composition of the plots with PC 1 and 2 seems to be different from what Anderson (1960) described for these PC. *Gonystylus bancanus* and *Dactylocladus stenostachys* which were taken by Anderson as indicators of PC 1 are conspicuously absent. This is understandable because these are valuable timber species and may therefore have been selectively extracted. Instead, species like *Parishia maingayi, Copaifera palustris* and *Dryobanalops rappa* dominate size classes above 50 cm dbh. The dominance of *Cephalomappa paludicola* in the middle and lower storeys of PC 1 along Transect R.1 is also apparent.

Some of the larger trees in PC 1 attain dbh of 85-95 cm. However, the average dbh of trees in various sub-plots of PC 1 are only 18.8-23.0 cm and the average heights range from 17.1 to 20.8 m (see Table 6.2). The stocking density averages 450-625 trees per ha (see Table 6.3).

In PC 2, the average dbh and heights are 19.7-27.7 cm and 15.5-24.2 m respectively. The larger size classes, with some dbh up to 114 cm, are dominated by *Shorea albida*. *Gonystylus bancanus* features quite prominently in the middle storey along Transect R.5. The stocking density is slightly higher than PC 1, averaging 470-785 trees per ha (Table 6.3).

Trees of PC 3 (Alan Bunga Forest) are on average bigger and taller than those of PC 1 and 2. Mean dbh and heights are 25.2-29.0 cm and 21.6-27.9 m respectively (see Table 6.2). However, the maximum dbh of 95 cm is lower than that of PC 1 (100 cm) and PC 2 (114 cm), and the density is also lower with only 360-485 trees per ha (see Table 6.3). The dominance of *Shorea albida* in the upper storey (and the middle storey of Plot R5/56/3) is clearly shown (see Table 6.4).

Plot R4/83/4 is not a good sample of PC 4. The other two plots of PC 4 are situated along Transect R.5 and are more typical of Padang Alan Forest (PC 4). Although the average dbh of about 26 cm is larger than that of PC 1 and even some plots in PC 2, maximum dbh recorded is only 56 cm, and the pole-like aspect of the forest is apparent from the average H:D ratios of 111.5 to 113.9, the highest recorded (see Table 6.2). The tree density is very high at 620-645 stems per ha. *Shorea albida* dominates the upper and middle storeys (see Table 6.4). In Plot R5/115/4, the lower storey is also dominated by *S. albida*.

There is only one plot each in PC 5 and 6. Both of them appear to be typical of their respective forest type. The smaller tree size in these forests, especially PC 6, is clearly seen Table 6.2. PC 5 has a very high density of 790 trees per ha (see Table 6.3); but this is still lower than figures of 1200-1350 reported by Anderson (1983). The understorey of PC 5 is also very dense. Apart from having shrub-like small trees, PC 6 also has a very low density of only 285 trees per ha. *Shorea albida* is still prominent in PC 5, but *Combretocarpus rotundatus* becomes significant in both PC 5 and 6. *Dactylocladus stenostachys* and *Tristania obovata* also feature prominently in PC 6.

There is a general trend towards higher H:D ratios in the lower diameter class (see Table 6.5). The smaller trees in the lower storey are therefore more slender. The larger, upper-canopy trees of PSF have a lower H:D ratio; such tree shapes are more sturdy and wind-resistant (Brunig, 1983).

In this study, a total of 1,614 trees in 131 species were recorded. In PC 1 and 2, 26-46 species are found in the five 20x20 m sub-plots (0.2 ha); in PC 3, 4 and 5, this number is reduced to 10-22, and in PC 6, it is further decreased to 7. Anderson (1983) reported a general reduction in the number of tree species per 0.2 ha from 30-55 of PC 1 and 2, through 12-25 of PC 3 and 4, to <5 of PC 6.

The most common species is *Shorea albida*, accounting for nearly 21% of the trees enumerated, followed by *Cephalomappa paludicola* (8%) and *Diospyros evena* (5%). The fact that larger trees from especially PC 1 and 2 have been selectively extracted is evident. Only about 40% of the trees recorded have a dbh of 20 cm or more. There are 84 species of these larger trees (>20 cm dbh) with *S. albida* making up 48% of the total; many species registered only a single tree. Only 9% of the total 1,614 trees have a dbh greater than 50 cm and *S. albida* accounts for 82% of these very large trees.

Despite initial care taken to avoid logged over sites, it is apparently difficult to obtain absolutely undisturbed vegetation plots in the PSF of Sarawak, especially those of MSF (PC 1) and Alan Forest (PC 2). Due to the valuable timber these forests produce and the long history of logging (see Section 3.3), most of the PSF in Sarawak have been subject to at least one cycle of selective logging, in which bigger and more valuable trees like "Ramin" (*Gonystylus bancanus*) had been extracted. The effects of such activities in PC 1 and 2 are clearly reflected in the data collected; the trees in such plots are smaller and the floristic compositions also differ slightly from what were reported by Anderson (1961; 1963 and 1983). In those study plots which had been disturbed, the selective extraction of timber was done more than a decade ago. As a result, very little telltale signs of past logging, such as tree stumps and old extraction routes, were observed during the field work. In PC 4, 5 and 6, where little or no marketable timber occurs, the data recorded are more indicative of the natural, undisturbed vegetation. Valuable trees (mainly *S. albida*) at marketable sizes are also available in PC 3 (Alan Bunga Forest). In this case, however, the evenness of the stands means that any past logging would be very conspicuous and easily recognized in the field.

As completely undisturbed PC 1 and 2 of PSF are difficult to find, detailed characterization of the original vegetation becomes meaningless. During the second phase of the field work, this part of the study was abandoned. As a result, the PC classification used by Anderson (1961) could not be tested statistically and subsequent scope of statistical analyses was reduced. The classification of PSF into six PC has to be accepted as being real and truly reflecting the differences in the plant characteristics. Soil-forest relationships are tested in Chapters 8 and 9 by using the PC as the grouping variable. Direct relationships between the actual forest characteristics (e.g. biomass and species diversity) and the soil properties could not be explored by techniques such as multivariate regression and canonical correlation analysis.

CHAPTER 7. VERTICAL CHANGES OF SOIL PROPERTIES WITH DEPTH

7.1 INTRODUCTION

From the writings of Hardy (1936) and many others, it is now well known that the nutrients in a soil under many mature tropical forests are maintained in a nearly closed cycle from which few nutrients are lost in the drainage. The downward movement by leaching is balanced by the upward movement through the plant and eventual return to the soil surface through the litter. The equilibrium between this leaching effect and the "pumping" action of the standing vegetation has produced characteristic distribution of nutrients within soil profiles. This is particularly noteworthy in the humid tropics where the highly leached soils under forest still contain more nutrients, especially P and Ca (Nye and Greenland, 1960), in the topsoils than in the lower horizons. This phenomenon, however, has mainly been noted in mineral soils. There are few reported studies of nutrient dynamics on tropical organic soils.

In temperate peats, Sillanpaa (1972) found that there was a notable surface concentration of all the 13 trace elements studied. This was followed by a decrease which came to a minimum in the mid-profile and then a marked increase in the transition zone, reaching a maximum in the underlying mineral subsoils. He attributed the pattern mainly to the result of nutrient recycling by the vegetation. He found that contamination from the air was very slight, but suggested that capillary rise of soluble elements and surface evaporation might be other factors.

In Indonesia, Driessen and Rochimah (1976) observed that the subsoils of deep peats were less decomposed than the surface layers. As a result, the subsoils also had higher porosities and lower bulk densities. Driessen and Sudjadi (1981) also reported that the mineral content of deep peats under both "Padang" and Mixed Swamp Forests decreased sharply with depth.

Parbery and Venkatachalam (1964) reported that total N, available P, and exchangeable Ca and Mg of South Malayan peats decreased with depth. They also observed that organic C and CEC in deep peats increased with depth while ash content decreased. Their depth of sampling, however, only extended to 45 cm below the surface.

Along one transect on a highly developed raised bog near Marudi (Sarawak), Anderson (1961) found a clear indication that the plant nutrients were stratified and most abundant in the top 15 cm. Since the feeding roots of the vegetation are concentrated at the surface, he suggested that the nutrient cycle is largely confined to this layer. Wall (1966) also found a similar vertical distribution of "reserve" P in the organic soils of Bekenu-Niah-Suai area in Sarawak. Levels of available P showed the same trend and were extremely low below 60 cm. Wall sampled to a depth of 120 cm and attributed the surface enrichment to nutrient recycling.

The primary objective of this part of the study is to investigate how the soil properties vary with depth. By tracing the vertical variations of soil properties right down to the mineral subsoils, it was also hoped that some complementary data could be gathered to support Anderson and Muller's (1975) palynological evidence of the transition from a marine or brackish type of environment to a freshwater one (see Section 4.3.1, p.36). Details of sampling procedures and analyses are described in Chapter 5. Twenty of the soil profiles had been sampled right down to the mineral subsoils. Four others along Transect R7 were also sampled in late 1986 for the analyses of total sulphur (TS).

7.2 RESULTS

The profiles are identified in the presentation below by two numbers with a slash in between : the first number denotes the transect number and the second the tape (or peg) number. All the analytical data are shown in the tables. The figures summarize data from selected profiles; only six profiles are shown to aid legibility. They are 1/97, 1/177, 5/15, 5/56, 6/28 and 7/60. Profiles 1/97 and 5/15 were under PC 1, 1/177 and 5/56 under PC 3, 6/28 under PC 4, and 7/60 was under PC 6. There are a few missing data from the sub-surface layers. This is mainly because the quantity of some samples was insufficient for all the analyses.

Physical Characteristics

The results for pyrophosphate colour index (PCI) and fibre after rubbing (FAR) are listed in Table 7.1. Both PCI and FAR are measures of the degree of decomposition of the organic soil materials (Soil Survey Staff, 1975). PCI values of 5 or more and FAR of 40% or more indicate a fibric material, while PCI of 3 or less and FAR below 17% (one-sixth) indicate sapric material. Hemic material has intermediate values. Within all the profiles studied here, there is a general increasing trend in both PCI and FAR of the first three or four layers. Below these, there are no major differences and the sub-surface materials are mostly fibric in nature. Profile 7/60 seems to be an exception where the whole profile right up to the surface is, as shown by PCI and FAR, composed of fibric materials. Profile 6/41 has a similar trend as Profile 7/60 in terms of PCI, but it has lower FAR in the top few layers.

Available data on bulk density (BD) are mostly confined to the first three or four layers (see Section 5.3.1). All of the profiles demonstrate a decreasing trend with the largest differences occurring commonly between the first and the second layer. The top 15 cm generally have a BD greater than 0.1 g/cm^3 while the sub-surface layers usually have values below this figure.

Organic C, Ash, N, Total and Available P, and pH

The data on organic carbon (OC), ash, total nitrogen (N), pH, total phosphorus (TP), and available phosphorus (AP) are presented in Tables 7.3-7.5. In order to show the vertical trends more clearly, these data (except AP and some ash and pH) of the six selected profiles are summarized in Figure 7.1.

For OC, most of the profiles show a slight increase of 2-3% within the first four layers (0-100 cm). Below 100 cm, the OC content remains fairly constant but it starts to decrease very sharply in the last 100-200 cm above the mineral subsoil. Profiles 5/9 and 5/15 are exceptions because the peats are relatively shallow; the OC content begins to decline immediately below 60 and 100 cm respectively.

TABLE 7.1 FIBRE AFTER RUBBING (FAR %) AND PYROPHOSPHATE COLOUR INDEX (PCI)

a. FAR (%)

DEPTH (cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	30	25	15	30	25	10	5	20	15	15	25	15	10	20	10	20	20	20	25	50
15-30	40	45	25	40	25	45	10	20	35	35	20	20	25	15	35	35	25	20	15	45
30-60	50	60	35	55	35	50	35	50	35	35	25	30	40	25	40	35	30	35	30	40
60-100	45	50	45	45	45	50	40	45	30	35	30	30	45	35	40	30	30	50	40	75
100-200	45	55	55	55	48	55	33	38	30	30	35	30	40	40	35	30	35	48	38	58
200-300	*	58	50	45	45	*	40	30	35	25	35	*	*	40	45	25	50	40	30	60
300-400		-	55	45	45		30	30	40	35	40		*	-	-	-	45	50	45	65
400-500		*	55	50	50		*	40	30	30	40			40	35	40	55	-	40	50
500-600			50	50	45			70	45	35	35			-	-	-	-	40	50	65
600-700			50	45	45			70	40	35	40			*	35	45	40	45	-	60
700-800			*	70	55			*	65	45	50				40	-	-	35	40	65
800-900				*	50				70	40	50				*	35	40	40	35	65
900-1000					75				60	45	50					*	*	*	25	45
1000-1100					63				*	45	40								*	55
1100-1200					*					*	*									*

b. PCI

DEPTH (cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	4	4	3	4	4	0	0	3	3	3	5	2	2	3	3	4	4	6	7	7
15-30	4	4	3	4	4	0	1	4	4	6	6	3	2	3	5	6	6	5	6	7
30-60	5	4	4	4	6	4	4	6	6	6	6	4	4	3	6	6	6	5	6	7
60-100	6	4	5	4	6	5	6	6	4	6	6	4	5	3	5	6	6	6	7	7
100-200	6	6	6	6	6	6	5	5	6	6	7	4	4	5	5	5	5	7	7	7
200-300	*	7	6	6	6	*	6	6	5	6	6	*	*	5	5	5	6	6	6	7
300-400		-	5	6	6		5	6	5	6	6		*	-	-	-	6	6	6	6
400-500		*	6	6	7		*	6	4	5	6			5	5	6	6	-	5	6
500-600			5	6	6			6	6	6	4			-	-	-	-	6	6	7
600-700			6	5	7			6	6	6	6			*	5	6	6	6	-	7
700-800			*	6	7			*	6	6	5				5	-	-	7	7	7
800-900				*	7				6	6	6				*	5	5	6	7	7
900-1000					7				6	6	6					*	*	*	6	7
1000-1100					7				*	5	6								*	7
1100-1200					*					*	*									*

** Mineral subsoil; - missing data.*

TABLE 7.2 BULK DENSITY (BD)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6
0-15	0.133	0.118	0.104	0.105	0.105	0.117	0.114
15-30	0.085	0.098	0.086	0.074	0.097	0.088	0.090
30-60	0.072	0.100	0.079	0.069	0.097	0.063	0.063
60-100	0.060	0.101	0.061	0.070	0.084	0.071	0.061

DEPTH(cm)	4/21	4/39	4/83	4/155	5/9	5/15	5/33
0-15	0.113	0.121	0.116	0.095	0.116	0.116	0.117
15-30	0.096	0.076	0.080	0.092	0.117	0.107	0.080
30-60	0.062	0.067	0.098	0.091	0.105	0.099	0.080
60-100	-	-	-	-	-	-	-

DEPTH(cm)	5/56	5/78	5/115	6/28	6/41	7/60
0-15	0.090	0.102	0.106	0.112	0.110	0.112
15-30	0.080	0.073	0.084	0.094	0.102	0.108
30-60	0.081	0.075	0.087	0.079	0.094	0.089
60-100	-	-	-	-	-	0.076

- Missing data.

TABLE 7.3 ORGANIC CARBON (OC) AND ASH OR MINERAL CONTENT

a. OC (%)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	37.9	37.5	36.5	40.4	40.5	36.3	38.8	35.2	39.7	40.5	42.5	39.3	34.8	37.1	39.3	40.6	39.6	43.0	38.4	37.7
15-30	39.3	37.4	38.3	41.8	45.0	39.4	39.1	35.5	40.8	44.9	40.1	35.0	36.7	37.6	38.8	42.1	42.1	43.5	44.9	37.8
30-60	39.6	41.2	38.7	40.8	44.0	44.9	39.0	43.2	41.8	44.1	43.2	39.1	39.4	38.3	42.3	43.3	43.5	42.9	43.0	39.2
60-100	39.5	37.1	40.0	38.0	44.3	42.0	43.0	49.0	40.8	43.3	43.7	20.2	42.4	40.3	41.9	41.6	42.9	44.8	43.0	38.8
100-200	39.5	40.6	41.4	41.3	43.8	43.4	42.5	42.1	43.9	42.9	44.8	26.0	27.2	38.2	38.4	41.8	41.9	45.4	45.0	40.5
200-300	1.9*	41.3	40.7	41.2	42.8	5.2*	42.8	42.1	45.2	44.9	46.3	4.5*	11.8*	41.4	43.3	43.9	42.9	45.2	45.7	39.4
300-400		-	43.9	42.7	45.0		42.7	42.5	43.1	43.6	45.6		2.9*	-	-	-	43.1	45.1	44.8	39.7
400-500		3.5*	42.7	41.0	43.2		5.7*	37.9	43.1	41.6	43.7			39.6	44.1	43.9	39.8	-	42.4	38.8
500-600			42.3	42.5	43.6			44.5	42.7	40.1	43.2			-	-	-	-	43.6	41.8	40.7
600-700			41.6	25.2	41.5			37.8	44.3	42.1	42.3			3.5*	38.3	41.7	43.2	44.8	-	39.9
700-800			4.0*	38.3	42.7			-*	43.1	41.8	42.5				25.8	-	-	42.4	43.2	38.5
800-900				5.5*	42.3				45.3	41.7	43.6				3.8*	23.0	30.8	24.5	43.3	39.8
900-1000					44.2				14.6	33.5	43.5					3.7*	2.7*	8.7*	35.0	40.6
1000-1100					22.3				-*	43.1	42.8								11.2*	25.8
1100-1200					4.8*					-*	-*									5.9*

b. ASH CONTENT (%)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	11.0	4.8	2.3	7.6	7.8	6.9	6.2	5.6	1.4	1.2	1.8	7.4	5.6	3.2	1.3	1.4	0.8	1.3	1.4	1.8
15-30	9.6	3.4	0.9	2.3	6.6	2.9	3.7	3.6	1.7	0.9	2.0	4.6	1.2	1.9	1.0	0.7	0.4	0.7	0.5	1.4
30-60	11.1	2.5	1.6	0.3	4.7	3.8	4.0	0.9	2.5	0.7	1.7	1.9	1.1	1.1	0.7	0.5	0.3	0.4	0.1	1.1
60-100	2.6	2.0	1.3	0.5	3.4	5.3	2.0	0.2	1.5	1.0	0.9	54.8	1.8	1.1	0.6	0.8	0.4	0.2	0.1	0.3
100-200	1.4	1.5	1.4	-	2.8	-	-	0.9	0.7	0.3	0.3	38.9	38.3	1.0	-	0.5	0.5	0.2	1.6	0.3
200-300	-*	-	-	-	2.0	-*	-	-	-	-	-	85.7*	69.8*	0.9	0.7	0.4	0.4	0.1	1.5	0.3
300-400		-	-	-	1.8		-	-	-	-	-		89.5*	-	-	-	0.4	0.4	2.0	0.3
400-500		-*	-	-	1.0		-*	-	-	-	-			6.2	1.2	0.7	1.2	-	1.4	0.6
500-600			-	-	1.2			-	-	-	-			-	-	-	-	0.6	1.2	0.3
600-700			-	-	2.1			-	-	-	-			87.5*	16.1	2.4	0.6	0.7	-	0.4
700-800			-*	-	2.2			-*	-	-	-				37.7	-	-	0.9	3.2	0.4
800-900				-*	2.5				-	-	-				88.1*	47.4	31.8	30.3	6.8	1.0
900-1000					3.4				-	-	-					87.0*	90.2*	72.2*	28.7	2.7
1000-1100					40.9				-*	-	-								-*	41.5
1100-1200					86.4*					-*	-*									81.3*

** Mineral subsoil; - missing data*

TABLE 7.4 TOTAL NITROGEN (N) AND pH

a. N (%)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	2.06	2.10	2.29	1.88	1.77	1.90	1.76	2.14	1.80	1.95	1.89	2.06	1.57	1.86	1.78	1.88	1.98	1.82	1.74	1.72
15-30	1.58	1.77	2.04	1.80	1.49	1.45	1.57	1.19	1.78	1.36	1.78	1.07	1.24	1.43	1.62	1.70	1.26	2.02	1.67	1.87
30-60	1.41	1.41	1.95	1.68	1.50	1.20	1.66	1.06	1.69	1.33	1.32	1.09	1.25	1.33	1.55	1.57	1.22	1.79	1.54	1.57
60-100	1.49	1.12	1.82	1.62	1.45	1.19	1.46	1.11	1.58	1.60	1.42	0.56	1.10	1.28	1.51	1.49	1.38	1.62	1.67	1.43
100-200	1.51	1.26	1.50	1.55	1.20	1.06	1.15	1.08	1.29	1.29	1.31	0.60	0.67	1.14	1.11	1.37	1.24	1.41	1.39	1.23
200-300	0.41*	1.29	1.41	1.52	1.15	0.12*	0.96	1.23	1.16	1.35	1.17	0.19*	0.37*	1.21	1.19	1.32	1.17	1.22	1.25	0.91
300-400		-	1.46	1.41	1.08		1.00	1.28	1.18	1.31	1.26		0.17*	-	-	-	1.21	1.14	1.32	0.93
400-500		0.49*	1.46	1.40	1.15		0.15*	1.28	1.27	1.33	1.25			1.03	1.09	1.17	1.09	-	1.22	0.85
500-600			1.26	1.27	1.04			1.07	1.21	1.37	1.27			-	-	-	-	1.10	1.03	0.94
600-700			1.14	0.73	0.93			0.78	1.18	1.31	1.38			0.20*	0.94	1.11	1.19	1.06	-	0.91
700-800			0.46*	0.94	1.02			-*	1.13	1.35	1.33				0.58	-	-	0.98	0.99	0.90
800-900				0.65*	0.99				1.02	1.40	1.28				0.17*	0.60	0.72	0.47	0.91	0.82
900-1000					0.91				0.37	0.94	1.30					0.24*	0.20*	0.65*	0.94	0.82
1000-1100					1.05				-*	1.17	1.20								0.28*	0.85
1100-1200					0.21*					-*	-*									0.22*

b. pH

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	3.8	3.9	3.7	3.7	3.8	3.7	3.5	3.5	3.6	3.7	3.7	3.6	3.8	3.6	3.6	3.7	3.6	3.9	3.6	4.0
15-30	3.7	4.0	3.7	3.7	3.8	3.6	3.6	3.7	3.8	3.8	3.6	3.6	3.6	3.7	3.6	3.6	3.5	3.9	3.7	3.9
30-60	3.7	3.8	3.7	3.8	4.0	3.7	3.7	3.7	3.8	3.7	3.7	3.6	3.6	3.7	3.6	3.6	3.4	3.8	3.8	4.0
60-100	4.0	3.9	3.7	3.8	4.0	3.8	3.7	3.7	3.7	3.9	3.7	3.6	3.8	3.7	3.7	3.6	3.6	3.8	3.7	3.6
100-200	4.6	4.1	3.7	3.7	3.9	3.6	3.7	3.7	3.8	3.8	4.0	3.5	4.4	3.7	3.8	3.6	3.8	3.9	3.8	4.0
200-300	5.0*	4.3	3.7	3.6	4.1	3.3*	3.7	3.8	3.8	3.8	4.2	3.7*	4.8*	3.6	3.7	3.6	3.8	4.0	4.0	3.9
300-400		-	3.9	3.7	4.3		3.7	3.8	3.9	4.0	4.4		4.8*	-	-	-	3.8	4.0	4.0	4.3
400-500		5.0*	4.1	4.0	4.4		3.9*	3.9	3.9	4.1	4.5			3.9	4.0	3.9	3.9	-	3.9	4.4
500-600			4.9	4.3	4.9			3.9	3.9	4.2	4.5			-	-	-	-	4.3	4.2	4.1
600-700			5.1	5.1	5.3			3.8	4.4	4.2	4.7			5.0*	4.8	4.5	4.3	4.2	-	4.3
700-800			4.1*	5.2	5.5			-*	4.5	4.4	4.7				3.7	-	-	4.4	4.5	3.9
800-900				5.5*	5.5				4.7	4.2	4.8				4.1*	4.8	5.0	3.7	4.9	4.7
900-1000					5.3				3.8	4.2	4.9					4.3*	4.6*	3.9*	4.6	4.7
1000-1100					5.8				-*	4.3	5.0								3.1*	4.8
1100-1200					6.6*					-*	-*									4.5*

** Mineral subsoil; - missing data.*

TABLE 7.5 TOTAL AND AVAILABLE PHOSPHORUS (TP AND AP)

a. TP (ppm)

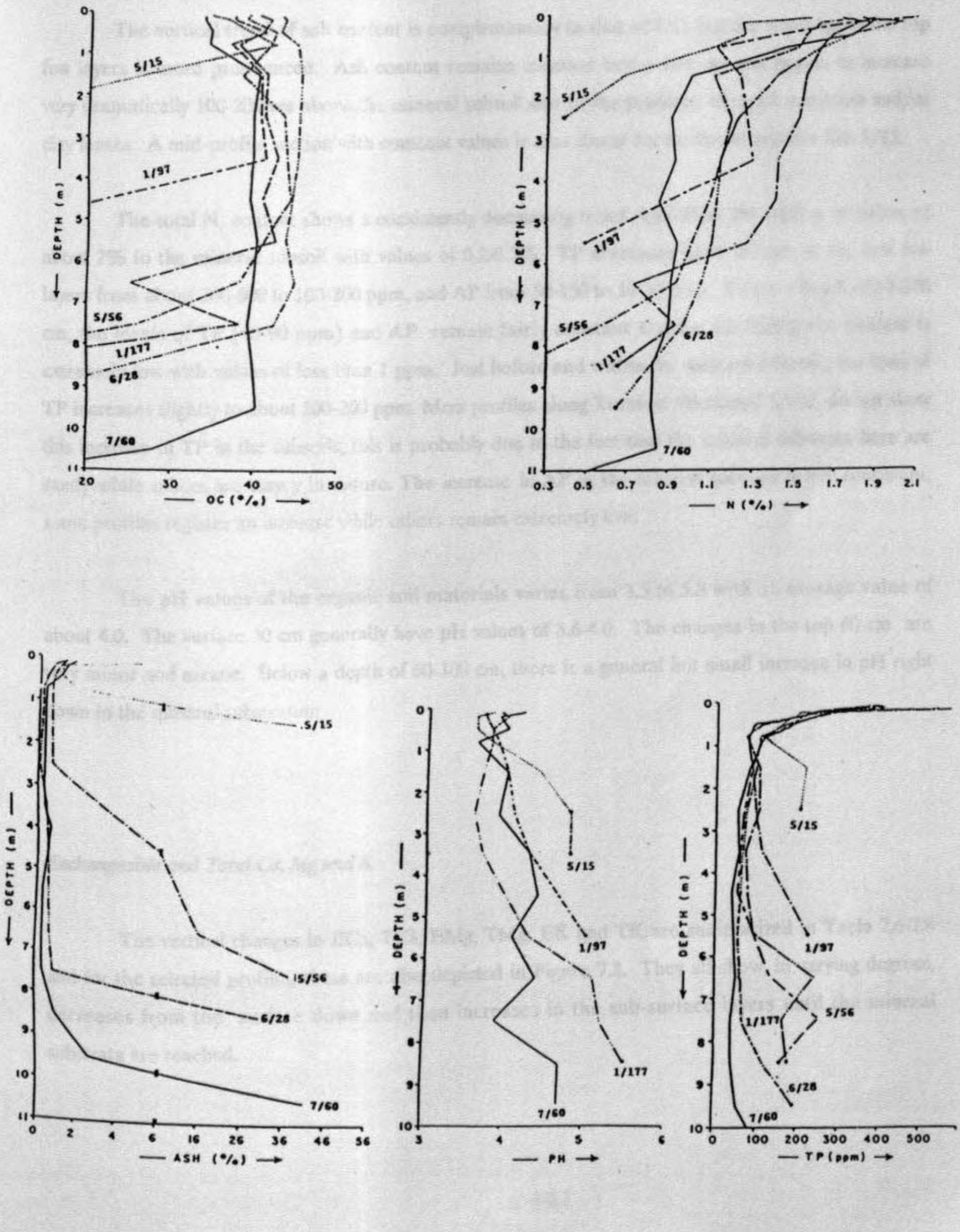
DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	601	573	600	391	381	537	291	507	362	289	298	577	540	366	400	464	309	404	416	338
15-30	369	371	380	210	134	257	323	156	237	127	218	256	306	150	299	178	120	244	260	277
30-60	146	91	153	107	124	147	242	93	137	97	161	152	158	141	182	233	85	156	149	188
60-100	161	76	102	73	95	79	90	74	88	104	116	210	116	132	110	110	67	101	104	113
100-200	139	93	84	101	68	87	92	59	59	50	68	191	221	67	88	68	76	94	87	83
200-300	170*	112	84	103	53	66*	113	51	57	61	55	133*	204*	80	69	57	56	75	67	52
300-400		-	95	72	48		77	55	52	46	52		127*	-	-	-	48	63	60	57
400-500		232*	92	78	48		57*	74	46	46	49			114	52	87	89	-	46	41
500-600			108	92	45			72	78	67	52			-	-	-	-	58	52	48
600-700			109	244	53			62	85	55	55			138*	134	97	53	63	-	52
700-800			249*	166	59			-*	86	78	58				259	-	-	69	56	43
800-900				180*	71				79	67	58				67*	230	259	117	65	43
900-1000					71				72	62	84					128*	104*	194*	144	59
1000-1100					133				-*	60	120								*-	116
1100-1200					-*					-*	-*									160*

b. AP (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	50	79	107	50	46	76	74	132	70	82	74	107	91	61	95	81	50	79	96	100
15-30	19	14	50	30	7	37	68	32	51	17	52	18	25	22	52	15	11	49	59	106
30-60	<1	<1	9	5	7	14	48	17	15	10	31	14	16	14	19	9	<1	29	28	35
60-100	<1	<1	<1	<1	4	3	10	6	6	9	15	6	<1	11	6	<1	<1	8	7	13
100-200	<1	<1	<1	<1	10	4	10	5	3	4	3	<1	<1	<1	<1	<1	<1	4	4	9
200-300	22*	<1	<1	<1	6	1*	11	4	<1	5	<1	<1*	<1*	<1	<1	<1	<1	<1	<1	<1
300-400		-	<1	<1	7		1	3	<1	3	4		<1*	-	-	-	<1	<1	<1	<1
400-500		12*	<1	<1	7		1*	5	<1	3	<1			<1	<1	<1	<1	-	<1	<1
500-600			<1	<1	8			<1	5	3	<1			-	-	·-	-	<1	<1	<1
600-700			<1	<1	9			<1	<1	<1	<1			<1*	<1	<1	<1	<1	<1	<1
700-800			66*	6	6			-*	<1	<1	<1				<1	-	-	<1	-	<1
800-900				31*	9				<1	<1	<1				<1*	<1	<1	<1	<1	<1
900-1000					12				<1	<1	<1					<1*	<1*	<1*	<1	<1
1000-1100					68				-*	<1	<1								<1*	10
1100-1200					33*					-*	-*									25*

** Mineral subsoil; - missing data.*

FIGURE 7.1. VERTICAL DISTRIBUTION OF OC, Ash, N, pH AND TP



Profile 1/177 displays a drastic decrease and then increase in OC at 600-700 cm depth because of the presence of clay lenses.

The vertical trend of ash content is complementary to that of OC, but the decrease in the top few layers is more pronounced. Ash content remains constant below 100 cm and begins to increase very dramatically 100-200 cm above the mineral subsoil due to the presence of muck materials and/or clay lenses. A mid-profile section with constant values is also absent for shallower profiles like 5/15.

The total N content shows a consistently decreasing trend right from the surface at values of about 2% to the mineral subsoil with values of 0.2-0.7%. TP decreases fairly sharply in the first few layers from about 300-600 to 100-200 ppm, and AP from 50-130 to 10-50 ppm. Below a depth of 60-100 cm, the levels of TP (40-90 ppm) and AP remain fairly constant and for the latter, the content is extremely low with values of less than 1 ppm. Just before and within the mineral subsoils, the level of TP increases slightly to about 100-200 ppm. Most profiles along Transect R4 except 4/155 do not show this increase in TP in the subsoils; this is probably due to the fact that the mineral substrata here are sandy while others are clayey in nature. The increase in AP in the mineral subsoils is not consistent; some profiles register an increase while others remain extremely low.

The pH values of the organic soil materials varies from 3.5 to 5.8 with an average value of about 4.0. The surface 30 cm generally have pH values of 3.6-4.0. The changes in the top 60 cm are very minor and erratic. Below a depth of 60-100 cm, there is a general but small increase in pH right down to the mineral substratum.

Exchangeable and Total Ca, Mg and K

The vertical changes in ECa, TCa, EMg, TMg, EK and TK are summarized in Table 7.6-7.8 and for the selected profiles, these are also depicted in Figure 7.2. They all show, in varying degrees, decreases from the surface down and then increases in the sub-surface layers until the mineral substrata are reached.

TABLE 7.6 EXCHANGEABLE AND TOTAL CALCIUM (ECa AND TCa)

a. ECa (me/100g)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	0.61	1.91	0.45	0.41	0.96	0.50	0.34	0.40	0.23	0.30	0.47	0.46	0.45	0.57	0.46	0.71	0.17	0.35	0.12	0.22
15-30	0.45	0.90	0.17	0.34	0.25	0.56	0.68	0.31	0.29	0.46	0.12	0.32	0.35	0.34	0.46	0.58	0.17	0.12	0.12	0.33
30-60	0.46	0.74	0.11	0.34	0.12	0.40	0.46	0.28	0.23	0.12	0.12	0.30	0.34	0.34	0.40	0.64	0.11	0.10	0.10	0.10
60-100	0.62	0.56	0.11	0.34	0.24	0.11	0.32	0.31	0.28	0.12	0.12	0.32	0.43	0.46	0.46	0.57	0.11	0.12	0.12	0.32
100-200	1.14	0.60	0.17	0.65	0.24	0.32	0.20	0.28	0.38	0.12	0.12	0.53	0.31	0.40	0.60	0.57	0.11	0.11	0.10	0.32
200-300	2.69*	0.64	0.26	0.40	0.24	0.13*	0.26	0.23	0.29	0.12	0.12	0.94*	0.33*	0.34	0.57	0.34	0.11	0.31	0.11	0.41
300-400		-	0.37	0.63	0.12		0.16	0.34	0.35	0.14	0.23		0.93*	-	-	-	0.12	0.29	0.10	0.32
400-500		2.29*	0.34	0.34	0.36		0.16*	0.53	0.29	0.36	0.46			0.80	0.57	0.34	0.45	-	0.10	0.32
500-600			1.39	0.63	0.83			0.68	0.69	0.35	0.23			-	-	-	-	0.12	0.10	0.21
600-700			1.73	1.09	1.17			0.62	0.81	0.35	0.81			1.15*	1.04	0.46	0.11	0.29	-	0.43
700-800			2.28*	1.83	3.83			-*	1.04	0.46	0.23				1.57	-	-	0.75	0.12	0.32
800-900				2.09*	2.59				1.63	0.46	0.35				1.85*	1.26	0.79	1.34	1.65	1.60
900-1000					3.32				0.89	0.48	0.69					1.46*	0.73*	1.40*	3.04	2.03
1000-1100					4.84				-*	0.46	0.82								2.30*	2.10
1100-1200					3.90*					-*	-*									3.22*

b. TCa (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	838	886	113	93	659	280	308	144	129	90	88	187	154	226	101	210	172	190	66	135
15-30	170	452	114	43	179	310	285	68	58	29	10	41	10	139	101	44	43	10	10	121
30-60	114	242	43	43	148	142	245	44	29	10	10	10	10	99	108	73	43	10	10	68
60-100	169	112	43	43	124	71	145	78	28	10	29	10	10	157	93	129	72	10	10	61
100-200	521	157	43	43	90	154	93	75	15	101	10	70	56	99	-	72	71	10	76	147
200-300	258*	261	58	11	75	54*	141	86	57	58	10	130*	-*	43	101	72	71	29	101	108
300-400		-	114	114	75		329	93	101	58	44		78*	-	-	-	42	29	72	215
400-500		260*	172	143	208		40*	57	172	101	44			186	316	131	269	-	157	187
500-600			636	200	532			142	230	144	73			-	-	-	-	86	72	294
600-700			776	300	846			149	522	101	231			118*	447	244	142	159	-	295
700-800			258*	629	1761			-*	633	172	288				464	-	-	431	365	294
800-900				287*	1691				659	144	331				254*	476	374	490	1135	1050
900-1000					2164				387	170	461					248*	126*	430*	1607	1070
1000-1100					1931				-*	200	640								-*	752
1100-1200					-*					-*	-*									1019*

** Mineral subsoil; - missing data.*

TABLE 7.7 EXCHANGEABLE AND TOTAL MAGNESIUM (EMg AND TMg)

a. EMg (me/100g)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	4.54	3.09	3.34	3.81	5.26	2.85	2.66	4.19	3.06	3.49	3.52	3.25	3.76	3.72	2.96	2.10	3.94	4.41	5.22	2.48
15-30	5.39	2.49	3.37	2.81	2.43	1.86	1.43	2.12	3.40	1.71	1.54	1.01	1.98	2.15	2.78	1.87	2.37	1.84	1.86	1.15
30-60	4.69	2.25	1.68	1.65	2.02	1.85	1.09	2.31	1.70	1.42	2.55	2.50	1.82	2.27	2.08	1.97	2.15	1.39	1.47	0.83
60-100	5.01	1.85	1.67	2.59	1.71	0.97	2.26	2.03	1.67	1.46	1.33	4.01	1.39	4.28	1.61	1.39	2.02	0.55	0.68	0.17
100-200	6.70	4.34	1.80	1.46	2.15	1.14	1.60	1.58	1.67	1.23	0.33	4.98	1.77	2.34	3.68	1.04	2.41	0.61	0.47	0.18
200-300	8.16*	8.29	1.79	1.99	2.64	-*	1.39	0.98	1.89	1.28	0.56	9.61*	2.09*	2.30	2.86	1.20	2.53	0.81	0.62	0.58
300-400		-	3.38	3.39	4.32		1.36	1.43	1.69	2.13	0.55		7.25*	-	-	-	2.24	1.64	0.73	1.17
400-500		12.0*	5.27	4.34	8.81		1.11*	1.53	1.38	2.40	1.31			3.76	3.93	3.82	4.65	-	1.14	2.02
500-600			11.0	4.89	13.1			1.31	3.14	2.61	1.68			-	-	-	-	3.98	1.97	1.25
600-700			11.9	9.35	15.0			1.33	3.55	4.23	1.67			5.86*	11.7	4.90	2.47	5.30	-	1.75
700-800			10.4*	16.6	19.3			-*	3.70	4.37	1.20				15.1	-	-	7.75	7.68	1.44
800-900				18.3*	18.6				3.86	3.41	2.05				16.8*	10.9	14.1	7.18	14.0	6.94
900-1000					21.3				3.84	2.79	2.05					8.92*	9.05*	8.68*	19.3	11.0
1000-1100					28.4				-*	3.38	2.48								13.9*	13.5
1100-1200					17.9*					-*	-*									20.6*

b. TMg (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	979	899	650	550	929	727	617	1148	891	944	876	944	1058	894	863	597	656	736	1028	486
15-30	876	568	570	412	544	676	713	738	866	490	617	344	470	474	718	465	429	335	540	256
30-60	741	426	412	254	466	496	662	653	372	468	320	423	452	635	438	407	397	261	406	175
60-100	619	393	254	365	384	213	391	432	339	316	290	1217	333	621	307	342	373	86	115	54
100-200	1055	743	334	248	545	257	342	342	395	287	137	1829	1467	522	377	285	618	87	79	21
200-300	5385*	1186	348	318	609	438*	325	343	430	319	231	4554*	2579*	514	573	300	644	144	72	149
300-400		-	514	543	924		246	371	432	518	204		3626*	-	-	-	613	287	100	188
400-500		6078*	658	701	1990		208*	300	445	632	230			771	948	493	1004	-	171	414
500-600			1705	873	2750			312	661	748	304			-	-	-	-	634	287	374
600-700			1840	1856	2976			269	928	749	317			3748*	1854	860	598	891	-	456
700-800			3652*	2431	3698			-*	834	804	331				2852	-	-	1120	1166	347
800-900				5085*	4234				1017	806	403				4446*	3153	2446	1119	2092	1550
900-1000					3202				457	766	518					3244*	3001*	2870*	2616	2140
1000-1100					5201				-*	770	698								-*	2503
1100-1200					-*					-*	-*									3582*

** Mineral subsoil; - missing data.*

TABLE 7.8 EXCHANGEABLE AND TOTAL POTASSIUM (EK AND TK)

a. EK (me/100g)

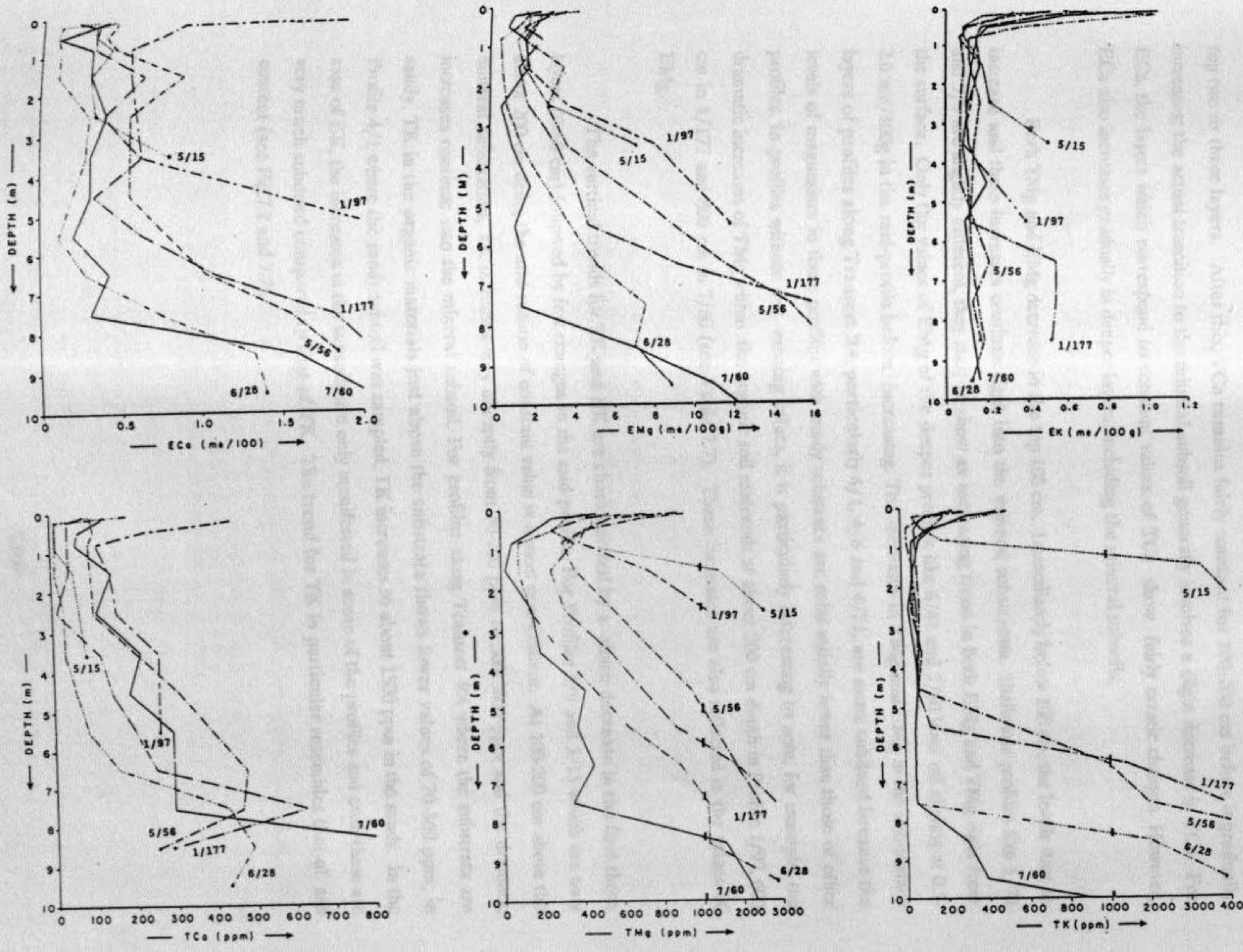
DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	0.56	0.52	0.70	0.71	1.07	0.85	0.26	0.66	0.40	0.25	0.54	0.46	0.51	0.33	0.33	0.54	0.58	1.04	1.59	1.06
15-30	0.35	0.31	0.58	0.49	0.39	0.37	0.16	0.25	0.18	0.13	0.21	0.15	0.18	0.57	0.28	0.17	0.11	0.59	0.90	0.60
30-60	0.14	0.10	0.20	0.17	0.32	0.22	0.16	0.34	0.13	0.08	0.15	0.14	0.08	0.12	0.10	0.14	0.09	0.37	0.58	0.20
60-100	0.17	0.07	0.11	0.15	0.28	0.07	0.09	0.11	0.10	0.09	0.14	0.13	0.09	0.07	0.07	0.08	0.10	0.11	0.12	0.15
100-200	0.12	0.12	0.10	0.17	0.16	0.08	0.09	0.08	0.09	0.06	0.29	0.10	0.18	0.09	0.09	0.11	0.12	0.12	0.09	0.13
200-300	0.46*	0.08	0.07	0.11	0.11	0.07*	0.10	0.07	0.10	0.08	0.30	0.05*	0.21*	0.09	0.07	0.11	0.12	0.17	0.13	0.10
300-400		-	0.14	0.08	0.21		0.08	0.08	0.10	0.09	0.24		0.50*	-	-	-	0.09	0.14	0.10	0.11
400-500		0.39*	0.16	0.11	0.27		0.07*	0.16	0.09	0.11	0.26			0.16	0.07	0.13	0.14	-	0.09	0.20
500-600			0.25	0.12	0.30			0.08	0.16	0.09	0.30			-	-	-	-	0.12	0.10	0.09
600-700			0.26	0.54	0.47			0.09	0.19	0.15	0.31			0.31*	0.21	0.17	0.15	0.13	-	0.11
700-800			0.26*	0.54	0.52			-*	0.13	0.15	0.33				0.13	-	-	0.15	0.15	0.11
800-900				0.52*	0.49				0.15	0.17	0.35				0.17*	0.48	0.30	0.19	0.21	0.14
900-1000					0.60				0.10	0.08	0.24					0.49*	0.46*	0.13*	0.30	0.17
1000-1100					0.76				-*	0.10	0.22								0.33*	0.09
1100-1200					0.65*					-*	-*									0.13*

b. TK (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	358	309	380	203	465	392	368	449	230	148	292	395	335	255	259	353	314	524	793	473
15-30	141	113	257	212	255	254	228	241	115	86	116	108	59	45	115	204	72	407	554	322
30-60	86	28	85	156	180	227	101	131	43	58	59	56	100	55	72	73	28	145	247	161
60-100	78	28	28	56	193	71	73	78	28	29	58	4424	202	72	71	114	29	58	58	81
100-200	285	43	43	57	53	150	72	41	29	29	166	4720	3399	78	-	57	84	58	115	54
200-300	9297*	95	71	65	30	1310*	71	57	29	89	202	6246*	4344*	72	86	72	71	58	26	27
300-400		-	57	72	75		69	72	29	29	160		4921*	-	-	-	70	86	17	54
400-500		9998*	86	72	105		990*	43	29	57	115			742	72	73	113	-	17	-
500-600			58	129	118			78	86	58	160			-	-	-	-	58	21	53
600-700			315	1473	263			128	87	58	202			5543*	996	315	171	58	-	54
700-800			7148*	3849	235			-*	58	57	230				1939	-	-	57	29	53
800-900				8918*	235				87	58	230				2688*	3586	3057	1986	53	294
900-1000					312				360	85	230					5080*	4797*	3954*	1272	388
1000-1100					4758				-*	157	233								-*	3241
1100-1200					-*					-*	-*									-*

** Mineral subsoil; - missing data.*

FIGURE 7.2. VERTICAL DISTRIBUTION



In the case of calcium, the decrease in the levels of TCa and ECa is mainly observed in the top two or three layers. After this, TCa remains fairly constant for 100-200 cm before it gradually increases; the actual transition to the mineral subsoil generally involves a slight decrease in TCa. For ECa, the layers which correspond to constant values of TCa show fairly erratic changes. However, ECa also increases gradually in deeper layers, including the mineral subsoils.

Both TMg and EMg decrease in the top 100 cm. Immediately below 100 cm, the levels start to increase and these increases continue right into the mineral substratum. Shallower profiles like 1/70 and 5/9 are slightly different; they start to show an increasing trend in both EMg and TMg right from the surface. Only the values of EMg of the deeper profiles like 6/41 and 7/60 level off slightly at 0.5-2.0 me/100g in the mid-profile before increasing. The increases in TMg and EMg in the sub-surface layers of profiles along Transect R4, particularly 4/1, 4/6 and 4/21, are more subdued because the levels of magnesium in these profiles with sandy substrata are substantially lower than those of other profiles. In profiles without any missing values, it is particularly interesting to note, for example, the dramatic increases of TMg within the organic soil materials at about 200 cm depth in Profile 1/97, 600 cm in 1/177 and 800 cm in 7/60 (see Table 7.7). These increases are also reflected in the values of EMg.

The vertical trends for TK and EK are characterized by a sharp decrease in the first three layers (0-60 cm) followed by few changes in the mid-profile. For Profiles 5/9 and 5/15 which are only about 200 cm deep, the mid-section of constant value is almost non-existent. At 100-200 cm above the mineral substratum, TK increases very abruptly from 50-200 ppm to 300-3800 ppm and the dramatic increases continue into the mineral subsoil. For profiles along Transect R4 where the substrata are sandy, TK in the organic materials just above the substrata shows lower values of 70-360 ppm; in Profile 4/1 where the sandy subsoil was sampled, TK increases to about 1300 ppm in the sands. In the case of EK, the increases in the subsoils are only manifested in some of the profiles and even these are very much subdued compared to that of TK. The trend for TK in particular resembles that of ash content (see Fig.7.1 and 7.2).

Total Trace Elements and Sulphur

Trace elements studied include Fe, Mn, Cu and Zn (Tables 7.9 and 7.10). The results plus those of TS (Table 7.11) for the selected profiles are depicted in Figure 7.3.

For TFe, there is a consistent decrease by about 20-50% in the first two to four layers. Below a depth of 100 cm, it begins to increase, the initial rate depending on the depth of the peats. They all show abrupt and dramatic increases as the mineral subsoils are approached. TFe contents in shallower profiles like 1/97 and 5/15 start to increase from about 1500 to more than 2500 ppm immediately below a depth of 100 cm. For the deeper profiles like 6/41 and 7/60, they remain fairly constant at 200-500 ppm in the mid-section and only increase to over 1000 ppm below 700 to 800 cm depth. For profiles along Transect R4, the values of TFe of the sandy substrata and the organic materials immediately above are lower at 1000-5000 ppm. In other profiles, TFe in the mineral substrata could be as high as 2.0%. The vertical trends of TFe and TMg are very much alike (cf. Fig.7.2 and 7.3).

In the case of TMn and TCu, there is a general decline below the topsoils. The shallower profiles then show a general increase while some deeper ones have some fluctuating values, particularly TCu, in the mid-profiles. TMn and TCu both show fairly large increases to 20-100 and 10-20 ppm respectively just before and in the mineral subsoils. Apart from these marked upswings in the subsoils, the trends are fairly subdued.

The vertical trend of TZn is fairly similar to that of TFe (see Fig.7.3) except that the initial decline is mainly observed in the first two or three layers and the trends below a depth of 60 cm, including deeper profiles like 7/60, tend to be somewhat erratic. The final increments to 40-130 ppm just before and within the mineral substratum are abrupt and substantial.

Only four profiles along Transect R.7 were analysed for TS. The vertical trends in these profiles are consistent. Surface enrichment as manifested by other elements in the topsoils is conspicuously absent. The low values of TS at the surface remain fairly constant at about 0.1% until they start to rise in the last 100-200 cm above the mineral substratum. The increase can be fairly gradual as in Profile 7/1 or very abrupt as in Profile 7/55, and it continues right into the mineral subsoils, where values range from 2 to 4%.

TABLE 7.9 TOTAL IRON AND MANGANESE (TFe AND TMn)

a. TFe (ppm unless stated otherwise)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	4805	2726	2523	1419	400	3357	1766	1490	1150	1210	453	4133	2673	3141	1840	1178	920	401	485	338
15-30	4576	3110	2323	1122	233	2282	1682	1114	981	404	233	1889	1911	1297	2198	1033	543	407	154	202
30-60	3150	2528	1050	438	226	1076	1784	768	429	454	368	1537	1668	1551	1268	713	482	377	116	202
60-100	3378	1417	905	815	296	736	945	462	396	374	145	3775	1561	1698	970	741	446	173	144	202
100-200	6198	2527	1184	925	324	1065	884	430	574	374	338	1.8%	3476	1460	-	626	689	166	215	385
200-300	1.3%*	2530	1375	1307	323	2727*	989	457	631	493	649	2.0%*	5688*	1572	1876	700	635	288	244	203
300-400		-	2472	1802	324		753	656	835	893	1323		8780*	-	-	-	808	430	243	436
400-500		1.3%*	2688	2202	372		1443*	784	1039	1321	1567			3569	3074	1854	2828	-	328	567
500-600			5722	2288	555			908	1350	1783	2545			-	-	-	-	835	402	434
600-700			6469	2648	875			1077	2262	1643	3673			1.4%*	4473	3639	1609	920	-	503
700-800			1.9%*	6864	1835			-*	2921	1925	3306				2.7%	-	-	1149	904	501
800-900				8292*	2279				3777	1842	3453				2.1%*	1.4%	1.1%	2182	1886	1136
900-1000					3040				2989	1788	3715					1.4%*	1.1%*	1.8%*	4662	1940
1000-1100					8060				-*	1626	4976								-*	1.6%
1100-1200					-*					-*	-*									-*

b. TMn (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	11	11	7	6	16	9	6	7	9	4	6	6	5	6	8	6	8	9	9	5
15-30	9	9	6	3	4	9	6	3	6	<1	3	11	6	3	3	3	3	12	6	3
30-60	11	6	<1	3	4	6	6	3	3	<1	6	<1	3	3	3	<1	3	12	6	<1
60-100	23	3	7	3	4	3	3	4	3	3	<1	<1	3	3	3	2	3	12	6	<1
100-200	62	6	7	3	<1	6	6	3	3	<1	<1	16	15	3	3	<1	3	15	5	<1
200-300	105*	14	4	5	<1	17*	6	3	3	3	<1	47*	22*	3	3	<1	3	15	3	<1
300-400		-	3	9	<1		3	3	6	3	<1		36*	-	-	-	3	11	6	<1
400-500		83*	6	9	4		23*	3	9	6	<1			9	6	3	3	-	6	<1
500-600			15	11	6			6	11	9	<1			-	-	-	-	17	6	<1
600-700			17	20	9			18	23	9	3			52*	9	9	5	6	-	<1
700-800			36*	29	23			-*	32	11	12				36	-	-	11	9	<1
800-900				52*	29				50	12	15				62*	34	25	11	24	5
900-1000					33				20	11	17					31*	31*	27*	35	11
1000-1100					53				-*	11	23								-*	58
1100-1200					-*					-*	-*									-*

** Mineral subsoil; - missing data.*

TABLE 7.10 TOTAL COPPER AND ZINC (TCu AND TZn)

a. TCu (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	4	3	2	2	3	7	3	3	2	2	2	5	3	2	2	1	2	2	3	3
15-30	6	2	2	1	2	7	2	2	3	2	<1	2	8	1	3	1	2	2	1	1
30-60	6	2	2	1	2	6	3	3	2	4	<1	10	7	1	2	<1	2	3	1	2
60-100	7	1	2	3	1	5	5	4	2	5	3	11	8	1	4	4	2	3	2	<1
100-200	8	6	7	6	4	6	2	3	3	4	2	12	12	4	6	2	1	3	2	3
200-300	11*	8	6	4	4	6*	3	3	7	3	5	9*	11*	6	8	5	1	2	2	3
300-400		-	11	5	4		4	9	2	2	3		13*	-	-	-	2	2	5	1
400-500		16*	7	5	2		5*	7	5	5	5			6	5	14	5	-	2	3
500-600			3	6	1			7	3	2	1			-	-	-	-	2	5	<1
600-700			5	5	1			16	2	12	1			9*	6	5	4	2	-	3
700-800			10*	9	4			-*	3	5	2				11	-	-	2	5	<1
800-900				11*	1				2	0	1				9*	15	12	2	6	4
900-1000					1				5	10	2					9*	10*	6*	9	3
1000-1100					6				-*	12	5								-*	7
1100-1200					-*					-*	-*									-*

b. TZn (ppm)

DEPTH(cm)	1/70	1/97	1/145	1/177	3/92	4/1	4/6	4/21	4/39	4/83	4/155	5/9	5/15	5/33	5/56	5/78	5/115	6/28	6/41	7/60
0-15	8	11	7	7	37	11	4	6	35	21	22	9	12	37	13	16	11	17	12	18
15-30	7	8	7	5	11	8	3	3	28	6	3	4	13	19	4	7	8	6	10	13
30-60	7	6	5	3	13	3	5	2	21	7	6	7	11	12	4	3	3	13	7	12
60-100	7	6	7	6	13	3	6	26	20	8	23	18	8	15	22	12	29	46	37	14
100-200	10	18	19	22	13	3	12	34	16	9	26	34	26	33	-	20	16	48	-	17
200-300	89*	18	16	29	21	49*	6	30	19	16	27	96*	43*	62	48	37	14	42	31	19
300-400		-	14	21	13		32	35	22	16	27		100*	-	-	-	16	44	38	17
400-500		82*	13	23	15		46*	67	29	21	26			32	33	56	36	-	41	19
500-600			7	33	13			44	67	38	25			-	-	-	-	54	37	36
600-700			9	21	22			49	84	48	38			159*	39	23	34	44	-	60
700-800			42*	18	19			-*	70	45	69				102	-	-	70	57	41
800-900				56*	34				46	87	55				103*	57	37	94	69	56
900-1000					45				74	124	82					115*	99*	137*	73	63
1000-1100					61				-*	124	74								-*	125
1100-1200					-*					-*	-*									-*

** Mineral subsoil; - missing data.*

TABLE 7.11 TOTAL SULPHUR CONTENT(TS) OF TANJUNG UPAR SAMPLES (R10)

Profile Sa1		Profile Sa2		Profile Sa3		Proifle Sa4	
DEPTH(cm)	TS(%)	DEPTH(cm)	TS(%)	DEPTH(cm)	TS(%)	DEPTH(cm)	TS(%)
0-50	0.11	0-19	0.08	0-50	0.08	0-28	0.11
50-100	0.10	27-70	0.11	100-150	0.12	150-200	0.06
100-150	0.13	70-200	0.09	250-300	0.07	300-350	0.09
200-250	0.22	300-468	0.09	350-400	0.07	440-500	0.16
250-300	0.31	500-550	0.11	700-800	0.07	550-600	0.22
300-350	0.33	550-600	0.14	900-950	0.09	600-650	0.22
400-450	0.66	700-790	0.50	1050-1085	2.59	700-750	0.61
450-500	3.99*	790-835	0.70	1085-1100	3.11*	750-800	2.53
		835-894	2.03*	1218-1285	4.07*	800-845	2.38
		894-950	3.26*			835-900	3.10*

* Mineral subsoil

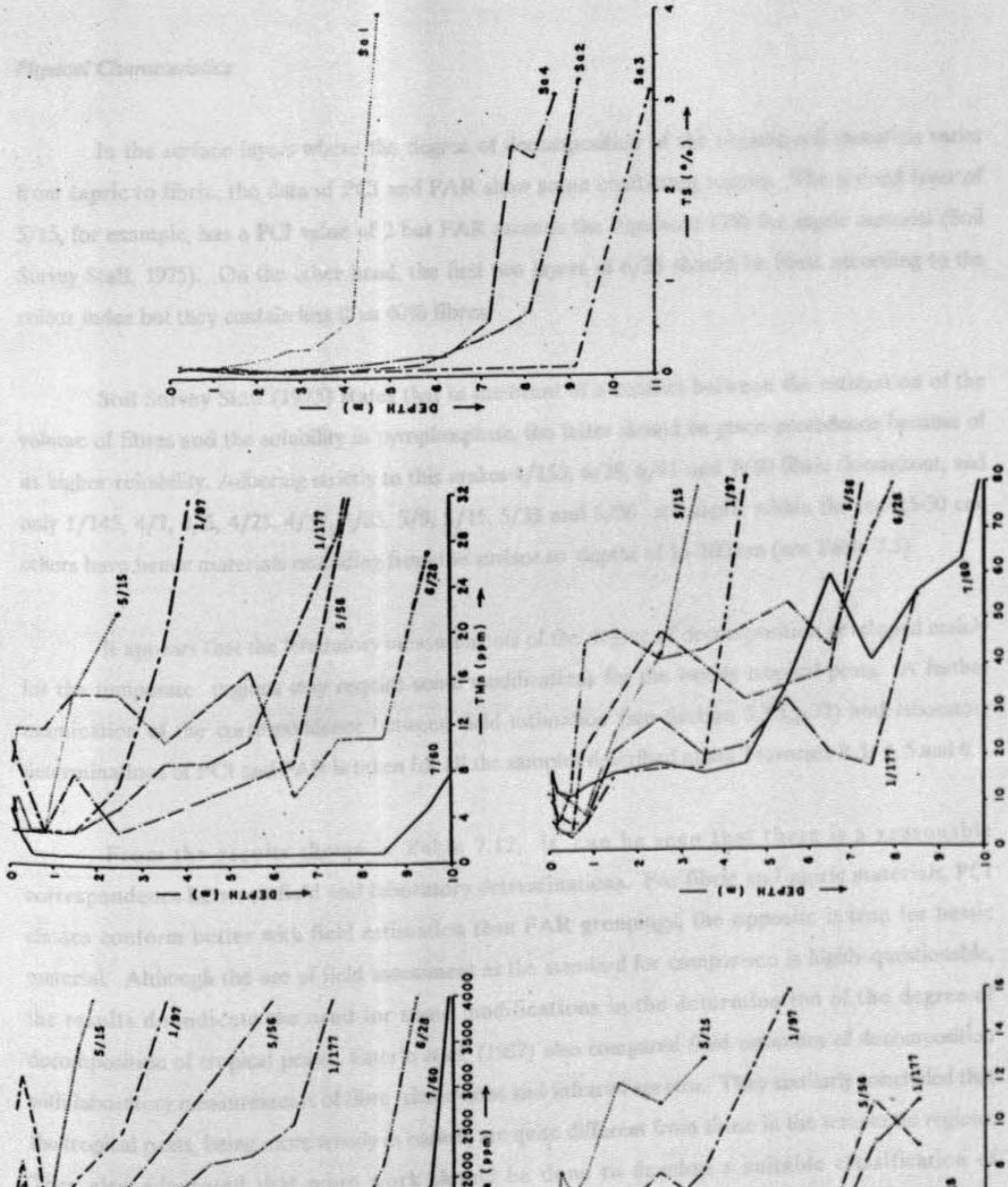


FIGURE 7.3 VERTICAL DISTRIBUTION OF TFe, TMn, TCu, TZn, and TS

7.3 DISCUSSION AND CONCLUSIONS

Physical Characteristics

In the surface layers where the degree of decomposition of the organic soil materials varies from sapric to fibric, the data of PCI and FAR show some conflicting results. The second layer of 5/15, for example, has a PCI value of 2 but FAR exceeds the stipulated 17% for sapric material (Soil Survey Staff, 1975). On the other hand, the first two layers of 6/28 should be fibric according to the colour index but they contain less than 40% fibres.

Soil Survey Staff (1975) states that in the event of a conflict between the estimation of the volume of fibres and the solubility in pyrophosphate, the latter should be given precedence because of its higher reliability. Adhering strictly to this makes 4/155, 6/28, 6/41 and 7/60 fibric throughout, and only 1/145, 4/1, 4/6, 4/21, 4/39, 4/83, 5/9, 5/15, 5/33 and 5/56 are sapric within the top 15-30 cm; others have hemic materials extending from the surface to depths of 15-100 cm (see Table 7.1).

It appears that the laboratory measurements of the degree of decomposition developed mainly for the temperate regions may require some modifications for the woody tropical peats. A further examination of the correspondence between field estimation (see Section 5.3.1;p.72) and laboratory determinations of PCI and FAR is taken for all the samples described along Traverses R.1, 4, 5 and 6.

From the results shown in Table 7.12, it can be seen that there is a reasonable correspondence between field and laboratory determinations. For fibric and sapric materials, PCI classes conform better with field estimation than FAR groupings; the opposite is true for hemic material. Although the use of field assessment as the standard for comparison is highly questionable, the results do indicate the need for some modifications in the determination of the degree of decomposition of tropical peats. Esterle *et al.* (1987) also compared field estimates of decomposition with laboratory measurements of fibre size classes and infrared spectra. They similarly concluded that the tropical peats, being more woody in nature, are quite different from those in the temperate regions. They also advocated that more work should be done to develop a suitable classification of decomposition classes for tropical peats.

Table 7.12. DISTRIBUTION OF PCI AND FAR CLASSES AMONG FIELD DETERMINED DECOMPOSITION CLASSES

FIELD DECOMPOSITION CLASS	PCI			FAR (%)		
	≤3 (S)	4 (H)	≥5 (F)	<17 (S)	17-39 (H)	≥40 (F)
Fibric (21)*	0	1	20	0	13	8
Hemic (33)*	4	17	12	1	23	9
Sapric (19)*	16	3	0	11	7	1

* = Number of samples.

It is well known that other things being equal, better decomposed organic soil materials generally have higher BD (e.g. Lynn *et al*. 1974; Driessen and Rochimah, 1976). Another important factor is the mineral or ash content, particularly variations due to mineral materials brought in by fluvial processes. However, in the profiles presently studied, the surface materials are all very low in ash content (see Table 7.3), indicating that the siltation effect due to flooding can be ignored. The decreasing trend of BD in the top few layers is therefore associated with an increasing rawness of the materials, as indicated by PCI and FAR determinations.

As BD of deeper samples was not determined (see Section 5.3.1;p.72), chemical data in this chapter could not be converted and compared on volume basis like those in Chapter 8. This omission is not critical because depth variation is more concerned with peat genesis whilst lateral variations discussed in the next chapter is more edaphically oriented.

Chemical Properties

As expected, the vertical trends of OC and ash content are in direct complement to each other. In the shallower profiles (e.g. 5/15), OC starts to decline immediately below 60-100 cm because of the influence of the shallow mineral subsoil.

The vertical trend of N was conspicuously different from other nutrient elements. As most of the soil N occurs in organic compounds, it is therefore not surprising that the mineral subsoils contain less total N than the overlying organic soil materials. Within the peat masses, the decline in total N from the surface can probably be explained by the less decomposed nature of the lower organic materials, a condition which is usually accompanied by a wider C:N ratio.

The variation of TS with depth is also unique in that it does not show a surface concentration and an initial decrease just below the surface. For all other nutrients, a concentration in the surface layers is clear. This confirms that even under the PS environment where there is considerable radial drainage (and therefore leaching) from the centre to the periphery of the peat dome, the effect of the standing vegetation in recycling and retaining plant nutrients in the topsoils is substantial.

Most of the organic soil materials are characterized by a low pH of around 4.0. At such low pH, free organic acids are probably present. In discussing the vertical trend of pH values, it must be pointed out that the pH determination was done on moist samples which had been subject to some air-drying in the laboratory during sample preparation. This is particularly important for the mineral subsoils which contain a fairly high level of TS mostly in the form of sulphides. Upon oxidation, the pH of soils with sulphidic materials drops substantially; the actual decrease depends on the amount of sulphides present and the condition and rate of air-drying (e.g. Dent, 1986). Because of this complication, the changes in pH of the present samples at the transition from the organic to the mineral soil materials are not discussed further.

A few properties like ECa, TMn, TCu and TZn show some erratic changes in the mid-profiles. Levels of AP also display inconsistent trend in the transitional zone from peat to mineral substratum. These could be due to the inherently low levels of these nutrients and the inability of the analytical methods to resolve minor differences at such low concentrations. Local experience at the Agriculture Research Centre has shown that analyses of organic soil materials are problematical. Many of the methods developed for mineral soils are not wholly suitable for organic soils. Even the methods which have been specifically recommended for organic soils (Day *et al.*, 1979) are not wholly reliable. Analysis of TCa in some batches of samples, for example, had given fairly unreliable results with repeats showing an average of 50% deviation from the means (Personal communication with the Chemists at ARC, Semongok). In many cases (e.g. those with TCa <30 ppm in Table 7.6), it resulted in the highly unsatisfactory situation whereby the values of ECa, after conversion to ppm, are higher than those of TCa. It is apparent that there is a need to look into the chemical analyses of tropical peats and to establish more proven standard testing procedures for these materials.

It is interesting to note that most of the nutrients start to show significant increases at depths of 100-200 cm above the mineral substratum. This suggests that the mineral subsoil does exert some influence on the chemical properties of the organic soil materials immediately above the interface. Such a phenomenon is to be expected because when the first one or two metres of peats were formed, the vegetation was still rooting into the mineral subsoils. The local classification of lowland organic soils in Sarawak has a major differentiation at 150-cm peat depth for families of shallow and deep organic soils (Tie, 1982). The information gathered here justifies this separation; for deep organic soils with more than 150 cm of surface peat, the influence of the mineral substratum would be relatively unimportant compared to that in shallow organic soils.

For shallow organic soils with less than 150 cm of surface peats, the subsoil texture is one of the differentiae that are used to classify these soils at family level (Tie, 1982). The validity of this is corroborated by profiles along Transect R4 which consistently show lower levels of TP, TMg, TK and TFe (and to a lesser extent, TCa) in the sandy substrata and the organic layers immediately above. This can be explained by the lower inherent nutrient levels in the coarse-textured subsoils as compared to those of the marine clays which underlie other profiles.

Palynological study done on a 13-m core collected from a peat dome near Marudi (Anderson, 1961; Anderson and Muller, 1975) had shown that the basal clay at 11.5-13 m was of marine origin. A sharp boundary occurred between 10 and 11 m with a decrease in mangrove pollen and an abrupt increase in PS pollen types. Profile 7/55 was sampled from the same PS near Marudi where Anderson and Muller took their core. The vertical trend of TS shows a sudden increase from 0.09% at 900-950 cm to 2.59% at 1050-1085 cm depth. In the absence of sulphur-bearing minerals, high sulphur content in soil is usually indicative of a marine origin. The distribution of TS in 7/55 therefore provides supplementary evidence for the presence of a previous marine environment in the initial stages of PS development.

Kawaguchi and Kyuma (1977) found that for (mineral) padi soils, EMg greater than 5 me/100g and EMg:ECa ratio greater than unity are indicative of marine or brackish origin. On the basis of these criteria, one may infer that for Profile 7/60, the brackish influence probably stopped at a depth of 800 cm. It seems that, although the mangrove and nipah vegetation was replaced when the peat was about 100 cm thick (c. 11 m below present ground surface), occasional flooding by brackish water continued at this locality until the peat had accumulated to a depth of about 250-350 cm. The trends for Profiles 1/97, 1/177 and 6/28 similarly suggest that the influence of brackish water was felt during the initial stages of peat formation until the peats were respectively 200, 200 and 300 cm deep. Inundation of low-lying peat areas by brackish water can be presently observed in some coastal areas of Sarawak (Tie, 1988a).

Profile 5/15 at the periphery of an inland swamp (Transect R.5) seems to have peats formed entirely under freshwater condition; even the basal marine clay below 270 cm (with 7.25 me/100g EMg) had apparently been overlain by 70 cm of riverine alluvium (200-270 cm with 2.09 me/100g EMG). This indicates that the peat at the edges was accumulated at a later stage after the transition from the original marine to a freshwater environment. In Profile 5/9 nearer to the river, the deposition of riverine alluvium is not so clearly expressed; it had only resulted in the formation of a muck layer with clay lenses (60-200 cm) immediately above the marine clay. Away from the periphery of the swamp, this layer of riverine alluvium is absent; in profiles like 5/33 to 5/115, the trends of EMg suggest that peat deposition was initiated under a marine or brackish environment. This is probably an good example where the PS had started off under a marine environment, and as the distance from the sea increased, the river level backed up depositing riverine alluvia along the banks. The poorly drained condition behind the levees was therefore maintained and the deposit had grown laterally at more advanced stages of development (Anderson,1961; also see Chapter 11).

CHAPTER 8. VARIATIONS OF SURFACE SOIL PROPERTIES ACROSS THE PEAT DOME WITH PARTICULAR REFERENCE TO FOREST TYPES

8.1 INTRODUCTION

Anderson (1961) examined the variation of plant nutrients in surface peats from the periphery to the centre of PS. In Loba Kabang Protected Forest near Sibu, he found that only the P content was lower in samples from the centre of the swamp. Other samples from a peat dome in Baram showed that the mineral (or ash) content was much lower than that of the Rajang samples, and there was a substantial decrease in the easily soluble P and K contents towards the centre. These trends were based on analytical results from non-replicated samples. He concluded that the samples collected had been inadequate to firmly support his hypothesis that the zonation of PSF from the periphery to the centre is due to increasing nutrient stress.

Wall (1966) found that the coastal surface peats in Bekenu-Niah-Suai area had higher levels of "reserve" P, Ca and Mg than peats further inland along the same transect. However, this trend was not reflected in the levels of exchangeable Ca, Mg and Na. Single soil samples collected at increasing distances from the coast showed that "reserve" P, for example, decreased from 750 ppm, through 620, 600, 335 to 240 ppm over a distance of 4 km.

In a similar study on the surface peats from the coastal area of Riau, Sumatra, Suhardjo and Widjaja-Adhi (1976) grouped the chemical characteristics according to peat depth classes and locality. The results suggested that surface soils of deeper peats away from the edges had higher C, N, total Ca and HCl-extractable Mg contents while pH and ash contents followed a reverse trend. No clear patterns were observed for total P, K and Mg, HCl-extractable P, K and Ca, and CEC. Driessen and Rochimah (1976) examined the physical properties of lowland peats in Kalimantan, Indonesia. From non-replicated samples taken at various distances from the river, they found that the peat soils of the centre dome area under "Padang" Forest had lower bulk density, showed less shrinkage on oven-drying and were less decomposed than those of the peats under Mixed Swamp Forest near the edges.

The main objective of this part of the study was to trace the variations of surface soil properties from the periphery to the centre of the peat swamp with particular reference to the Phasic Communities (PC). If there is a trend in the amounts of plant nutrients across the peat dome, it may indicate that nutrients are at least partly responsible for the zonation of forest types in PSF.

It has been shown in Chapter 7 that there is a surface enrichment of plant nutrients under the PSF. Furthermore, it is well known that roots in many tropical forests, especially those on oligotrophic sites, are concentrated near the soil surface where the uptake of nutrients is most active (Jordan, 1985). This is also true in the PSF where the trees are mainly shallow-rooted (Anderson, 1964b; also see Plate 7). Anderson (1961) suggested that the nutrient cycle in PSF is probably confined to the top 15 cm, avoiding the stagnant water table beneath. The discussion below is therefore based on the data of the surface samples taken in the top 15 cm (see Sections 5.2 and 5.3 for details of sampling and analyses).

8.2 GENERAL TRENDS OF VARIATIONS

The general trends of variations in surface soil properties along Transects R1, R2, R4, R5, and R7-9 were examined (see Fig.5.1 and 5.2 for location). Along these transects, samples at each site were not replicated; the results for the surface layers (0-15 cm) are summarized in Table 8.1. Transects R3, R6 and R11 had too few samples to be included. In the following discussion, the soils from the various plots are referred to by the name of associated forest type (PC).

There is a general increasing trend in pyrophosphate colour index (PCI) towards the centre of the peat dome (see Table 8.1), indicating that the surface peats are less decomposed at the centre. However, this trend is not reflected by FAR values which, except for Transect R7, are very erratic. For BD values, there are notable decreases between PC 1 and 2 along R1 and R2; between PC2 and 3 along R5; between PC 3 and 6 along R7; between PC 3, 4 and 5 along R8; and between PC 3 and 4

TABLE 7.1 PROPERTIES OF SURFACE (0-15 cm) PEATS

Transect No. Tape No./ Forest Type	PCI*	FAR (%)	BD (g/cc)	OC (%)	Ash (%)	N (%)	pH
R1/ 23/1	3	20	0.111	39.8	3.5	2.23	3.9
R1/ 70/1	4	30	0.133	37.9	11.0	2.06	3.8
R1/ 97/1	4	25	0.118	37.5	4.8	2.10	3.9
R1/145/2	3	15	0.104	36.5	2.3	2.29	3.7
R1/177/3	4	30	0.105	40.4	1.6	1.88	3.7
R2/ 50/1	2	15	0.122	37.9	5.4	2.20	4.0
R2/110/1	4	35	0.120	36.1	3.0	2.18	3.9
R2/150/2	6	25	0.104	40.9	1.2	1.77	3.8
R2/170/2	4	20	0.101	42.7	1.0	2.10	3.8
R2/210/3	5	25	0.108	40.2	0.7	1.75	4.0
R2/240/3	6	30	0.104	41.4	0.4	1.74	3.7
R4/ 1/1	0	10	0.117	36.2	6.9	1.90	3.7
R4/ 6/1	0	5	0.114	38.8	6.2	1.76	3.5
R4/ 21/2	3	20	0.113	35.2	5.6	2.14	3.5
R4/ 39/3	3	15	0.121	39.7	1.4	1.80	3.6
R4/ 83/4	3	15	0.116	40.5	1.2	1.95	3.7
R4/155/4	5	25	0.095	42.5	1.8	1.89	3.7
R5/ 9/1	2	15	0.116	39.3	7.4	2.06	3.6
R5/ 15/1	2	10	0.116	34.8	5.5	1.57	3.8
R5/ 33/2	3	20	0.117	37.1	3.2	1.86	3.6
R5/ 56/3	3	10	0.090	39.3	1.3	1.78	3.6
R5/ 78/4	4	20	0.102	40.6	1.4	1.88	3.7
R5/115/4	4	20	0.106	39.6	0.8	1.98	3.6
R7/ 20/3	3	25	0.128	42.2	1.1	1.50	3.8
R7/ 29/6	6	20	0.109	42.2	0.8	1.50	3.7
R7/ 35/6	7	35	0.099	41.6	0.5	1.66	3.7
R7/ 45/6	7	45	0.102	44.5	0.1	1.43	3.8
R7/ 55/6	7	50	0.103	44.8	0.6	1.57	4.0
R8/ 3/1	1	15	0.129	38.7	5.3	1.59	3.4
R8/ 11/3	3	28	0.125	39.7	2.0	1.86	3.4
R8/ 24/4	6	40	0.119	42.6	1.2	1.57	3.6
R8/ 31/5	7	35	0.094	42.9	2.4	1.48	3.4
R8/ 40/6	7	35	0.102	41.6	0.4	1.75	3.8
R8/ 46/6	6	35	0.100	43.0	0.6	1.63	3.8
R9/ 11/1	5	40	0.134	40.0	2.8	1.94	3.5
R9/ 24/2	3	30	0.146	41.0	1.4	1.61	3.7
R9/ 32/3	6	45	0.131	41.8	1.1	1.74	3.5
R9/ 41/4	7	45	0.110	42.2	0.8	1.54	4.0
R9/ 50/5	7	55	0.106	38.7	1.5	1.47	3.7
R9/ 55/5	7	40	0.104	40.4	0.7	1.53	3.6

*PCI = Pyrophosphate colour index.

TABLE 7.1 (Cont.)

TABLE 8.1 (Cont.)

Transect No. /Tape No./ Forest Type	ECa	EMg	EK	ENa	CEC	TP	AP
	(meq/100g)					(ppm)	
R1/ 23/1	1.52	4.03	0.49	0.86	87.86	688	53
R1/ 70/1	0.61	4.54	0.56	0.71	80.67	601	50
R1/ 97/1	1.91	3.09	0.52	0.65	79.13	573	79
R1/145/2	0.45	3.34	0.70	0.57	95.15	600	107
R1/177/3	0.41	3.81	0.71	0.43	92.64	391	50
R2/ 50/1	2.52	4.82	1.11	0.62	64.27	819	115
R2/110/1	2.26	3.92	1.24	0.51	64.61	637	58
R2/150/2	1.25	5.25	1.03	0.80	69.51	602	41
R2/170/2	1.77	4.72	1.08	0.69	66.74	553	60
R2/210/3	1.44	4.65	0.64	0.55	63.25	566	26
R2/240/3	1.18	3.92	0.65	1.08	67.38	432	23
R4/ 1/1	0.50	2.85	0.85	0.40	93.32	537	76
R4/ 6/1	0.34	2.66	0.26	0.36	99.77	291	74
R4/ 21/2	0.40	4.19	0.66	0.70	96.15	507	132
R4/ 39/3	0.23	3.06	0.40	0.57	85.10	362	70
R4/ 83/4	0.30	3.49	0.25	0.74	87.10	289	82
R4/155/4	0.47	3.52	0.54	0.36	82.92	298	74
R5/ 9/1	0.46	3.25	0.46	0.40	60.13	577	107
R5/ 15/1	0.45	3.76	0.51	0.38	58.44	540	91
R5/ 33/2	0.57	3.72	0.33	0.50	73.22	366	61
R5/ 56/3	0.46	2.96	0.33	0.76	84.77	400	95
R5/ 78/4	0.71	2.10	0.54	0.35	66.05	464	81
R5/115/4	0.17	3.94	0.58	0.70	71.36	309	50
R7/ 20/3	0.24	5.14	1.10	2.26	67.68	414	73
R7/ 29/6	0.46	6.41	0.96	0.79	59.10	396	62
R7/ 35/6	0.30	1.22	0.97	0.83	46.86	375	79
R7/ 45/6	0.35	1.48	1.12	0.89	53.17	145	10
R7/ 55/6	0.52	3.51	1.10	0.66	47.52	269	53
R8/ 3/1	3.56	5.54	0.81	0.43	48.89	704	79
R8/ 11/3	1.27	6.94	0.67	0.49	56.44	362	67
R8/ 24/4	0.50	9.41	0.83	0.73	54.95	412	122
R8/ 31/5	1.65	7.38	1.45	0.52	68.20	591	203
R8/ 40/6	0.98	1.85	1.51	1.38	71.66	501	83
R8/ 46/6	0.48	5.40	0.94	1.00	74.66	334	73
R9/ 11/1	0.50	9.06	1.61	0.90	50.08	872	91
R9/ 24/2	0.91	6.32	0.84	0.84	57.97	448	59
R9/ 32/3	0.54	7.65	0.80	1.50	52.17	641	85
R9/ 41/4	0.71	6.70	2.06	0.87	50.90	557	116
R9/ 50/5	0.30	5.01	1.78	2.12	53.64	362	47
R9/ 55/5	0.42	2.45	1.09	2.06	50.90	290	31

TABLE 7.1 (Cont.)

Transect No. /Tape No./ Forest Type	TCa	TMg	TK	TMn	TCu	TZn	TFe
	(ppm)						
R1/ 23/1	1131	965	463	10	9	14	7814
R1/ 70/1	838	979	358	11	4	8	4805
R1/ 97/1	886	899	309	11	3	11	2726
R1/145/2	113	650	380	7	2	7	2523
R1/177/3	93	550	203	6	2	7	1419
R2/ 50/1	1261	852	439	17	6	10	2452
R2/110/1	1463	687	379	13	5	9	2906
R2/150/2	891	919	439	9	3	4	1293
R2/170/2	1027	718	397	9	5	6	972
R2/210/3	422	718	370	11	3	6	455
R2/240/3	329	623	374	12	5	3	542
R4/ 1/1	280	727	392	9	7	11	3357
R4/ 6/1	308	617	368	6	3	4	1766
R4/ 21/2	144	1148	449	7	3	6	1490
R4/ 39/3	129	891	230	9	2	35	1150
R4/ 83/4	90	944	148	4	2	21	1210
R4/155/4	88	876	292	6	0	22	453
R5/ 9/1	187	944	395	6	5	9	4133
R5/ 15/1	154	1058	335	6	3	12	2673
R5/ 33/2	226	894	255	6	2	37	3141
R5/ 56/3	101	863	259	8	2	13	1840
R5/ 78/4	210	597	353	6	1	16	1178
R5/115/4	172	656	314	8	2	11	920
R7/ 20/3	231	863	278	12	5	8	207
R7/ 29/6	278	1110	282	10	2	10	229
R7/ 35/6	163	758	287	10	1	6	224
R7/ 45/6	29	153	158	6	5	5	473
R7/ 55/6	76	255	203	6	4	4	76
R8/ 3/1	1028	1019	783	20	3	9	2546
R8/ 11/3	585	1434	240	21	1	3	1089
R8/ 24/4	340	1500	319	9	2	5	260
R8/ 31/5	517	1210	643	14	2	8	262
R8/ 40/6	495	1205	482	10	2	8	240
R8/ 46/6	337	813	349	6	2	4	186
R9/ 11/1	222	1375	545	18	3	6	1024
R9/ 24/2	219	1085	338	4	2	4	979
R9/ 32/3	334	1221	357	8	4	5	863
R9/ 41/4	541	852	658	18	2	6	187
R9/ 50/5	163	925	623	8	3	4	373
R9/ 55/5	168	409	492	4	1	2	417

along R9. However, it is not possible to determine, on the basis of non-replicated samples, whether such differences are statistically significant.

The pH values do not show any clear pattern along most transects. They are slightly higher at the centre of the PS along R7 and R8, but the opposite seems to be true along R1. CEC values also have some conflicting results: while R4 has decreasing values towards the centre, the trend along R8 is reversed. Along R1, CEC increases substantially on transition from PC1 to PC 2 and 3. Other transects do not show any obvious pattern.

For OC, there are notable increases on transition from PC 2 to 3 along R1 and R4; from PC1 to 2 along R2; and from PC 3 to 4 along R8. There is no clear trend along R5 and R9. Along R7, the levels of OC are generally higher in PC 6, particularly from Tape 45 onwards. The pattern for ash content shows a consistent, decreasing trend towards the centre of the PS for all the transects.

Almost all of the nutrient elements examined show some decreases from the periphery to the centre of the peat domes. The only exception is in the levels of TZn which increases from PC 1 and 2 to PC 3 and 4 along R4. These variations are summarized in Table 8.2. The decreasing trends, however, vary and some are more consistent and clearly expressed than others. Total levels of P, Ca, Mg and K seem to demonstrate more consistent and conspicuous decreases than the available/exchangeable forms. There are no obvious trends along most transects for AP and exchangeable bases, especially Mg and K. Fe is the element which shows the most consistent and notable decreases along all the transects examined.

8.3 VARIATIONS ALONG R10 - A MORE DETAILED ASSESSMENT

The main drawback of the data presented above is that the sample at each site was not replicated. The comparisons therefore could not be tested statistically. Interpretation is made more difficult when, as for most variables, the transects do not show the same pattern of variations.

TABLE 8.2 TRENDS OF NUTRIENT LEVELS ALONG TRANSECTS

Nutrient	Transect R1	Transect R2	Transect R4	Transect R5	Transect R7	Transect R8	Transect R9
Total N	PC1-2 > PC3	PC1 > PC3	--	--	--	--	PC1-3 > PC4-5
ECa	PC1 > PC 2-3	PC1 > PC2 > PC3	--	--	--	PC1 > PC3-6	PC1-4 > PC5
TCa	PC1 > PC2 > PC3	PC1 > PC2 > PC3	PC1> PC2> PC3> PC4	--	Lower from T45	PC1 > PC3-6	PC1-4 > PC5
EMg	--	--	--	--	Lower from T35	--	PC1-4 > PC5
TMG	PC1 > PC2 > PC3	--	--	PC1> PC2-3> PC4	Lower from T45	--	PC1-3 > PC 4-5
EK	--	PC1-2 > PC3	--	--	--	--	--
TK	PC1-2 > PC3	--	PC1-2 > PC3-4	--	Lower from T45	PC1 > PC2-6	--
ENa	PC1 > PC2 > PC3	--	--	--	PC3 > PC6	--	--
TP	PC1-2 > PC3	PC1 > PC2 > PC3	PC1-2 > PC3-4	PC1 > PC2-4	PC3 > PC6	PC1 > PC3-6	PC1 > PC2-4 > PC5
AP	--	PC1 > PC2 > PC3	--	PC1 > PC4	--	--	PC1-4 > PC5
TMn	PC1 > PC2-3	PC1 > PC2-3	--	--	PC3 > PC6	PC1,3 > PC4-6	--
TCu	PC1 > PC2-3	--	PC1 > PC2-4	PC1 > PC2-4	--	--	--
TZn	PC1 > PC2-3	PC1 > PC2-3	PC3-4 > PC1-2	--	Lower from T35	--	--
TFe	PC1 > PC2 > PC3	PC1 > PC2 > PC3	PC1> PC2> PC3-4	PC1-2> PC3> PC4	Lower at T55	PC1>PC3>PC4-5>PC6	PC1-2> PC3> PC4-5

-- Data erratic; no clear pattern.

NB. Significance not tested statistically

In order to overcome some of these problems, surface peat samples (0-15 cm) along Transect R10 were replicated five times at each site for a more detailed assessment of the variations of soil properties across a peat dome. Table 8.3 gives the summarized data, each figure being the mean of five replicates. Comparison between the forest types was done by first running an analysis of variance (ANOVA). The ANOVA for all the 21 properties were found to be significant at $P<0.05$; that of pH was the least significant, at $P = 0.035$. Differences between forest types were tested for significance by using Least Significant Difference (LSD) *a posteriori* contrast test.

The same results are shown by graphs in Figure 8.1 where a solid line connecting two points means a significant difference ($P<0.05$) between them and a broken line, non-significant difference.

8.3.1 RESULTS

Physical Properties

Both **pyrophosphate colour index (PCI)** and **fibre after rubbing (FAR)** show a significant increase from PC 3 to PC 4, but there are no other significant differences. PCI values of 5 or more and FAR exceeding 40% generally indicate a fibric material (see Section 7.3). The surface organic materials of PC 4 and 6 are therefore raw and undecomposed. On the other hand, the surface layers under PC 1, 2 and 3 are found to have PCI values of 3 or less. These materials, however, have FAR higher than the stipulated "one-sixth of the soil volume" for sapric materials (Soil Survey Staff, 1975). As the solubility test should be given precedence (see Section 7.3), the surface layers of organic soil materials in PC 1, 2 and 3 therefore mainly qualify as sapric or well decomposed materials.

It has been shown in many studies (e.g. Lynn *et al.*, 1974) that the degree of decomposition is an important factor affecting **bulk density (BD)** of organic soils. The decreasing trend in BD values from an average of 0.212 at the periphery to 0.065 g/cm^3 at the centre (Table 8.3) is similar to but more complicated than that of PCI and FAR. While there are no significant differences between PC 1 and 2, 3 and 4, and 4 and 6, BD of PC 1 and 2 are significantly higher than the rest; that of PC 3 is also significantly higher than PC 6.

TABLE 8.3. SUMMARIZED SURFACE SOIL DATA IN RELATION TO FOREST TYPES ALONG TRANSECT R10, TANJUNG UPAR

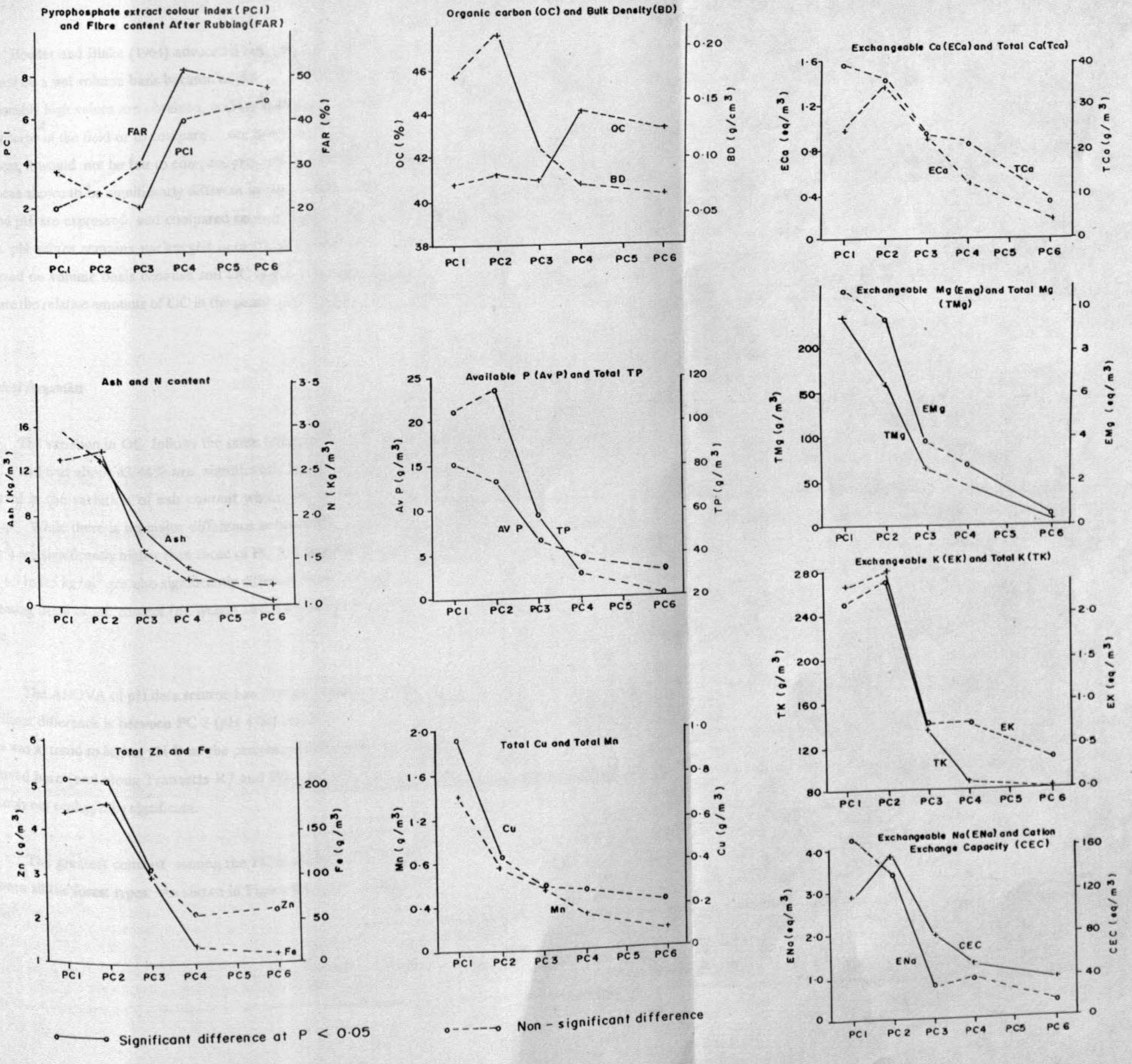
Forest Type (PC)	PCI	FAR (%)	BD (g/cm^3)	OC (%)	Ash (kg/m^3)	N (kg/m^3)	ECa (eq/m^3)	EMg (eq/m^3)	EK (eq/m^3)	ENa (eq/m^3)	CEC (eq/m^3)
1	2.0^{a*}	28^{a}	0.172^{c}	40.7^{a}	15.8^{d}	2.61^{b}	1.07^{bc}	10.72^{c}	2.10^{b}	4.25^{b}	113.7^{d}
2	2.8^{a}	23^{a}	0.212^{c}	41.2^{a}	13.1^{d}	2.71^{b}	1.38^{c}	9.36^{c}	2.40^{b}	3.43^{b}	154.6^{e}
3	2.0^{a}	30^{a}	0.107^{b}	40.9^{a}	6.9^{c}	1.62^{a}	0.93^{bc}	3.77^{b}	0.76^{a}	0.77^{a}	79.6^{c}
4	6.0^{b}	49^{b}	0.073^{ab}	44.1^{b}	3.5^{b}	1.32^{a}	0.45^{ab}	2.71^{b}	0.77^{a}	1.00^{a}	52.0^{b}
6	6.8^{b}	47^{b}	0.065^{a}	43.3^{b}	0.5^{a}	1.24^{a}	0.17^{a}	0.51^{a}	0.36^{a}	0.40^{a}	35.5^{a}
S.E.(Diff)	0.4	4	0.019	0.7	1.4	0.20	0.30	0.82	0.62	0.75	7.6

Forest Type (PC)	TCa (g/m^3)	TMg (g/m^3)	TK (g/m^3)	TP (g/m^3)	AP (g/m^3)	TMn (g/m^3)	TCu (g/m^3)	TZn (g/m^3)	TFe (g/m^3)	pH (water)
1	39.4^{c}	232.7^{d}	265.1^{c}	104.9^{c}	15.5^{b}	1.42^{b}	0.96^{b}	5.23^{b}	171.9^{c}	4.14^{ab}
2	36.4^{bc}	162.4^{c}	281.7^{c}	114.5^{c}	13.3^{b}	0.75^{ab}	0.43^{a}	5.24^{b}	183.0^{c}	4.08^{a}
3	23.5^{abc}	62.6^{b}	136.2^{b}	57.2^{b}	6.5^{a}	0.58^{a}	0.29^{a}	3.14^{a}	97.9^{b}	4.16^{ab}
4	21.9^{ab}	42.3^{b}	86.9^{a}	31.0^{a}	4.5^{a}	0.33^{a}	0.29^{a}	2.10^{a}	20.2^{a}	4.24^{b}
6	8.3^{a}	6.5^{a}	80.7^{a}	21.3^{a}	3.0^{a}	0.16^{a}	0.21^{a}	2.28^{a}	11.6^{a}	4.24^{b}
S.E.(Diff)	7.8	17.1	21.6	11.4	3.0	0.32	0.13	0.59	14.0	0.06

*Figures followed by different alphabets are significantly different at $P<0.05$ by LSD.

NB. Since the sampling depth is only 15 cm, a volume of 1 m^3 represents a surface area of about 6.7 m^2.

FIGURE 8. I. VARIATIONS OF SURFACE SOIL PROPERTIES AMONGST FOREST TYPES



Boelter and Blake (1964) advocated that physical and chemical data of organic soils are best expressed on a wet volume basis because of the very low bulk density. On weight or dry volume basis, unreasonably high values are obtained, making it difficult to determine the properties of organic soils as they occur in the field or to compare the properties with those of mineral soils. Based on similar argument, it would not be fair to compare properties on weight basis between the PC because the BD have been shown to be significantly different in some cases. As a result, the rest of properties except OC and pH are expressed and compared on wet volume basis after conversion with the help of BD values. pH values remains unchanged because this property is dimensionless. OC content is not expressed on volume basis because soil OC is not a nutrient element and the intention here is to compare the relative amounts of OC in the peats rather than the absolute quantity per unit volume.

Chemical Properties

The variation in **OC** follows the same trend as PCI and FAR (see Fig.8.1). The OC contents of PC 4 and 6 at about 43-44% are significantly higher than those of PC 1, 2 and 3. This trend is reflected in the variation of **ash content** which, on a volume basis, exhibits a greater degree of contrast. While there is no major difference between PC 1 and 2 in ash content, their values (13-16 kg/m^3) are significantly higher than those of PC 3, 4 and 6. The ash contents of PC 3, 4 and 6 ranging from 6.9 to 0.5 kg/m^3 are also significantly different from each other. This is supported by the general decreasing trend of ash content (on weight basis) by all the other transects, as discussed in Section 8.2 above.

The ANOVA of pH data returned an F-value which is barely significant at 5% level. The only significant difference is between PC 2 (pH 4.08) and PC 6 (pH 4.24). Anderson (1961) reported that there was a trend to higher pH from the periphery to the centre of the peat dome. The same trend is observed here (and along Transects R7 and R8 - see Section 8.2) but the minor differences are probably not ecologically significant.

The greatest contrast among the PC is shown by CEC which gives significant differences between all the forest types. As shown in Figure 8.1, CEC peaks in PC 2 with a mean value of 154.6 eq/m^3.

All the nutrients show a general decreasing trend from PC 1 through to PC 6. They differ only in magnitude and the stage at which the changes are significant. Table 8.4 summarizes the comparisons between adjacent PC.

The level of N decreases significantly from PC 2 to PC 3 (2.71 to 1.62 kg/m^3). There are no significant differences between PC 1 and 2, and between PC 3, 4 and 6. Variations in calcium and manganese are the least pronounced (see Table 8.3 and Fig. 8.1):

(a) For ECa, no large differences are observed between PC 1, 2 and 3, and between PC 4 and 6; ECa of PC 1,2 and 3 are however significantly higher than that of PC 6.

(b) For TCa, no significant differences are shown between PC 1, 2 and 3, PC 2, 3 and 4 and PC 3, 4 and 6. TCa of PC 1 is however significantly higher than that of PC 4 and 6, as is TCa of PC 2 when compared to that of PC 6.

(c) For TMn, PC 1 is significantly higher than PC 3, 4 and 6; there are no major differences between PC 1 and 2, and between PC 2, 3, 4 and 6.

EK, ENa, AP and TZn depict the same trend (see Table 8.3 and Fig. 8.1). No significant differences exist between PC 1 and 2, and between PC 3, 4 and 6. There is, however, a significant decrease from PC 2 to PC 3. The trends of TK, TP and TFe are similar but they show an additional significant drop between PC 3 and PC 4.

TMg and EMg have very similar trend. For EMg, there are no major differences between PC 1 and 2, and between PC 3 and 4. However, there are significant decreases from PC 2 to PC 3 (9.36 to 3.77 eq/m^3) and from PC 4 to PC 6 (2.71 to 0.51 eq/m^3). The same could be said for TMg except that the difference between PC 1 and 2 at values of 232.7 and 162.4 g/m^3 (19.14 and 13.36 eq/m^3 respectively) is also significant.

Levels of copper (total) are the lowest amongst the nutrients studied. The highest value found in soils of PC 1 is just about 1 g/m^3. There is a significant drop from PC 1 to PC 2. Between PC 2 and the rest, there are no major differences with values ranging from 0.21 to 0.43 g/m^3. Organic soils have long been noted for deficiency in copper because of the very low inherent content in the peats, as indicated here and the strong fixation by organic matter (Lucas and Davis, 1961) which

TABLE 8.4. SUMMARY OF DIFFERENCES AMONGST ADJACENT PC ALONG TRANSECT R10

Soil Properties	Difference between PC: 1 & 2	2 & 3	3 & 4	4 & 6
PCI	NS	NS	*	NS
FAR	NS	NS	*	NS
BD	NS	*	NS	NS
OC	NS	NS	*	NS
Ash	NS	*	*	*
pH	NS	NS	NS	NS
N	NS	*	NS	NS
TP	NS	*	*	NS
AP	NS	*	NS	NS
TCa	NS	NS	NS	NS
ECa	NS	NS	NS	NS
TMg	*	*	NS	*
EMg	NS	*	NS	*
TK	NS	*	*	NS
EK	NS	*	NS	NS
ENa	NS	*	NS	NS
CEC	*	*	*	*
TCu	*	NS	NS	NS
TMn	NS	NS	NS	NS
TZn	NS	*	NS	NS
TFe	NS	*	*	NS

NS = Non-significant; * = Significant at $P<0.05$.

makes whatever copper present unavailable to plants. Tie and Lim (1976) also reported that Morgan-extractable copper is practically zero (i.e. less than 1 ppm) in Sarawak peats.

8.3.2 DISCUSSION AND CONCLUSIONS

Physically, the surface peats change from a well decomposed, sapric material to a raw, fibric material as one traversed from PC 3 into PC 4 and 6. Such changes have pronounced influence on other properties like BD, OC, ash content and CEC. While OC shows some increases by a transition from sapric to fibric material, other properties like BD, ash content and CEC decrease significantly. These confirm the findings by Driessen and Rochimah (1976) that peats under "padang" forest (probably equivalent to PC 6) in Kalimantan, Indonesia had lower BD and were less decomposed than those under Mixed Swamp Forest (equivalent to PC 1).

Anderson (1961) noted the importance of flooding in raising the mineral or ash content of the peats and suggested 75% loss of ignition (LI) as the limit for differentiating between "freshwater swamp" from true "peat swamp". All the present samples have very high LI with values ranging from 92 to 99%. These indicate that the areas where these samples were collected are not subject to flooding. The decreasing ash content from PC 1 and 2 through to PC 6 is therefore a reflection of the variation in the degree of decomposition. As the organic soil materials decomposes, the mineral fraction is left behind to enrich the resultant material in terms of mineral or ash content. The sapric materials at the periphery of the peat dome therefore generally have higher ash content than the less decomposed hemic or fibric materials at the centre.

The decreasing trend of CEC from PC 1 and 2 through to PC 6 can be explained primarily by the effect of the degree of decomposition. The CEC of organic soils is largely due to the carboxyl groups, and increased humification is generally associated with increases in CEC (Coleman and Thomas,1967). The lower CEC of PC 4 and 6 can therefore be mainly attributed to the undecomposed nature of the organic soil materials. In the case of PC 1, 2 and 3, it must be pointed out that the differences in CEC are not significant when they are expressed on weight basis. These minor differences of CEC on weight basis mirror the slight variations in the degree of humification of

PC 1, 2 and 3. On volume basis, the small differences are accentuated by the substantial variations in BD, thereby producing significant differences in CEC between PC 1, 2 and 3.

While most of the nutrients show a general decrease from PC 1 through to PC 6, they differ in magnitude and the stage at which a significant change occurred. Variations in pH, ECa, TCa and TMn are the least pronounced; as a result, no significant changes occur between adjacent PC (see Table 8.4). All other nutrients show at least one significant change between two adjacent PC along the transect. Magnesium, particularly TMg, is perhaps the element which changes most drastically, with significant decreases from PC 1 to PC 2, PC 2 to PC 3, and PC 4 to PC 6. These are substantiated by the trend of TMg (on weight basis) along Transects R1 and R5 (see Section 8.2).

Overall the sharpest transition seems to have occurred between PC 2 and PC 3 where 13 out of 21 soil properties vary significantly (see Table 8.4). They include BD, ash, N, TP, AP, TMg, EMg, TK, EK, ENa, CEC, TZn and TFe. Differences in the soils of PC 1 and PC 2 are very much less distinctive; only TMg, CEC and TCu change significantly. Anderson (1963) regarded PC 2 as a transitional zone between PC 1 and PC 3. The soil properties seem to suggest that PC 2 is more akin to PC 1 than PC 3.

From PC 3 to PC 4, the soils also change quite substantially. This is particularly so in the physical properties relating to the degree of decomposition. The surface soils of PC 3 are well decomposed while those of PC 4 (and PC 6) are fibric in nature. Other major variations involve OC, ash, TP, TK, CEC and TFe. Anderson (1963) also considered PC 4 in the Baram swamps as a transitional zone between PC 3 and the more advanced PC 5 and 6. Again, the soil properties suggest that the soils of PC 4 are more like those of PC 6 than PC 3. Significant differences between soils of PC 4 and PC 6 are only found in ash, TMg, EMg and CEC values.

Therefore, the change from the floristically rich, high volume forest of PC 1 to the low stature, floristically poor forest of PC 6 is reflected by the generalized soil fertility gradient as manifested by the decreasing trends of all nutrients examined from PC 1 through to PC 6. However, it is difficult at this stage to isolate which properties are the critical edaphic factors. This will be examined further in the next chapter.

CHAPTER 9. RELATIONSHIPS BETWEEN FOREST TYPES AND SOIL PROPERTIES

9.1. INTRODUCTION

There are limited possibilities to adapt conventional methods of univariate data analysis to complex materials with a large number of variables. Multiple and stepwise regression techniques are efficient and reliable when the number of causative variates is not large, and when these variates are not themselves correlated. Results of multiple regression analysis become unreliable when correlations exist among the variables. Other techniques from multivariate statistics are to be preferred when the causative variates are not statistically orthogonal to each other. In the case of principle component analysis (PCA) and some forms of factor analysis, for example, the eigenvalue-eigenvector numerics suppress the effect of intercorrelations by reducing the problem dimensionality to a small number of new, orthogonal variates called components or factors.

Multivariate statistical techniques are frequently applied in ecological studies. They have been proven to be reliable and are especially useful in situations with relatively few observations (or cases) and many variables. The following examples include only a few which dealt with ecosystems in swampy environments with peat or organic soils.

Walker and Wehrhahn (1971) made use of PCA to examine the relationships between derived vegetation gradients and measured environmental variables in Saskatchewan wetlands, Canada. Four environmental gradients, namely disturbance, available nutrients, water regime and salinity accounted for the bulk of variations in the vegetation. PCA was also used by Johnson (1977) as an empirical procedure for defining ecological niches in plant populations in raised bogs in Southern Maine, USA. The two niche dimensions identified within the bogs were related to mineral-ion concentration: (1) atmospheric input differences owing to proximity to the ocean; and (2) mineral-soil groundwater influence. Bohlin *et al.* (1989) successfully used PCA to probe relationship between peat properties and to group similar peat samples according to botanical composition and degree of decomposition.

Multivariate linear discriminant analysis was employed by Sim *et al.* (1982) to find the soil and water parameters which best described various classes of treed peatland in Canada. With 16 soil and water properties, the discriminant classification showed 93% agreement with the three *a priori* groups of peatland classified on the basis of vegetational physiognomy. Swanson and Grigal (1984) also attempted to use discriminant analysis technique to predict type of dominant surface organic soil material from vegetation data. They found that vegetation structure and pH were weakly related to the degree of peat decomposition. They concluded that extensive field sampling is needed to map taxonomically based units of Histosols, but vegetation cover can be used as a surface indicator to classify sites as oligotrophic, mesotrophic and eutrophic with about 90% accuracy.

The preceding chapter has shown that the zonation of the PSF in Sarawak is reflected by the generalized soil fertility gradient as manifested by the decreasing trends of nutrients from PC 1 through to PC 6. However, it has not been able to isolate the critical edaphic factors. In this part of the study, the relationships between forest types and soil properties were further explored by means of multivariate statistical analyses. As mentioned in Section 6.3.2, this study did not intend to test the PC classification, which is accepted as being real and adequately reflecting the changes in the vegetation across the peat domes. The actual relationships between the botanical characteristics (e.g. biomass and species diversity) and the soil properties are not studied. The main objective here was to find the soil properties which are most closely associated with the zonation of the forest types.

Forty-two empirical and derived variables were included (Table 9.1), but they were not all used at the same time. In factor analysis, for example, it is imperative to screen the data prior to the factorization procedure (see Section 9.2.1 for explanation). Preliminary investigations made use of a wider range of properties but there were fewer cases. The list was subsequently trimmed down to 28 (not counting forest type which was used as a "grouping" variable in discriminant analysis) when the final set of data was considered. However, it must be pointed out that Properties 8 to 42 in Table 9.1 were repeated over five or more peat horizons. The total number of variables for each case is therefore a multiple of the number of horizons and the number of properties to be considered.

During the preliminary investigations done after the first phase of field work (see Section 5.1), only 21 cases were examined. In the final statistical analyses, 58 cases were used, namely 14 cases with Mixed Swamp Forest (PC 1), 10 Alan Forest (PC 2), 12 Alan Bunga Forest (PC 3), 10

TABLE 9.1. VARIABLES USED IN MULTIVARIATE STATISTICAL ANALYSES

FOREST TYPES

1. Phasic communities or PC

GROUNDWATER PROPERTIES

*2. Electrical conductivity (uS/cm)
*3. Dissolved nitrogen (ppm)
*4. Dissolved calcium (ppm)
*5. Dissolved magnesium (ppm)
*6. Dissolved potassium (ppm)
*7. pH

PHYSICAL PROPERTIES OF PEAT

8. Bulk density [BD][£] (g/cm^3)
9. Particle density [PD] (g/cm^3)
10. Fibre before rubbing [FBR] (%)
11. Fibre after rubbing [FAR] (%)
12. Pyrophosphate colour index [PCI]
13. Pyrophosphate solubility index[PSI]
*14. Shrinkage after air-drying(%)
*15. Shrinkage after re-saturation(%)
*16. Shrinkage after oven-drying(%)

CHEMICAL PROPERTIES OF PEAT

17. pH in water [pH]
*18. pH in KCl [pHK]
*19. pH in 0.01M $CaCl_2$ [pHCa]
20. Organic carbon [OC] (%)
21. Total nitrogen [N] (%)
22. Exch. calcium [ECa] (me %)
23. Exch. magnesium [EMg] (me %)
24. Exch. potassium [EK] (me %)
25. Exch. sodium [ENa] (me %)
26. Cation exch. capacity [CEC] (me %)
27. Available phosphorus [AP] (ppm)
28. Total phosphorus [TP] (ppm)
29. Total calcium [TCa] (ppm)
30. Total magnesium [TMg] (ppm)
31. Total potassium [TK] (ppm)
*32. Total sodium [TNa] (ppm)
33. Total iron [TFe] (ppm)
34. Total manganese [TMn] (ppm)
35. Total zinc [TZn] (ppm)
36. Total copper [TCu] (ppm)
@37. C:N ratio
@38. Total exch. bases [TB] (me %)
@39. Base saturation [BS] (%)
40. Loss on ignition [LI] (%)
@41. Ash (or mineral) content (%)
@42. Pore space (%)

** Not used in the final analyses of data.*

£ Abbreviations of the analyses are shown in square brackets. Peat properties are repeated over several layers which were sampled separately: A=0-15 cm, B=15-30 cm, C=30-60 cm, D=60-100 cm, E=100-150 cm and so on. The symbol used in the text for a particular analysis of a particular layer is made up of a letter (A, B, C, etc.) denoting the layer followed by the abbreviation of the analysis, e.g. BLI means the loss on ignition for the B (15-30 cm) layer.

@ Variables derived through calculations.

Padang Alan Forest (PC 4), 5 PC 5 and 7 Padang Paya Forest (PC 6). Therefore, the number of cases was relatively few in comparison with the large number of variables. This situation led to a number of statistical problems (see sections below). However, it was probably inevitable if the soils were to be characterized in detail and the whole range of properties tested to identify the more important ones. More plots with fewer variables would just be a repeat and continuation of some of the work done by Anderson (1961).

Multivariate statistical analyses were mainly done at the Polytechnic of North London using the Statistical Package for the Social Sciences (SPSS-X Release 3.1 for VAX/VMS) from SPSS Inc., USA. In the final stages of data analyses, some of them were run at the Forest Department, Sarawak using the personal computer version of SPSS (SPSS/PC+ for IBM PC/XT/AT, Version 3.0). For some procedures which are not available on SPSS, use was made of the programmes of the Biomedical Package (BMDP), prepared by the University of California, Los Angeles.

As explained in Section 5.1, data collection was undertaken in two phases. Some preliminary assessments of the data collected after the first phase of field work were carried out in 1984-85. The main objectives of the preliminary exercises were to scrutinize the data collected, and to explore the possibility of using some of the multivariate statistical techniques to analyze these data. The preliminary results influenced some decisions made in the second phase of data collection and in the final statistical analyses. These analyses are therefore reported in their chronological order.

9.2 TREATMENT OF PRELIMINARY DATA

9.2.1 Factor Analysis (FA) of Soil Variables

Due to the large number of soil variables and the high degree of intercorrelation between some of them, it was decided to simplify the preliminary data set by factor analysis. Factor analysis includes a range of methods which differ in their criteria for the preparation of correlation matrix, factor extraction, and factor rotation. It differs from regression analysis in that there is no dependent variable to be explained by a set of independent variables. The most common applications may be categorized into:

(a). Exploratory uses - the exploration and detection of underlying patterns in sets of variables with a view to the discovery of new concepts and a possible reduction of data;

(b). Data transformation - the rewriting of a data set in the form of factor scores to be used as new variables (usually fewer in number and non-correlated) in later analyses; and

(c). Confirmatory uses - the testing of hypothesis about the structuring of variables in terms of the expected number of significant factors and factor loadings.

Prior to factor analysis, the data set was scrutinized and some of the less satisfactory variables were discarded. Firstly, it was decided that the factor analysis was to be performed only with soil variables from the first three horizons (0-15; 15-30 and 30-60 cm depths) because deeper horizons in two of the cases, R1/T4 and R5/T6 comprising shallow peats were distinctively different due to the presence of clay lenses first and then mineral subsoil at 60 and 160 cm depths respectively. These two cases were discarded in the analysis of the final set of data (Section 9.3).

Determination of peat pH was originally carried out in three media: water, 1N KCl and 0.01M $CaCl_2$. Student's t-test showed that pH(KCl) and pH($CaCl_2$) are not significantly different at 5% level. The correlation matrix of these three variables is as follows:

	pH(H_2O)	pH(KCl)	pH($CaCl_2$)
pH(H_2O)	1.00	-	-
pH(KCl)	0.847	1.00	-
pH($CaCl_2$)	0.817	0.920	1.00

Such high degrees of correlation are almost equivalent to linear dependence which will lead to rank deficiency in the data matrix and have a destabilizing effect on the subsequent factor analysis. Consequently, only pH(H_2O) was retained, and pH(KCl) and pH($CaCl_2$) discarded. In the second phase of data collection, only pH(H_2O) was measured.

Shrinkage upon air-drying and shrinkage upon re-saturation were omitted because of many missing values. Derived variables such as C:N ratio, total bases, base saturation, ash content and pore space were also omitted from factor analysis. Such variables are dependent on the original variables.

As in most statistical procedures, factor analysis requires data which are approximately normally distributed. The final data examination prior to factorization was therefore to test the normality of the chosen variables. This was done by Kolmogorov-Smirnov test. The results showed that out of the 78 variables retained, only BLI, BTCu, BTK, CpH, CLI, CTMn, and CTK (these symbols are listed and explained in Table 9.1) did not have near normal distributions. Since most of the variables were found to be normal, factor analysis proceeded without any data transformation. Furthermore, this factorization is presently viewed as an exploratory technique rather than hypothesis testing. For such a purpose, some departure from normality is accepted (Afifi and Clark, 1984).

The final 21x78 matrix, with the 21 samples as objects and the values of the peat properties in the first three horizons as 78 variables, was subject to exploratory factor analysis using the SPSS FACTOR programme. Both PCA and principal factor (or axis) analysis (with iterations) were tried out. In the latter case, BLI, CLI, CTFe and CTCa had to be omitted due to their high degrees of correlation with BTK (r=-0.926), CTK (r=-0.971), ATFe (r=0.908), and BTCa (r=0.913) respectively. Otherwise, iteration stopped after the first step and no solution was possible.

The first step in factor analysis involves the preparation of a matrix of correlations between the variables. One could calculate the correlation between each pair of variables (R-Type) or between each pair of samples (Q-type). If FA is applied to a correlation matrix of sample (objects or case), it is called a **Q-factor analysis,** while the more common version based on correlations between variables is known as **R-factor analysis.** The latter is employed in the present study. Some statistical package like BMDP can make use of either correlation or covariance matrix to perform factor analysis; SPSS is programmed to use the correlation matrix only. Analyzing correlation matrix instead of covariance matrix is equivalent to factorization using standardized variables (Afifi and Clark, 1984). When principal components are derived from the correlation matrix, interpretation becomes easier in two ways:

(a). The total variance is simply the number of variables N, and the proportion of variance explained by each component is the corresponding eigenvalue divided by N; and

(b). The coefficients or loadings of a component can be compared to quantify the relative degree of dependence of that component on each of the standardized variables.

In the second step of factor extraction, the goal is to determine the factors on the basis of the interrelations exhibited in the data. The first component or factor is a combination of the observed variables that accounts for the largest amount of variance in the sample. The second component or factor, orthogonal to the first, accounts for the most residual variance after the effect of the first is removed from the data, and so on. The factors may be defined as exact mathematical transformation of the original data, or assumptions may be made about the structuring of variables and their source of variation. The former approach is called **principal component analysis** (PCA) where there is no need for a unique factor in the model, and the communality of a variable is 1 for all variables. On the other hand, it is assumed in the other forms of factor analysis that the observed variable is influenced by various determinants, some of which are shared by other variables in the set (common factors) while others are not shared by any other variables (unique factors). The communality of a variable is the amount of variance accounted for by the common factors of that variable. The determination of communalities remains one of the most difficult and ambiguous tasks in factor analysis. The methods for their determination is one of the main characteristics that differentiates the various techniques of factoring. It is a common practice to use the squared multiple correlation coefficients as estimates of the communalities at the first step of factor extraction. After this, the communalities are reestimated from the factor loadings and the procedure is iterated until negligible change in communality estimates occur. For discussions of the different factor estimation algorithms, readers are referred to Harman (1967) and Kim and Mueller (1979).

Various forms of factor analysis including PCA were tried out in the analysis of the preliminary data. The axes so extracted were also rotated using different techniques to obtain a structure which was simple and easier to interpret. The unrotated principal components and the **varimax** rotated factors extracted by PCA explained the largest amount of the total variance. It is debatable whether there is any need or justification for rotating the principal components (Daultrey, 1976). Although the main objective of this exercise was to simplify the original data set rather than trying to detect and test the underlying pattern of the variables, there would be added advantages if the set of factors could also be interpreted. Since the varimax rotated solutions were easier to interpret than the unrotated principal components, the former was therefore adopted and reported below.

Several procedures have been proposed for determining the number of components to be used in a model. One suggestion is that only factors with eigenvalue greater than 1 should be included; those with a variance of less than 1 are no better than a single variable, since each variable has a variance of 1. Another technique is to make use of a plot of the total variance or eigenvalue associated with each factor, commonly called the **scree plot** (Cattell, 1966); a distinct break between the steep slope of the large factors and the gradual trailing off of the others signifies the number of factors that are sufficient for the model.

In the present analysis, the "scree plot" (see Fig. 9.1) shows that the cutoff point is at the 11th component; beyond this, each additional component accounts for approximately similar and trivial amount of variance. Therefore, the first 11 components, all with eigenvalues of more than 1, were selected. Together they account for about 90% of the variance. The slight loss in variance was acceptable in view of the simplification and clarification of the original data set.

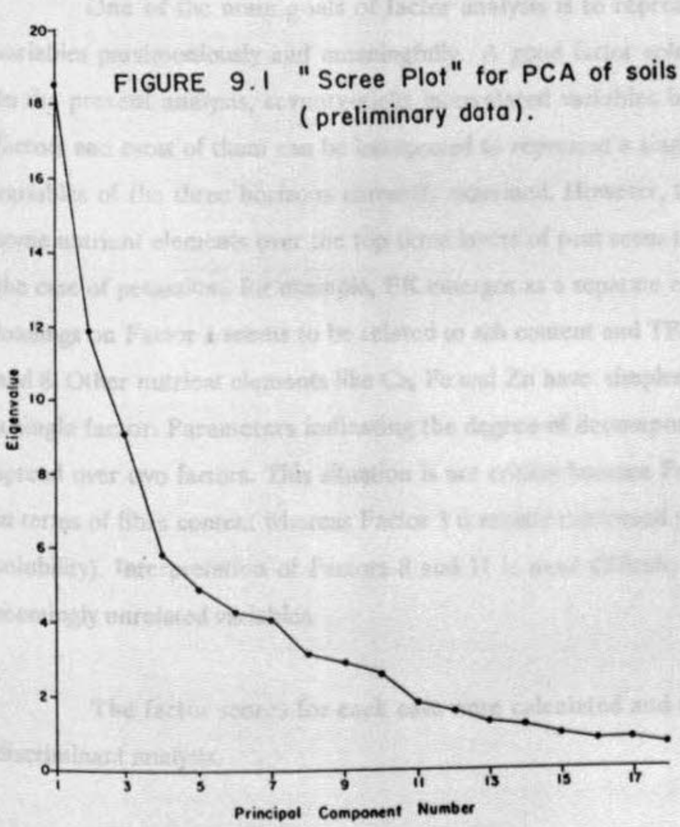


FIGURE 9.1 "Scree Plot" for PCA of soils variables (preliminary data).

Table 9.2 presents the results of the **varimax** rotated solution. Only those variables with large loadings on the components are shown. Factor 1, accounting for 24% of the variance, has very high loadings on LI (negative), TK and TP. Since LI is the inverse of ash content, Factor 1 can perhaps be regarded as an "ash-TK-TP" factor. This also shows that ash content, TK and TP have a high degree of intercorrelation. Factor 2 represents the status of "TFe-TCu-subsoil Mg". Factor 3 has high loadings on PCI and PSI (negative) which are measures of the degree of decomposition (see Section 7.3). Since high values of PCI and low values of PSI mean lower degree of decomposition, Factor 3 therefore indicates the "degree of rawness" of the peat materials. Similarly, Factors 4-11 can be termed as "Ca status", "EK", "subsoil (15-60 cm) N status", "subsurface (15-30 cm) Mg status", "surface (0-15 cm) N status", "fibre content", "TZn status" and "CEC-TMn" respectively.

One of the main goals of factor analysis is to represent real relationships among sets of variables parsimoniously and meaningfully. A good factor solution is both simple and interpretable. In the present analysis, seventy-eight interrelated variables have been simplified to 11 orthogonal factors and most of them can be interpreted to represent a single variable or a small group of related variables of the three horizons currently examined. However, the underlying patterns of variation of some nutrient elements over the top three layers of peat seem to be more complicated than others. In the case of potassium, for example, EK emerges as a separate component by itself while TK with high loadings on Factor 1 seems to be related to ash content and TP. Total N is also spread over Factors 6 and 8. Other nutrient elements like Ca, Fe and Zn have simpler structures, each with high loadings on a single factor. Parameters indicating the degree of decomposition (PCI, PSI, FBR, and FAR) are spread over two factors. This situation is not critical because Factor 9 describes the physical measure in terms of fibre content whereas Factor 3 is mainly concerned with the chemical tests (pyrophosphate solubility). Interpretation of Factors 8 and 11 is most difficult; they appear to have high loadings on seemingly unrelated variables.

The factor scores for each case were calculated and added to the data file for subsequent discriminant analysis.

Table 9.2 VARIMAX ROTATED FACTOR MATRIX

Factor 1 (24.2%)*		Factor 2 (15.4%)		Factor 3 (11.8%)	
BLI	-0.940	CTFe	0.953	APCI	0.804
CLI	-0.921	ATFe	0.842	BPCI	0.918
ALI	-0.661	BTFE	0.824	CPCI	0.640
CTK	0.956	CTMn	0.953	APSI	-0.921
BTK	0.807	CTMg	0.870	BPSI	-0.863
BTP	0.666	CEMg	0.863	CPSI	-0.671
CTP	0.573	BTCu	0.603	AFBR	0.646
ATP	0.512	ATCu	0.572		
BPD	0.883	CPH	0.801		
CTNa	0.859				
CBD	0.833				

Factor 4 (7.5%)		Factor 5 (6.4%)		Factor 6 (5.5%)	
ATCa	0.946	AEK	0.870	BN	0.739
BTCa	0.874	BEK	0.755	CN	0.699
CTCa	0.845	CEK	0.909	BAP	0.724
AECa	0.883	ATK	0.743	ABD	-0.625
BECa	0.835				
CECa	0.762				

Factor 7 (5.3%)		Factor 8 (4.0%)		Factor 9 (3.8%)	
BTMg	0.883	AN	0.848	BFBR	0.755
BEMg	0.551	CAP	-0.705	CFBR	0.768
CCEC	0.766	AENa	0.600	BFAR	0.625
				CFAR	0.510

Factor 10 (3.4%)		Factor 11 (2.3%)	
ATZn	0.863	ACEC	-0.759
BTZn	0.778	BTMn	0.689
CTZn	0.721	CTCu	0.595

* *The percentages in brackets denote variance explained.*

9.2.2. Discriminant Analysis

Discriminant analysis techniques can be employed to distinguish among several mutually exclusive groups on the basis of a set of variables not originally used in deciding group membership. The data used in computing the discriminant functions are the variables of cases whose group memberships are known. The techniques can also be used to identify which variables are important for separating the groups and to predict group membership for new, undetermined cases. The underlying concept of discriminant analysis is that linear mathematical combinations of the independent or predictor variables can be formed and used as a basis for classifying cases into one of the groups.

As in most statistical techniques, certain assumptions about the data must be fulfilled for the linear discriminant functions to be optimal. These include:

(a). The cases in each group are randomly chosen;

(b). The probability of an unknown case belonging to any of the groups is equal;

(c). Variables within each group are from a multivariate normal distribution;

(d). The variance-covariance matrices of the groups are equal and homogeneous; and

(e). None of the cases used to calculate the function have been misclassified.

Some of these conditions may be difficult to fulfill. Fortunately, discriminant analysis is not very sensitive to slight departures from normality or by limited inequality of variances (Davis, 1973). If the assumption of equal abundance is violated, *a priori* assessment of the relative abundance of the groups can be made and prior probability of a case belonging to a group may be entered into the model.

Since one of the main objectives of the preliminary data analysis was to explore the usefulness of applying these multivariate statistical techniques to the types of data collected, little attention was paid at this stage to various tests for possible violation of the assumptions mentioned above. In the final data analyses, the data were examined more critically.

In all the discriminant analyses performed in this study, a stepwise selection of variables on the basis of minimizing Wilks' lambda (or U statistic) was used. Wilks' lambda of a variable is the ratio of the within-group sum of squares to the total sum of squares. It is a measure of the differences between group means: large values of lambda indicate that group means do not appear to be different, while small values suggest that group means are probably different. The significance of the change in Wilks' lambda when a variable is entered or removed from the model can be based on F statistics. When two or more variables are in the model, the Wilks' lambda is calculated jointly and its F-test is a multivariate significance test for group differences. Either the actual value of F or its significance level can be used as the criterion for variable entry or removal. In the present analysis, the latter was used and set at 5% probability of F-to-enter and F-to-remove; such specifications are available in SPSS DISCRIMINANT programme (Nie *et al.*,1975).

Forest types were used as the grouping variable. In the preliminary data analysis, there were only five groups (PC 1-5) with 20 valid cases; one (R5/T6) was out of range because the forest type was intermediate between PC 1 of PSF and riparian forest. For exactly the same reason, another case (R1/T6) should have also been omitted but was overlooked at that time; it was discarded in the final analyses. Prior probability was specified; this was estimated from the observed proportion of the cases in each group. The significance level of the discriminant functions derived was tested; only those with a significance level of 5% or less were retained.

One of the first discriminant analyses was performed using the 11 factor scores derived from factor analysis discussed above (Section 9.2.1). Only one significant discriminant function was derived. It accounts for about 97% of the variance. Seven of the 11 factors were significant enough to be entered into the function. Their standardized canonical discriminant function coefficients are:

Variable entered	Coefficient
Factor 1 (Ash-TK-TP)	1.88
Factor 2 (TFe-TCu-subsoil Mg)	2.45
Factor 3 (Degree of rawness)	-3.56
Factor 4 (Ca status)	2.43
Factor 7 (Subsurface Mg status)	1.17
Factor 8 (Surface N status)	1.51
Factor 11 (CEC(-ve)-TMn)	1.61

The group centroids along the single discriminant function for PC 1 to PC 5 are 6.64, 3.42, -3.70, -7.86 and -10.41 respectively. An impression of the relative effect of each variable on the discriminant function may be obtained from the standardized discriminant coefficient (Nie *et al.*, 1975; Afifi and Clark, 1984). By looking at the variables which have coefficients of different signs, one can determine which variable values will result in large or small function values. In this analysis, the group centroids and the signs of the coefficients show that from PC 1 through to PC 5, the organic soils become less decomposed, and ash content and nutrient concentrations including TK, TP, Ca, Mg, surface N and trace elements like Fe, Mn and Cu decrease. The magnitudes of the coefficients suggest that Factors 2, 3 and 4 have a larger influence on the final value of the function and hence the classification.

Comparisons between pairs of groups using F statistics indicate that there are no significant differences (at $P < 0.05$) between PC 3 and 4, and between PC 4 and 5. However, the classification result shows that all the 20 cases are correctly classified, i.e. the predicted grouping according to the extracted discriminant function based on the soil properties agrees with the original PC classification.

Many other discriminant analyses were tried out using different combinations of soil and groundwater variables (see Table 9.1) directly. The following combinations were explored:

(a) Soil variables of the first horizon only;

(b) Soil variables of the first two horizons;

(c) Soil variables of the first three horizons;

(d) Those which were averages of the first two horizons;

(e) Those which were weighted (by depths of sampling) averages of the first three horizons; and

(f) Those found to be significant from exercise (c) plus those of groundwater and/or those of deeper horizons.

Discriminant analysis using the soil variables from the first three horizons gave the solution with the clearest group separation, the highest variance explained by the functions and the most accurate classification of various cases.

For this solution, the stepwise procedure for the selection of variables stopped at step 3. Three variables were entered, and only one significant linear discriminant function was extracted, accounting for nearly 98% of the total variance. F-statistics of comparisons between pairs of groups show that all of them except PC 1 and 2, and PC 4 and 5 are significantly different at $P<0.05$. Classification result shows that apart from those cases with PC 2, all the other group memberships predicted by the discriminant function agree with the original PC classification. This can also be seen in the stacked histogram for PC 1 to PC 5 on the basis of the single discriminant function (Fig. 9.2). The variables (in the order at which they were entered into the solution), the standardized coefficients, and the group centroids are given in Table 9.3. Looking at the group centroids and the coefficients, it can be seen that the function is essentially describing EMg and the degree of decomposition of the second horizon. From PC 1 to 5, there is a decrease in EMg and the surface soil becomes less decomposed.

FIG. 9.2 Stacked histogram of preliminary discriminant analysis using soil variables of the first three horizons.

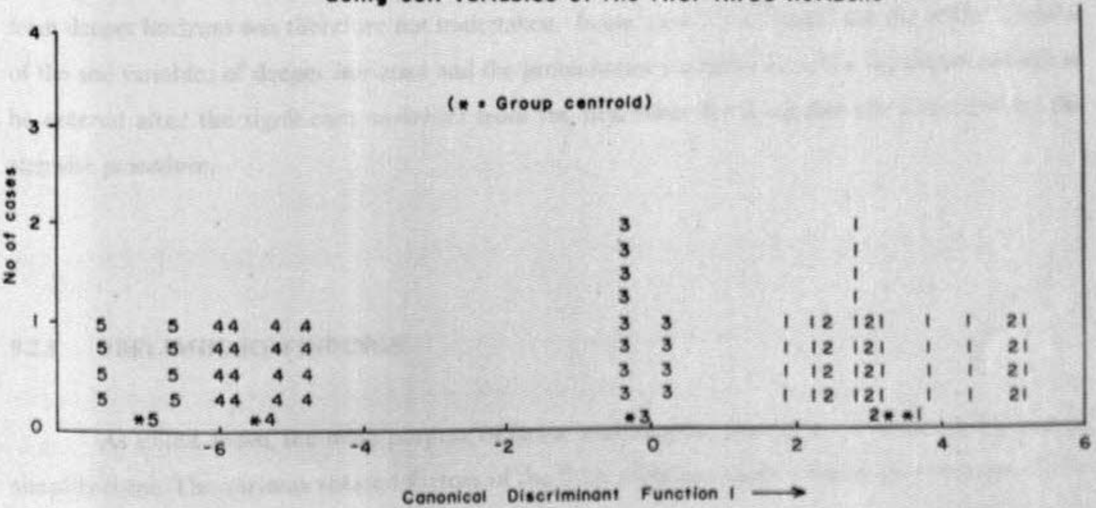


Table 9.3 Coefficients of Discriminant Functions and Group Centroids

Function 1		Group Centroid	
Variable	Coefficient	Group	Value
BPSI	1.873	1	3.48
BEMg	1.081	2	3.28
BFAR	-0.808	3	-0.22
		4	-5.46
		5	-7.10

Although it is not the intention of these preliminary analyses to produce detailed ecological interpretations, it is interesting to note that magnesium turns out to be an important nutrient element in discriminating amongst the forest types in a peat swamp environment. Baillie (1978) also found that magnesium, besides phosphorus, is particularly important in determining the distribution of species in the MDF of Sarawak.

When the variables of deeper horizons were included, it was necessary to exclude some of the cases with shallower peats because of missing data. If the variables from the 6th horizon (150-200 cm depth) were included, only 17 cases were valid; further experimentation with the inclusion of variables from deeper horizons was therefore not undertaken. In any case, it was found that the Wilks' lambdas of the soil variables of deeper horizons and the groundwater variables were not significant enough to be entered after the significant variables from the first three horizons had been selected by the stepwise procedure.

9.2.3 PRELIMINARY FINDINGS

As stated above, the main purpose of factor analyzing the present set of soil variables was to simplify them. The varimax rotated factors of the PCA solutions explain the largest amount of the variance and have the simplest structure. Seventy-eight interrelated soil variables were simplified to 11 orthogonal factors. Together they account for about 90% of the total variance. Most of the factors extracted can also be interpreted to represent a single variable or a small group of related variables of the three horizons currently examined.

The results of the discriminant analyses using either the factor scores or the soil variables are also acceptable. The discriminant functions derived were able to explain most of the variance and separate the various groups. The classification results also show satisfactory agreement between the predicted group memberships and the original PC classification.

Both of these multivariate statistical methods have therefore been shown to perform effectively with the preliminary set of data. Hence, it was decided to apply the same techniques to analyze the final set of data. However, many of the soil variables were either redundant because of very high degree of intercorrelations, or they were insignificant as predictor variables. As a result, the second phase of field work was simplified so that more cases could be sampled. Some of the soil variables such as pH(KCl) and pH ($CaCl_2$) were excluded. Groundwater sampling and the taking of soil samples beyond 150 cm depth (see section 5.3.1) were also terminated. It is perhaps not very surprising that soil variables from very deep horizons do not contribute significantly to the separation of various forest types. Since the rooting depths of the trees in the PSF is relatively shallow (Anderson, 1964b), the soil properties of the deeper layers are therefore not directly associated with the standing vegetation.

9.3 ANALYSES OF FINAL SET OF SOIL DATA

9.3.1 FACTOR ANALYSIS

The primary objective of factor analyzing the final set of soil data was to simplify and summarize the large number of interrelated soil variables. No particular assumption about the underlying structure of the variables was made. The best linear combinations of the original variables which would account for the greatest amount of variance possible were to be obtained. Therefore, it was decided right from the beginning that the initial factor extraction would be done by the PCA approach. This decision was also supported by the preliminary findings (see Sections 9.2.1 and 9.2.3). However, principal axis factoring was also done for comparison purposes after the number of significant factors had been identified by PCA. The new variables in the form of factor scores were intended to be used in later analyses.

Twenty-four laboratory-determined soil properties in the final set of data were used for factor analysis. Another four calculated variables, namely total bases, base saturation, C:N ratio and ash content (see Table 9.1) were omitted because they are linearly dependent on the original variables. The soil variables, except bulk density (data of which were available for the first three layers only), were repeated over five peat layers. As a result, there were 118 valid soil variables per case to be considered initially for factor analysis. These variables were tested for normality and most of them were found to have near normal distributions (see Section 9.3.2) .

The first attempt to factor analyze this final 58x118 data matrix failed. Iterations stopped after a few steps and no solution was possible. This is not surprising because many of the variables, particularly those of the same determination but different horizons, are highly correlated. Furthermore, there were many more variables than cases. The resulting correlation matrix was therefore ill-conditioned for factor processing.

The logical thing to do next was to trim the number of variables by inspecting the correlation matrix and omitting highly correlated variables. After a few trials, it was apparent that the number of variables to be excluded could be quite substantial. It was therefore decided to reduce the size of the data matrix first by treating the data of each horizon separately or in some combination.

The third attempt was to separately analyze the soil variables in two groups. The top A and B layers were grouped together as "surface soil", resulting in a 58x48 data matrix. The C,D and E layers were analysed in a 58x70 "subsoil" data matrix. For the variables of the "surface soil", high correlations among some of them were still encountered but the smaller data matrix was easier to handle and reasonable solutions were obtained after some highly correlated variables were omitted. On the other hand, factor analysis of the "subsoil" variables was not so successful. Inspection of the correlation matrix showed that many of the variables were very highly correlated with coefficients up to 0.969. Many trial runs were performed sequentially, each time omitting a few of the most highly correlated variables. The ill-conditioned correlation matrix still persisted when 38 out of the 70 valid variables were excluded. It was therefore decided to drop this approach, and try to factor analyze the soil variables horizon by horizon.

When the soil variables of each sampling depth were handled separately, the data matrices were smaller (see Table 9.4, "Remarks" column), and they were much easier to manage because the expected high correlations of the same determination between adjacent layers were removed. The results are summarized in Table 9.4. High correlations between some of the variables still presented some problems (especially D horizon), but this problem was quickly resolved by removing a few of the highly correlated variables. The number of components to be retained was decided by looking at the scree plot and the amount of variance explained by each successive component (see Section 9.2.1). Six factors each were extracted from Horizons A, C and E, seven from Horizon B and five from Horizon D. The total amount of variance accounted for varies from 73.6 to 78.0%.

TABLE 9.4 SUMMARIZED RESULTS OF FACTOR ANALYSIS OF SOIL VARIABLES

Horizon	No. of Factors	Variance Explained	VARIMAX Rotated Factors and Associated Variables with High Loadings	Remarks
A (0-15 cm)	6	75.2%	Factor 1: FBR, FAR, PCI, PSI, ENA, PD, N, CEC Factor 2: TMN, TCA, EK, TK, TP Factor 3: TCU, TFE, LI Factor 4: TMG, EMG, AP, PH Factor 5: TZN Factor 6: OC	ECA omitted because of high correlation with TCA(0.82); BD omitted due to low Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (Norusis, 1986).
B (15-30 cm)	7	78.0%	Factor 1: LI,TFE,TCU,PD Factor 2: TCA,ECA,TMN Factor 3: TK, EK, TP Factor 4: FAR, FBR, ENA, PCI Factor 5: TMG, EMG, AP Factor 6: N, PSI, PH, OC Factor 7: TZN, CEC	Not necessary to exclude any variable.
C (30-60 cm)	6	73.6%	Factor 1: TP, AP, EK, TK, ENA Factor 2: TMN, TFE, PH, LI Factor 3: PD, OC, TCA, PSI, TCU Factor 4: EMG, TMG, N Factor 5: FAR, FBR, TZN Factor 6: BD, CEC	PCI and ECA omitted; high correlation with PSI(-0.83) and TCA(0.78) respectively.
D (60-100 cm)	5	73.9%	Factor 1: LI, TK, PD, OC Factor 2: EK, FAR, FBR, ENA, CEC, TZN Factor 3: TCA, ECA, PCI Factor 4: N, AP, EMG Factor 5: TFE,TCU,TP	PSI, PH, TMG and TMN had to be omitted due to high correlations with other variables. BD excluded because of missing values.
E (100-150 cm)	6	75.8%	Factor 1: TMG, EMG, TMN, PH, TFE, ENA Factor 2: PD, TP, TK, OC, TCU Factor 3: PSI, PCI, N Factor 4: TCA, ECA Factor 5: CEC, EK, FAR, AP Factor 6: TZN	LI highly correlated with TK(-0.98) TFE(-0.84) and PD(-0.77); and FBR with FAR(0.74). LI and FBR were therefore omitted. BD excluded because of missing values.

** The figures in brackets under "Remarks" column are the correlation coefficients.*

After the extraction of factors through PCA approach, all of the factors were rotated by varimax and oblique methods. This was done not so much as to explore the underlying patterns of variations but more to simplify the structure of the factors so that each factor could be associated with a few of the original, interrelated variables. The factor matrices of varimax and oblique rotated solutions were almost identical; only those of the former are therefore reported here. These are shown in column 4 of Table 9.4. The factor matrices of the five sampling depths are not identical but they are not too dissimilar. For bases like calcium, magnesium and potassium, the exchangeable fractions and the total contents tend to stay together in the same factor. Total N seems to be most closely related to PSI which is a chemical measure of the degree of decomposition. Ash content (complement of LI) is usually associated with TFe, TCu and TK. LI and OC, which are supposed to measure very similar characteristic, do not come under the same factor in most horizons. Similarly, FBR, FAR, PCI and PSI which are all measures of the degree of decomposition do not have high loadings on the same factor except in Horizon A. FBR and FAR, however, tend to stay together.

After the number of components of PCA had been decided, factorization using the principal factor (or axis) analysis was also tried out. As expected, the total amount of variance explained decreased. The extracted factors were subject to varimax and oblique rotations. Oblique rotation did not produce better results, and the factor matrices of the varimax rotated factors were very similar to those produced by the varimax rotation of the principal components. The final decision was therefore to retain the factor scores for all the factors extracted separately for each horizon by the PCA approach, and these 30 "new variables", summarizing about 75% of the original variance, are used for discriminant analysis (see Section 9.3.2).

As the main aim of this exercise was to try to reduce the data set, no further attempts were made to interpret the factors and to scrutinize the underlying patterns of variations. However, since similar variables of adjacent horizons are correlated, some of the factors extracted for different horizons are expected to be correlated to a certain extent. Such correlations are shown in the correlation matrix of the factor scores in Table 9.5. FSA3 with high loadings on LI, Fe and Cu of the A horizon, for example, seems to have a high correlation coefficient (0.76) with FSB1 which is loaded on the same parameters of B horizon. The factor scores (FS) are named from FSA1 to FSE6; the third letter indicates the horizon and the number at the end, the factor number.

TABLE 9.5 CORRELATION MATRIX OF FACTOR SCORES.

	FSA 1	FSA 2	FSA 3	FSA 4	FSA 5	FSA 6	FSB1	FSB2	FSB3	FSB4	FSB5	FSB6
FSB1	-.23725	.04914	.76172	-.00424	.09687	-.16325	1.00000					
FSB2	-.34642	.54942	.03114	-.16082	.43078	-.02047	-.00000	1.00000				
FSB3	.48361	.32673	.12483	.09102	.04523	-.05004	.00000	-.00000	1.00000			
FSB4	.54954	-.16371	.10848	-.11510	.27847	.02011	-.00000	.00000	-.00000	1.00000		
FSB5	-.04031	.04118	-.12002	.72493	.00347	-.01552	.00000	-.00000	.00000	-.00000	1.00000	
FSB6	.13549	.31703	-.14406	-.36052	-.11162	.25073	.00000	-.00000	-.00000	-.00000	-.00000	1.00000
FSB7	-.18786	-.16374	.22071	-.05952	-.41786	.04371	-.00000	.00000	-.00000	.00000	-.00000	-.00000
FSC1	.38470	.29005	.06374	.23633	-.00958	.06560	-.05188	-.03823	.67703	.05644	.21793	.13343
FSC2	-.02875	.24684	.58046	-.32607	-.11186	.09902	.65134	.03188	-.04093	.04390	-.17595	.43852
FSC3	.36707	-.21998	-.26218	.04476	-.47296	.31552	-.34690	-.59268	.02951	.00195	.11314	.31694
FSC4	-.06420	-.08403	.21853	.62658	.11318	-.21772	.40938	-.20076	.02664	-.06644	.56440	-.36353
FSC5	.46605	-.01874	-.07603	-.04545	.31537	-.05235	-.01525	-.03110	.24992	.42641	.12608	.00596
FSC6	.08011	.51028	-.33378	-.11030	.31916	-.06345	-.22631	.40095	.05851	.01256	-.03037	.21932
FSD1	.04726	.03790	-.14839	-.11050	.05053	.12360	-.07479	.02805	.03358	.18681	.15225	.27292
FSD2	.65962	.24299	-.02675	-.01292	.27697	-.22898	-.06061	.10527	.56025	.41384	.11894	.04336
FSD3	.35845	-.55159	-.02507	.40228	-.32474	.12466	-.17439	-.69212	.15017	.14224	.24140	-.26209
FSD4	.15586	.07671	-.20173	-.38244	-.40800	.28249	-.27221	-.13685	.11143	-.23231	-.23621	.50430
FSD5	.00707	-.03737	.76286	.01914	-.04539	.05521	.78796	-.14998	.07782	.04341	.01457	.09111
FSE1	.01986	.03736	.67774	.29105	.10569	-.03947	.71032	-.07732	.02615	.21222	.29579	-.07014
FSE2	-.06685	-.01727	.30871	-.23291	-.08962	-.08317	.33142	-.04453	-.05648	-.19042	-.40270	.03286
FSE3	.32469	.09562	.06894	-.14742	-.25454	.34127	-.07312	-.07709	.05436	.17819	.06761	.53036
FSE4	-.27288	.34511	.13241	-.41730	.21031	-.11447	.32690	.48723	-.09707	-.05877	-.10996	.35522
FSE5	.51151	.11026	-.08830	-.06048	.28808	-.19654	-.04816	.01634	.30483	.52137	-.09199	-.00193
FSE6	-.22848	-.21618	.05924	.14324	-.29183	-.02109	.06015	-.20422	-.20796	-.09890	.10158	-.08980

	FSB7	FSC1	FSC2	FSC3	FSC4	FSC5	FSC6	FSD1	FSD2	FSD3	FSD4	FSD5
FSB7	1.00000											
FSC1	.05560	1.00000										
FSC2	.13358	.00000	1.00000									
FSC3	.08901	-.00000	-.00000	1.00000								
FSC4	-.26930	-.00000	.00000	.00000	1.00000							
FSC5	-.37433	-.00000	.00000	-.00000	.00000	1.00000						
FSC6	-.47657	-.00000	-.00000	-.00000	-.00000	-.00000	1.00000					
FSD1	.17044	.04297	.16091	.13018	-.04525	.17155	.00292	1.00000				
FSD2	-.32325	.43633	.01061	.03122	.04335	.68708	.28686	.00000	1.00000			
FSD3	.22854	.09057	-.28792	.53224	.24704	.14660	-.51297	-.00000	.00000	1.00000		
FSD4	.18833	.28329	.15212	.38001	-.56370	-.08093	-.03810	-.00000	-.00000	.00000	1.00000	
FSD5	.13499	.13236	.75159	-.08914	.35186	-.08120	-.24678	.00000	.00000	-.00000	-.00000	1.00000
FSE1	.00306	.04260	.57832	-.14206	.61766	.00197	-.15225	.06198	.02494	.06955	-.49898	.76643
FSE2	-.00942	-.02849	.30541	-.08053	-.14720	-.25987	.05050	-.68138	-.05955	-.15037	.30756	.35143
FSE3	.21376	.12455	.30606	.38211	-.27530	.18218	-.12140	.27357	.12473	.25580	.48207	.11793
FSE4	-.13928	-.17108	.33027	-.37531	-.14601	.10468	.18082	.21071	.03751	-.70556	.09912	.17367
FSE5	-.35587	.10765	-.13266	-.00837	-.04693	.46574	.35722	-.03931	.59618	-.00889	-.21001	-.16251
FSE6	.23691	-.28389	-.10356	.20751	.10596	-.24496	-.14503	-.14696	-.36271	.20494	-.05475	-.06126

Correlations between FSA 1 and FSA 6, and FSE1 and FSE6 are not shown; these factors are orthogonal to each other.

9.3.2 Discriminant Analysis

Common applications of discriminant analysis have been mentioned in general terms in Section 9.2.2. In this study, discriminant analysis techniques are mainly used to see whether the six phasic communities (PC) of the PSF can be mutually distinguished from each other on the basis of soil properties, and if so, which soil variables are important for separating the groups.

Screening of Data

Out of the 58 cases, eight of them were originally sampled to be utilized as "test cases". These "test cases" were not included in the derivation of the discriminant functions but they were classified as a test for the robustness of the functions. Due to the limited number of cases, it was very tempting to include these eight "test cases" and use the "jack-knife" procedure to test the classification result of every case. However, "jack-knife" procedure is not available under the SPSS DISCRIMINANT programme, and so this technique was not applied.

As previously indicated, linear discriminant analysis works best if the variables in each group have multivariate normal distributions. There is a variety of tests for multivariate normality (Andrews *et al.*, 1973). However, such tests have not been included in the softwares available. It was therefore decided to examine the distributions of each variable within each group individually. It must be pointed out that this alternative is not wholly satisfactory because even if all the variables are, by themselves, normally distributed, the joint distribution is not necessarily multivariate normal. However, there is more reason to suspect that the multivariate normality assumption is violated if any of the variables have markedly non-normal distributions. Fortunately, the discriminant functions are not seriously affected by slight departure from multivariate normality (Davis, 1973).

Individual soil variables and the factor scores obtained from Section 9.3.1 were tested for normality using the EXAMINE procedure available under the SPSS package (SPSS/PC+ Version 3.0 Updated Manual). The "stem-and-leaf" plots, and the normal probability and detrended normal plots were examined to test the normality of the data. Lilliefors statistical test of normality was also computed. The Lilliefors test is based on a modification of the Kolmogorov-Smirnov test for the situation when means and variance are not known but must be estimated from the data. For sample sizes smaller than 50, SPSS EXAMINE procedure also performs the Shapiro-Wilks test which has been found to have good power in many situations when compared to other tests of normality (Conover, 1980).

An example of the computer printouts is shown in Figure 9.3. The results of these tests show that although some variables are not normally distributed, the departures from normality are not too serious. Out of the 708 cases (118 variables x 6 groups) tested for normality, only 20% of them showed departures from normality at 5% significance level. No data transformation was deemed necessary and the original data were used with a fair degree of confidence that the data as a whole were approximately normally distributed. It is probably impossible to find, in real life situation, data with perfect normal distribution. For most statistical tests, it is sufficient that the distributions of the data are approximately normal.

Another condition which optimizes the performance of linear discriminant analysis is the equality of the covariance matrices for all groups. Like the test of normality, however, it was decided to look at the univariate statistics first before the discriminant analysis was run. The EXAMINE procedure includes the option of the Levene test of equality of variance. This test is less dependent on the assumption of normality than most of the other tests. It is obtained by computing for each cell the absolute difference from its cell mean and then performing a one-way analysis of variance on these differences (SPSS/PC+ V3.0 Update Manual). Where variances are not equal, a power transformation of the original variables is frequently used to stabilize variances. The appropriate transformation can be obtained by requesting the "spread-and-level" plot under the EXAMINE procedure. There were 118 soil variables and 30 factor scores tested for equality of variance and only 16 of them (11%) showed inequality at 0.1% significance level. Transformations (mainly logarithms or reciprocals) were done on all those variables with unequal variances among the groups, but trial runs of discriminant analysis using these transformed variables together with others which did not require transformation showed that none of the transformed variables were significant enough to be entered into the discriminant functions. Subsequently, discriminant analyses were done using the original set of data without any transformation.

There are several ways to test the homogeneity of covariance matrices. Under SPSS, Box's M

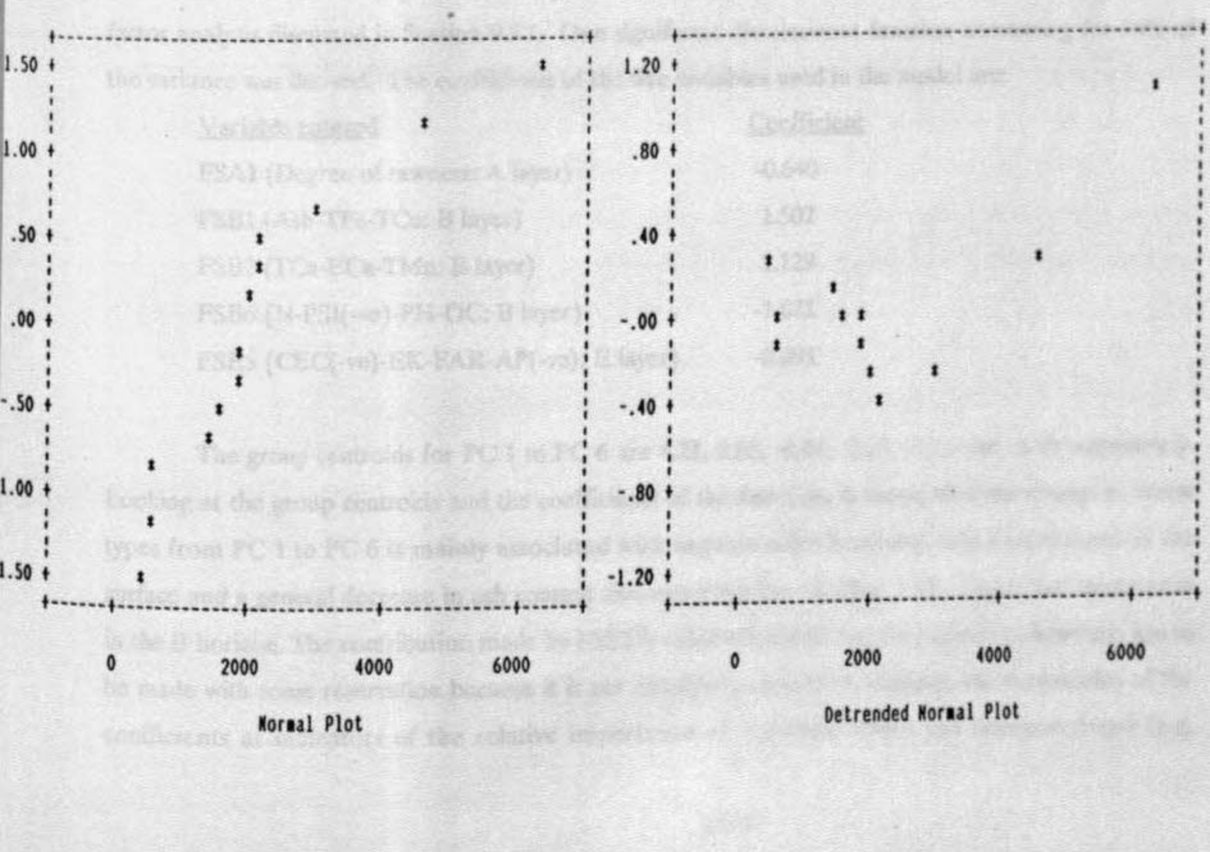
Figure 9.3 AN EXAMPLE OF THE PRINTOUTS FOR TESTS OF NORMALITY (BFe for Group 1)

BFE
By FT 1 MIXED PSF

	Statistic	df	Significance
Shapiro-Wilks	.8775	14	.0583
K-S (Lilliefors)	.2223	14	.0592

Frequency	Stem &	Leaf
3.00	0 .	466
4.00	1 .	5689
3.00	2 .	012
2.00	3 .	11
1.00	4 .	5
1.00 Extremes		(6321)

Stem width: 1000
Each leaf: 1 case(s)



test can be requested under DISCRIMINANT and MANOVA procedures (Norusis, 1986). If the covariance matrices are not too dissimilar, the linear discriminant analysis performs reasonably well, especially if the sample sizes are small (Wahl and Kronmal, 1977). In the present study, however, Box's M test could not be carried out satisfactorily because there were too few cases in most groups (particularly Group 5 with only 5 cases of PC 5) for the matrices to be non-singular. As a result, discriminant analyses had to proceed on the assumption that the covariance matrices were reasonably homogeneous since most of the individual variables had equal variances.

As in the preliminary analyses, a stepwise selection of variables on the basis of minimizing Wilks' lambda was used here. The significance of the change in Wilks' lambda when a variable is entered or removed from the model is based on F-statistics, and the entry and removal criteria were set at 5% probability (see Section 9.2.2).

Discriminant Analysis Using Factor Scores

Discriminant analysis was first performed using the 30 factor scores derived from the last factor analysis discussed in Section 9.3.1. One significant discriminant function accounting for 94% of the variance was derived. The coefficients of the five variables used in the model are:

Variable entered	Coefficient
FSA1 (Degree of rawness: A layer)	-0.640
FSB1 (Ash-TFe-TCu: B layer)	1.502
FSB2 (TCa-ECa-TMn: B layer)	1.129
FSB6 {N-PSI(-ve)-PH-OC: B layer}	-1.021
FSE5 {CEC(-ve)-EK-FAR-AP(-ve): E layer}	-0.091

The group centroids for PC 1 to PC 6 are 4.21, 2.05, -0.64, -2.27, -3.15 and -3.58 respectively. Looking at the group centroids and the coefficients of the function, it seems that the change in forest types from PC 1 to PC 6 is mainly associated with organic soils becoming less decomposed at the surface and a general decrease in ash content and nutrients like calcium, iron, copper and manganese in the B horizon. The contribution made by FSE5 is relatively small. Such a statement, however, has to be made with some reservation because it is not absolutely correct to interpret the magnitudes of the coefficients as indicators of the relative importance of variables which are intercorrelated (e.g.

Norusis,1986).

Comparisons between pairs of groups using F-statistics show that there are no significant differences at $P<0.05$ between PC 3 and 4, and PC 4 and 5. Classification results (see Fig. 9.4) indicate that out of the 50 "grouped" cases, only 62% of them were classified correctly; the wrongly classified cases came mainly from those of PC 3 and 5. PC 5 in particular has a higher probability of being grouped under PC 4. Out of the eight "test" cases, six were correctly classified; one PC 1 was misclassified as PC 2, and one PC 2 as PC 3.

Discriminant analysis with factor scores does not seem to be very satisfactory in terms of group separation and the percentage of correctly classified cases. Although it reduces the complexity of the problem initially, the use of factors has also masked the final solution in the sense that no particular soil variable can be pinpointed as being the most important discriminator. Further discriminant analyses were therefore undertaken using the soil variables directly.

Discriminant Analysis Using Soil Variables

When all the valid soil variables were used in discriminant analysis, step-wise selection of variables stopped at step 7 when further addition of any of the remaining variables would not cause a significant change in Wilks' lambda (see Section 9.2.2). The variables entered include BPD, BPCI, BTFe, BTCa, CTCU, DN and EEK. Two significant canonical discriminant functions are derived, and together they account for about 97% of the variance. The standardized coefficients of these functions, and the group centroids are given in Table 9.6.

The magnitudes of the standardized discriminant coefficients (Table 9.6) show that BPD, BTCa, BTFe and BPCI have greater effects on Function 1 which accounts for 86% of the variance explained. Function 2, accounting for 11% of the variance, also loads most heavily on BPD. The contributions made by DN, CTCu and EEK, which load more heavily on Function 2, are relatively less important. However, such a statement has to be made with some reservation because these variables are intercorrelated (see Table 9.7). Large values of BPD and small values of BTCA and BTFe will

FIGURE 9.4 STACKED HISTOGRAM AND CLASSIFICATION RESULTS OF DISCRIMINANT ANALYSIS WITH FACTOR SCORES

```
               Canonical Discriminant Function 1
   8 +                                                     +
     I                                                     I
     I                                                     I
     I                                                     I
   6 +             6                                       +
     I             6                                       I
     I             6                                       I
     I             6                                       I
     I             6                                       I
   4 +             65   £     £                            +
     I             65   £     £                            I
     I             556 44£    3£3    2  1                  I
     I             556 44£    3£3    2  1                  I
   2 +           65544£443    3£22   1  111                +
     I           65544£443    3£22   1  111                I
     I       6   644433333 £ 2221221£11111                 I
     I       6   644433333 £ 2221221£11111                 I
      X----+----+----+----+----+----+----+----+----X
    Out -6.0 -4.0 -2.0    .0  2.0  4.0  6.0     Out
 Class    666666666666644443333332222211111111111
 Centroids            65 4   3     2    1
```

Classification Results -

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5	6
Group 1	12	11	1	0	0	0	0
MIXED PSF		91.7%	8.3%	.0%	.0%	.0%	.0%
Group 2	8	1	7	0	0	0	0
ALAN		12.5%	87.5%	.0%	.0%	.0%	.0%
Group 3	9	0	2	4	3	0	0
ALAN BUNGA		.0%	22.2%	44.4%	33.3%	.0%	.0%
Group 4	9	0	0	2	5	0	2
PADANG ALAN		.0%	.0%	22.2%	55.6%	.0%	22.2%
Group 5	5	0	0	0	3	0	2
PC 5		.0%	.0%	.0%	60.0%	.0%	40.0%
Group 6	7	0	0	0	3	0	4
PADANG PAYA		.0%	.0%	.0%	42.9%	.0%	57.1%
Ungrouped Cases	8	1	3	3	1	0	0
		12.5%	37.5%	37.5%	12.5%	.0%	.0%

Percent of "grouped" cases correctly classified: 62.00%

Table 9.6 RESULTS OF DISCRIMINANT ANALYSIS USING SOIL VARIABLES

Canonical Discriminant Functions

Fcn	Eigenvalue	Pct of Variance	Cum Pct	Canonical Corr		After Fcn	Wilks' Lambda	Chisquare	DF	Sig
					:	0	.0134	183.373	35	.0000
1*	15.4903	86.15	86.15	.9692	:	1	.2205	64.255	24	.0000
2*	2.0372	11.33	97.48	.8190	:	2	.6697	17.040	15	.3165
3	.3420	1.90	99.38	.5048	:	3	.8987	4.537	8	.8057
4	.0881	.49	99.87	.2846	:	4	.9780	.947	3	.8140
5	.0225	.13	100.00	.1485	:					

* marks the 2 canonical discriminant functions remaining in the analysis.

Standardized Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
BPD	.84241	.96231
BPCI	.49348	-.51638
BTFe	-.71964	.42103
BTCA	-.77504	-.01307
DN	.43082	-.78991
EEK	.39716	.55219
CTCu	-.13345	.77993

Step	Action Entered	Action Removed	Vars In	Wilks' Lambda	Sig.
1	BPD		1	.18714	.0000
2	BPCI		2	.10272	.0000
3	BTFe		3	.06771	.0000
4	DN		4	.04541	.0000
5	BTCA		5	.03188	.0000
6	EEK		6	.02006	.0000
7	CTCu		7	.01337	.0000

Canonical Discriminant Functions evaluated at Group Means (Group Centroids)

Group	FUNC 1	FUNC 2
1	-5.14316	1.26503
2	-2.71868	-2.74639
3	.64177	.33899
4	2.97787	.49936
5	5.05497	.82570
6	3.65939	-.69755

Table 9.6 (Cont.)

F statistics and significances between pairs of groups after step 7
Each F statistic has 7 and 38.0 degrees of freedom.

Group	1 MIXED PSF	2	3	4	5
2 ALAN	13.060				
	.0000				
3 ALAN BUNGA	22.318	11.333			
	.0000	.0000			
4 PADANG ALAN	42.410	22.679	3.2692		
	.0000	.0000	.0081		
5 PC 5	46.084	28.249	9.3683	2.9506	
	.0000	.0000	.0000	.0143	
6 PADANG PAYA	44.567	21.032	5.3986	1.1308	2.7454
	.0000	.0000	.0002	.3647	.0208

Classification Results -

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5	6
1 MIXED PSF	12	12	0	0	0	0	0
		100.0%	.0%	.0%	.0%	.0%	.0%
2 ALAN	8	0	8	0	0	0	0
		.0%	100.0%	.0%	.0%	.0%	.0%
3 ALAN BUNGA	9	0	0	9	0	0	0
		.0%	.0%	100.0%	.0%	.0%	.0%
4 PADANG ALAN	9	0	0	1	6	2	0
		.0%	.0%	11.1%	66.7%	22.2%	.0%
5 PC 5	5	0	0	0	1	4	0
		.0%	.0%	.0%	20.0%	80.0%	.0%
6 PADANG PAYA	7	0	0	0	0	0	7
		.0%	.0%	.0%	.0%	.0%	100.0%
Ungrouped Cases	8	1	2	4	1	0	0
		12.5%	25.0%	50.0%	12.5%	.0%	.0%

Percent of "grouped" cases correctly classified: 92.00%

Table 9.7. GROUP MEANS, WILKS' LAMBDAS AND CORRELATION MATRIX OF SOME VARIABLES

(a) Group Means

Group(PC)	APD	BPD	BPCI	BTCa	BTFe
1	1.315	1.309	2.5	469	2472
2	1.325	1.298	4.0	397	1081
3	1.358	1.370	4.3	161	819
4	1.372	1.398	5.4	140	465
5	1.401	1.408	6.6	116	211
6	1.398	1.395	6.6	73	232

Group(PC)	BTP	CTCu	DN	EPCI	EEK
1	349	5.0	1.20	5.3	0.13
2	335	2.3	1.52	5.5	0.16
3	243	2.2	1.38	5.2	0.13
4	254	2.0	1.54	5.8	0.17
5	258	1.0	1.53	5.8	0.34
6	268	1.3	1.55	6.6	0.16

(b) Wilks' Lambda (U-statistic) and Univariate F-ratio with 5 and 44 degrees of freedom

Variable	Wilks' Lambda	F	Significance
APD	0.461	10.31	.000
BPD	0.187	38.22	.000
BPCI	0.330	17.89	.000
BTCa	0.761	2.765	.030
BTFe	0.496	8.952	.000
BTP	0.895	1.033	.410
CTCu	0.535	7.649	.000
DN	0.740	3.095	.018
EEK	0.681	4.123	.004
EPCI	0.732	3.227	.014

(c) Correlation Matrix of some variables

	BPD	BPCI	BTFe	BTCa	DN	EEK	CTCu
BPD	1.00						
BPCI	0.59	1.00					
BTFe	-0.43	-0.49	1.00				
BTCa	-0.33	-0.40	0.21	1.00			
DN	0.38	0.22	-0.15	0.04	1.00		
EEK	0.16	0.33	-0.26	0.05	0.15	1.00	
CTCu	-0.50	-0.41	0.41	0.12	-0.35	-0.30	1.00

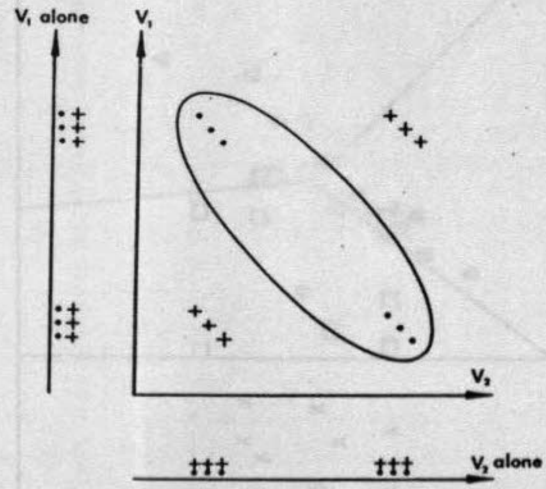
result in large values of Function 1, and similarly, large values of BPD and CTCU and small values of DN will give large value of Function 2. Judging from the location of the group centroids along Function 1, it can be deduced that BPD increases, while BTCA, BTFe, CTCU and the degree of decomposition (as indicated by BPCI) decrease from PC 1 to PC 6. Such variations are also indicated by the changes in the group means of these variables shown in Table 9.7 (also see Section 9.4 for further discussion).

Although the inter-relationships among all the variables were considered during discriminant analysis, it is often helpful to examine the group differences by looking at the univariate statistics. Under the SPSS DISCRIMINANT procedure, various group statistics like means and standard deviations can be printed. Another useful statistic that can be displayed is the Wilks' lambda (or U-Statistic) with its univariate F-ratio. When variables are considered individually, lambda is the ratio of the within-groups sum of squares to the total sum of squares. Table 9.7 shows some of the soil variables which were entered into the discriminant functions derived; most of them have significantly small values of lambda.

Though the univariate statistics can indicate the relative importance of individual variables, it must be stressed that the multivariate relationships are generally more important than the univariate ones. It is often the case that two individual variables are by themselves not very good discriminators, but taken together they may be highly effective (see Fig. 9.5). Variable BTP shown in Table 9.7 is an example; by itself, it is not significant, but in one of the analyses (see below), BTP is a component of the discriminant function with a very significant Wilks' lambda. Such complex multivariate relationships are catered for by discriminant analysis, as long as they are linear.

The F-statistics for comparison between pairs of groups (see Table 9.6) indicate that only the separation between PC 4 and 6 is not significant at 5% level. The scatterplot of the 50 "grouped" cases (Fig. 9.6) also depicts fairly good separation between the groups. Classification results (see Table 9.6) show that 92% of them were classified correctly. Cases of PC 1, 2, 3 and 6 were all correctly allocated. Misclassifications occurred for cases of PC 4 and 5 which seem to be closely related; 22% of PC 4 cases were misclassified as PC 5, and 20% vice versa. Of the eight "test cases", six were correctly classified; one PC 1 was misclassified as PC 2, and one PC 2 as PC 3. Therefore, it appears that the discriminant functions with the soil variables BPD, BPCI, BTCa, BTFe, CTCu, DN and EEK have been quite successful in distinguishing amongst the six PC of PSF.

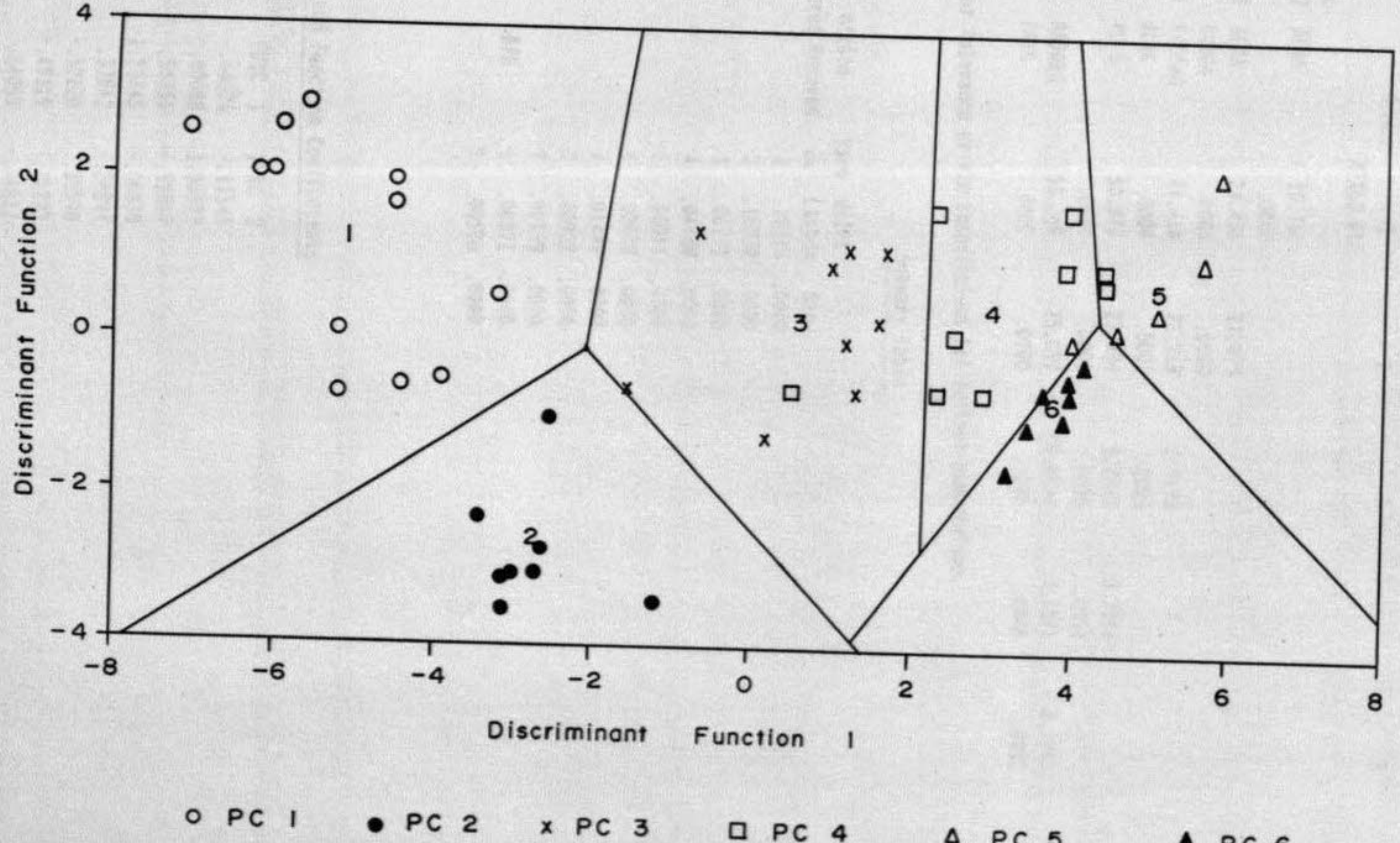
FIGURE 9.5 THE IMPORTANCE OF USING MULTIVARIATE RELATIONSHIPS (Hand, 1981: p.122).



Of the major plant nutrients, only calcium has been selected as an important parameter in separating the forest types. In order to further explore the significance of other major nutrients, it was decided to rerun the analysis after omitting BTCa. The results are shown in Table 9.8. Two significant functions consisting of nine variables and accounting for about 96% of the variance were derived. Omission of BTCa had led to the inclusion of APD, BTP and BAP. Discrimination between pairs of groups has been improved and all pairs are now significantly separated. The territorial map still looks very similar to the one with BTCa in the model. However, the classification results (see Table 9.8) show a slight decrease in the percentage of cases correctly classified, with the misclassified cases associated with PC 3 and 4. Of the eight "test cases", three were wrongly allocated: one PC 1 was misclassified as PC 2, and one each of PC 2 and 3 came under PC 1.

The physical characteristics feature very strongly in these discriminant analyses. Further discriminant analyses were performed after omitting these parameters to see if the chemical properties by themselves could successfully differentiate the various forest types. The results (see

Figure 9.6 Scatterplot of cases along the two significant discriminant functions derived using soil variables.



(The numbers indicate the group centroids)

Table 9.8 RESULTS OF DISCRIMINANT ANALYSIS AFTER OMITTING BTCa

F statistics and significances between pairs of groups after step 11
Each F statistic has 9 and 36.0 degrees of freedom.

Group		1 MIXED PSF	2	3	4	5
2	ALAN	10.766 .0000				
3	ALAN BUNGA	24.436 .0000	11.075 .0000			
4	PADANG ALAN	44.410 .0000	22.268 .0000	2.9693 .0095		
5	PC 5	50.879 .0000	29.984 .0000	9.7832 .0000	3.2814 .0051	
6	PADANG PAYA	53.369 .0000	25.897 .0000	8.4957 .0000	3.3371 .0046	3.2743 .0052

F level or tolerance or VIN insufficient for further computation.

Summary Table

Step	Action Entered	Action Removed	Vars In	Wilks' Lambda	Sig.
1	BPD		1	.18714	.0000
2	BPCI		2	.10272	.0000
3	BTFe		3	.06771	.0000
4	BAP		4	.04488	.0000
5	DN		5	.03011	.0000
6	BPH		6	.02078	.0000
7	EEK		7	.01449	.0000
8	BTP		8	.00922	.0000
9	CTCu		9	.00659	.0000
10		BPH	8	.00871	.0000
11	APD		9	.00586	.0000

Standardized Function Coefficients

	FUNC 1	FUNC 2
APD	.66526	-.11545
BPD	.80088	1.00927
BPCI	.55351	-.52867
BTP	-1.25345	-.06838
BAP	.37942	-.24894
BTFe	-.52220	.35598
CTCu	-.49319	.71222
DN	.84055	-.76817
EEK	.39765	.58260

Table 9.8 (cont.)

Canonical Discriminant Functions evaluated at Group Means (Group Centroids)

Group	FUNC 1	FUNC 2
1	-6.30409	1.18641
2	-3.40441	-2.71815
3	.78283	.49048
4	3.37013	.66312
5	6.19444	1.00440
6	4.93365	-1.12801

Classification Results -

Actual Group		No. of Cases	Predicted Group Membership 1	2	3	4	5	6
Group MIXED PSF	1	12	12 100.0%	0 .0%	0 .0%	0 .0%	0 .0%	0 .0%
Group ALAN	2	8	0 .0%	8 100.0%	0 .0%	0 .0%	0 .0%	0 .0%
Group ALAN BUNGA	3	9	0 .0%	1 11.1%	6 66.7%	2 22.2%	0 .0%	0 .0%
Group PADANG ALAN	4	9	0 .0%	0 .0%	1 11.1%	7 77.8%	1 11.1%	0 .0%
Group PC 5	5	5	0 .0%	0 .0%	0 .0%	0 .0%	5 100.0%	0 .0%
Group PADANG PAYA	6	7	0 .0%	0 .0%	0 .0%	0 .0%	0 .0%	7 100.0%
Ungrouped Cases		8	3 37.5%	2 25.0%	2 25.0%	1 12.5%	0 .0%	0 .0%

Percent of "grouped" cases correctly classified: 90.00%

Table 9.9) are very disappointing, with only half of the cases classified correctly. Comparisons between pairs of groups show that PC 2, 3 and 4, and PC 4 and 5 are not significantly separated. Two significant canonical discriminant functions were derived and they explain nearly 92% of the variance. These functions are described by five variables, namely ATFe, BTCa, BAP, DN and EEK. Looking at the standardized coefficients, Function 1 is dominated by ATFe and BTCa, and Function 2 by BAP. It is interesting to note that TCa and AP both feature strongly after the effects of the physical characteristics are excluded. The group centroids show that Function 1 mainly distinguishes between PC 1 and 2; it also gives a fair separation between other adjacent pairs except PC 5 and 6. The later pair is better separated by Function 2.

Discriminant analyses have so far made use of soil properties expressed on weight basis. In Section 8.3, data of replicated samples from one transect show that edaphic factors in organic soils should best be expressed on volume basis because the bulk densities of the soils are significantly different under different forest types. Therefore, all the nutrient contents were converted to volume basis and the discriminant analysis repeated. In this analysis, only the variables of the first three horizons were used because the bulk density data of the two deeper layers had many missing values. The results are shown in Table 9.10. Variables entered include APD, BPD, BPCI, VATP and VCCu (Letter V indicates variables expressed on volume basis). Two discriminant functions were derived and together they explain about 99% of the total variance. Discriminations between all the groups except PC 5 and 6 are significant at 5% level. The classification results, however, indicate that only 76% of the "grouped" cases were correctly classified. Cases of PC 5, in particular, show a very low percentage of correct classification; most of them were wrongly grouped under PC 6. Of the eight "test" cases, only four were correctly placed into the right groups.

9.4 DISCUSSION AND CONCLUSIONS

The change from the floristically rich, originally high volume forest of PC 1 to the low stature, floristically poor forest of PC 6 has been described and quantified in Section 6.3. Chapter 8 examines the variations of surface edaphic properties, and concludes that the changes in forest types across a peat dome are associated with a general decline in soil fertility, as manifested by the decreasing trends of all soil nutrients, from PC 1 to PC 6.

Table 9.9 RESULTS OF DISCRIMINANT ANALYSIS AFTER OMITTING PHYSICAL PARAMETERS

F statistics and significances between pairs of groups after step 5
Each F statistic has 5 and 40.0 degrees of freedom.

Group	1 MIXED PSF	2	3	4	5
2 ALAN	5.8554				
	.0004				
3 ALAN BUNGA	10.401	1.1254			
	.0000	.3627			
4 PADANG ALAN	15.917	2.1905	.79378		
	.0000	.0744	.5606		
5 PC 5	17.269	5.3903	4.3926	2.4286	
	.0000	.0007	.0028	.0516	
6 PADANG PAYA	18.977	5.1822	4.1302	2.9155	4.2997
	.0000	.0009	.0041	.0246	.0032

Standardized Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
ATFe	.88017	-.05689
BTCA	.85200	.17202
BAP	-.10387	.80414
DN	-.65513	-.03402
EEK	-.28165	-.61840

Group Centroids

Group	FUNC 1	FUNC 2
1	2.84239	.01144
2	.37370	-.03269
3	-.34396	-.06463
4	-1.20197	-.24408
5	-2.10899	-1.39037
6	-1.80572	1.40778

Classification Results -

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5	6
Group 1 MIXED PSF	12	9	3	0	0	0	0
		75.0%	25.0%	.0%	.0%	.0%	.0%
Group 2 ALAN	8	1	3	4	0	0	0
		12.5%	37.5%	50.0%	.0%	.0%	.0%
Group 3 ALAN BUNGA	9	0	2	5	2	0	0
		.0%	22.2%	55.6%	22.2%	.0%	.0%
Group 4 PADANG ALAN	9	0	0	3	3	0	3
		.0%	.0%	33.3%	33.3%	.0%	33.3%
Group 5 PC 5	5	0	0	0	4	1	0
		.0%	.0%	.0%	80.0%	20.0%	.0%
Group 6 PADANG PAYA	7	0	0	0	3	0	4
		.0%	.0%	.0%	42.9%	.0%	57.1%
Ungrouped Cases	8	1	3	2	2	0	0
		12.5%	37.5%	25.0%	25.0%	.0%	.0%

Percent of "grouped" cases correctly classified: 50.00%

Table 9.10 RESULTS OF DISCRIMINANT ANALYSIS WITH NUTRIENT CONTENTS EXPRESSED ON VOLUME BASIS

Canonical Discriminant Functions

Function	Eigenvalue	Percent of Variance	Cumulative Percent	Canonical Correlation	:	After Function	Wilks' Lambda	Chi-squared	D.F.
					:	0	.0290356	153.96 ***	25
1*	14.35488	93.08	93.08	.9668889	:	1	.4458387	35.139 **	16
2*	.88433	5.73	98.82	.6850601	:	2	.8401070	7.5788	9
3	.12335	.80	99.62	.3313639	:	3	.9437305	2.5193	4
4	.03452	.22	99.84	.1826812	:	4	.9763124	1.0428	1
5	.02426	.16	100.00	.1539077	:				

* marks the 2 canonical discriminant functions remaining in the analysis.

Summary Table

Step	Action Entered	Action Removed	Vars In	Wilks' Lambda	Sig.
1	BPD		1	.18446	.0000
2	BPCI		2	.10078	.0000
3	VBFE		3	.06759	.0000
4	APD		4	.05011	.0000
5	VATP		5	.03430	.0000
6		VBFE	4	.04407	.0000
7	VCCU		5	.02904	.0000

Standardized Canonical Discriminant Function Coefficients

	FUNC 1	FUNC 2
APD	.78222	-.19783
BPD	.63473	.84364
BPCI	.57008	-.44965
VATP	-.74249	.34128
VCCU	-.31503	.79349

Canonical Discriminant Functions evaluated at Group Means (Group Centroids)

Group	FUNC 1	FUNC 2
1	-4.73491	.77670
2	-2.99271	-1.80207
3	.66030	.31624
4	2.43442	.62744
5	4.62464	-.10020
6	4.25499	-.41372

Table 9.10 (cont.)

F statistics and significances between pairs of groups after step 7
Each F statistic has 5 and 40.0 degrees of freedom.

Group	1 MIXED PSF	2	3	4	5
2 ALAN	8.5890 .0000				
3 ALAN BUNGA	27.826 .0000	13.862 .0000			
4 PADANG ALAN	48.419 .0000	27.279 .0000	2.9217 .0243		
5 PC 5	56.835 .0000	34.185 .0000	9.5085 .0000	3.3445 .0129	
6 PADANG PAYA	66.260 .0000	37.403 .0000	10.356 .0000	3.8259 .0063	.51463 .7636

Classification Results -

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5	6
Group 1 MIXED PSF	12	11 91.7%	1 8.3%	0 .0%	0 .0%	0 .0%	0 .0%
Group 2 ALAN	8	0 .0%	8 100.0%	0 .0%	0 .0%	0 .0%	0 .0%
Group 3 ALAN BUNGA	9	0 .0%	0 .0%	7 77.8%	2 22.2%	0 .0%	0 .0%
Group 4 PADANG ALAN	9	0 .0%	0 .0%	2 22.2%	6 66.7%	0 .0%	1 11.1%
Group 5 PC 5	5	0 .0%	0 .0%	0 .0%	0 .0%	1 20.0%	4 80.0%
Group 6 PADANG PAYA	7	0 .0%	0 .0%	0 .0%	0 .0%	2 28.6%	5 71.4%
Ungrouped Cases	8	3 37.5%	2 25.0%	3 37.5%	0 .0%	0 .0%	0 .0%

Percent of "grouped" cases correctly classified: 76.00%

In the analyses of the final set of data, PCA was used to rewrite the large data set in the form of factor scores. When all the variables were considered, the technique did not work because the data matrix was ill-conditioned for factor processing. Reasonable results were obtained when the five sampling depths were analyzed separately. However, the 30 derived variables in the form of factor scores did not perform satisfactorily when they were used in discriminant analysis (see Sections 9.3.1 and 9.3.2).

Discriminant analyses using the soil variables produced more satisfactory results in terms of the variance explained and the number of "grouped" and "test" cases correctly classified. The results show that soil properties like APD, BPD, BPCI, BTCa, BTP, BAP, BTFe, CTCu, DN and EEK have the closest associations with the zonation of the six phasic communities. Judging from the magnitudes of the coefficients of the standardized canonical discriminant functions and the variance explained by each function, BPD, BTCa, BTFe and BPCI are probably more important. BTP and BAP were entered into the functions only when BTCa was omitted from the analysis. When the nutrient contents are expressed on volume basis, the prominence of particle density and pyrophosphate colour index as important discriminators is still apparent but the classification results are not as satisfactory.

With limited samples and a narrow range of soil properties, Anderson (1961) hypothesized that there is a general decline in soil fertility from PC 1 to PC 6. Results in this study show that the zonation of the forests is mainly associated with soil physical properties such as particle density (PD) and degree of decomposition (as indicated by PCI), and some nutrient elements like iron, calcium, and to a lesser extent, phosphorus, copper, nitrogen and potassium.

Particle or specific density (PD) of a material is an intrinsic property which directly reflects the denseness of that material (see App. 1 for methodology). Since the materials that have formed the present surface peats have originated from different vegetation with practically no addition of mineral materials through fluvial or aeolian processes, it is therefore not surprising that the varying particle densities of these materials at the surface are a good indicator of the standing vegetation. There is a general increase of particle density of the surface organic materials from PC 1 to PC 6. This observation is supported by the data of lowland peats from Indonesia (Driessen and Rochimah, 1976), and will be further discussed in Section 11.2.

The degree of decomposition of the surface peats (particularly at 15-30 cm depth) is also an important discriminating variable. BPCI increases from 2.5 in PC 1 to about 4.0-4.3 in PC 2 and 3, 5.4 in PC 4, and 6.6 in PC 5 and 6 (see Table 9.6). In the terminology of Soil Taxonomy (Soil Survey Staff, 1975), the surface peats in PC 1 would be sapric, PC 2 and 3 hemic, and PC 4 to 6 fibric. The occurrence of more humified materials at the edges of the peat dome will be elaborated in the next chapter.

The extremely low inherent fertility of peat soils in Sarawak have been well documented (e.g. Tie and Kueh, 1979). Of the nutrients which stand out as important discriminators, it is most interesting to note the presence of total calcium, and total and available phosphorus. It seems that in the peat swamp environment, calcium and phosphorus are significantly associated with the changes in forest types across the peat dome. BTCa decreases from PC1 to PC 6. BTP also decreases from PC 1 to PC 3 but those of PC 3 to PC 6 are similar. For the Mixed Dipterocarp Forest (MDF) in Brunei and Sarawak, Ashton (1964; 1973) had suggested that the single most important nutrient as a forest determinant is phosphorus. Changes in the level of calcium have also been found to be significantly associated with vegetation classes of hill forests in Gunung Mulu (Newbery and Procter, 1984).

Baillie (1978) found that chemical characteristics related to the soil parent material, particularly reserve levels of phosphorus and magnesium, are the most influential on species distributions in the MDF. Looking at the edaphic factors along a single transect (R.10: see Chapter 8), magnesium stands out as the nutrient element which seems to change most significantly from PC 1 through to PC 6. Magnesium is also an important variable in the preliminary set of data (Section 9.2.2), but its importance disappears when a larger set of data is analysed. The different outcomes may have resulted from the difference in the scope of study. While Chapter 8 examines the differences of nutrient levels within a specific area and the preliminary statistical analyses (Section 9.2.2) look at a smaller data set, the final set of data analysed in Section 9.3.2 include many more samples spread over Sarawak. As reviewed in Section 4.4, the relative variability of the different factors, the range of samples and the intensity of investigation will affect the outcome of each individual study (Baillie, 1978). This apparent difference may also result from the fact that only univariate statistics are examined in Chapter 8 while multivariate relationships between characteristics are taken into account in the present analysis. As mentioned in Section 9.3.2, the importance of a variable may be drastically affected when multivariate relationships are considered.

Apart from calcium and phosphorus, total iron and copper of the sub-surface peat layers are also important differentiating parameters for the forest types. These two trace elements also decrease from PC 1 through to PC 6 (see Table 9.6). Organic soils are well known for their extremely low level of copper; availability is further reduced by strong fixation. The level of iron and copper have been found to be generally associated with the ash content (Section 9.3.1).

The pattern of variations of DN and EEK does not follow a nice declining trend from the periphery to the centre of the peat dome. It is therefore difficult to explain how nitrogen and exchangeable potassium of the subsoil (60-150 cm) are associated with the forest types. In particular, it is difficult to see why the level of EEK in the soils of PC 5 is suddenly doubled compared with other forest types. Due to the small sample size of PC 5, this figure should be taken as suspect, and further investigations are needed to confirm this observation. It is noteworthy that DN and EEK are of lesser importance compared with other included variables. They contribute more to Function 2 which only accounts for 11% of the variance (see Table 9.6).

Deficiencies of calcium, phosphorus, copper and iron have been observed in crops growing on tropical lowland organic soils (Tie and Kueh, 1979). Looking at the distribution of these nutrients across the peat dome, these problems are expected to be more severe if organic soils nearer to the centre of the peat dome are reclaimed for agriculture. The greatest change in the levels of BTCa, BTP and BTFe (see Table 9.7) seems to occur between PC 2 and 3. With more decomposed peats at the surface, soils under PC 1 and 2 also have more favorable physical properties compared with those of PC 4 to 6. When agricultural development of the PS is planned, it would therefore be advisable to consider PC 1 and 2 separately from PC 3 to 6 where nutritional and other problems are expected to be more serious. It may be a prudent policy to keep agricultural development of the PS, when required, to the fringes of the peat domes where the soils under PC 1 and 2 are comparatively better. With its wealth of valuable timber, PC 3 may be used for silviculture under proper management. The central parts of the peat domes may best be kept under the natural conditions for conservation purposes. On this account, the forest zonation which can be easily picked up on aerial photographs (Wall, 1966; also see Plate 8) can serve as a useful guideline to soil survey and land evaluation.

CHAPTER 10. SMALL LITTER PRODUCTION AND LOSS OF MATERIALS THROUGH DECOMPOSITION AND LEACHING

10.1 INTRODUCTION

In an attempt to semi-quantify the growth of tropical ombrogenous peat in Indonesia, Driessen and Subagjo (1975) expressed the net annual change in the thickness of peat (dh) as a function of several processes:

$$dh = h_a - h_b - h_c - h_m - h_r$$

where h_a = gross annual <u>addition</u> of organic matter (O.M.);

h_b = annual <u>burning</u> of O.M.;

h_c = annual <u>compaction</u> of the peat;

h_m = annual <u>mineralization</u> of O.M.;and

h_r = annual <u>removal</u> of O.M.

Loss of organic materials either through burning or removal by man or wind seems negligible under the natural peat swamp condition. However, removal through leaching and loss due to mineralization (decomposition) deserve attention. Compaction also needs to be considered if growth is described in terms of thickness rather than weight per unit area.

Some of these processes will be examined as far as possible in the following sections. Litter production and decomposition were investigated to have some ideas on the production:accumulation dynamics. Loss of materials through leaching was also briefly studied. In Chapter 11, some new radio-carbon dates were considered together with those given by Wilford (1961) and Anderson (1961). The main objective of this part of the study was to develop a model which would explain the development of PS dome-shaped morphology.

10.2 COMPARATIVE RATES OF SMALL LITTER PRODUCTION

Introduction

Unlike peats in the temperate regions where *Sphagnum* mosses, grasses, reeds and other aquatic plants have provided the basic building materials, peats in Sarawak have been formed largely from plant remains of a forest vegetation. The organic materials, therefore, come in the forms of leaf and small woody litter, branches, trunks of fallen trees and roots. Without exhaustive study on the productivity of all these components, it is difficult to assess the contribution made by each component to the build-up of peat materials. However, it is assumed that the finer matrix of the peat has been derived mainly from the small litter and fine roots,and the large woody fragments from larger tree trunks, branches and medium to large roots.This is supported by field observations, particularly those of fibric and hemic materials which allow easy recognition of plant forms.

In Sarawak, the peats are very woody, and well-preserved tree trunks, branches and large roots are present in abundance (Tie and Kueh,1979). In field description of organic soil profiles, five classes of woodiness have been recognized, namely non-woody (<2% wood by volume), low (2-10%), moderate (10-30%), high (30-60%) and very high (>60%). Twenty-two soil pits were dug and described in this study; the degree of woodiness in the various peat layers down to a depth of 60 or 100 cm is summarized in Table 10.1 It can be seen that the top 15 cm are largely non-woody in nature. The second horizon from 15 to 30 cm has low to moderate wood content. Below this layer, the wood content is predominantly moderate to high with an average value of about 40%.

It is difficult to measure the production of coarse litter which includes large branches and tree trunks. Such additions are spasmodic but the amount of materials added at any one time may be substantial. As a result, their measurements would require monitoring of a large area over a long period of time. Driessen and Subagjo (1975) observed that about one-third of the accumulating organic materials in the PS of Indonesia consisted of wood and the rest were leaves, fine twigs and roots.

TABLE 10.1 WOODINESS OF VARIOUS PEAT LAYERS

Depth (cm)	Frequency in various classes of woodiness				
	None	Low	Moderate	High	Very High
0-15	16 (73%)*	6 (27%)	0	0	0
15-30	2 (10%)	6 (27%)	9 (41%)	5 (22%)	0
30-60	0	0	10 (45%)	10 (45%)	2 (10%)
60-100	0	0	4 (40%)	4 (40%)	2 (20%)

** Figures in brackets are percentages of total observations for that depth.*

Below-ground production and subsequent addition of root litter to soils are even more difficult to ascertain. Stewart and Reader (1970) estimated the subsurface net production of vegetation on organic terrain in Canada by the following relationship :

$$\frac{\text{Max. subsurface net production}}{\text{Mean subsurface biomass}} = \frac{\text{Max. aerial net production}}{\text{Mean aerial biomass.}}$$

Koopmans and Andriesse (1982) found that in a 10-15 year secondary MDF in Sarawak, the root biomass was only 13% of the total biomass; they also reviewed that such percentages ranged from 7-23% (averaging about 17%) in five other studies in Sri Lanka, Congo, Ghana and Nigeria. Whittaker and Marks (1975) reported that a root/shoot ration of 0.2 has usually been used as an approximate value for forest trees. Kyuma and Pairintra (1983) estimated that the annual dry matter production of roots in a semi-deciduous forest of Northeastern Thailand was about 15% of the above-ground production. These figures indicate that the above relationship between net production and biomass given by Stewart and Reader (1970) may also be approximately correct for the forests in the Tropics and Sub-Tropics. In a tall PSF, the ratio of the subsurface to the aerial biomass is likely to be similar to the values reported above, and hence the subsurface net production would also be a small fraction of the aerial net production. Although relatively minor as a proportion of the total organic additions, a larger fraction of the dead roots may be preserved since they are buried in the peat masses right from the start.

From the above discussion, it appears that a fairly large part of the peat materials have originated from the aerial small litterfall. It was therefore decided to have some measurements of small litter production and to use this as an index for comparing the rates of organic matter addition in three main PC of the PSF. The three forest types chosen included PC 1 (Mixed Peat Swamp Forest) at Plot C, PC 4 (Padang Alan Forest) at Plot B and PC 6 (Padang Paya Forest) at Plot A. Detail of the methodology is given in Section 5.3.3 (p.64).

Results and Discussion

Small litterfall here includes leaves, small wood (<2 cm diameter), fruits, flowers and trash. The data collected over a period of one year from August,1987 to July,1988 are summarized in Table 10.2.

TABLE 10.2 MEAN SMALL LITTERFALL FROM NINE LITTER TRAPS IN THREE FOREST TYPES ALONG TRAVERSE R.7 (t/ha/yr ± SE).

Litter type	Forest Type (Plot No. in brackets)		
	PC 6 (A)	PC 4 (B)	PC 1 (C)
Leaf litter	$2.57^{a} \pm 1.12$	$4.61^{b} \pm 1.29$	$5.57^{c} \pm 1.64$
Non-leaf litter	$0.88^{a} \pm 0.87$	$1.62^{b} \pm 1.39$	$1.60^{b} \pm 1.40$
Total	$3.45^{a} \pm 1.64$	$6.23^{b} \pm 2.16$	$7.17^{c} \pm 2.26$

**Means with same superscript within each litter type are not significantly different at P=0.05 (DMRT).*

The mean total litterfall in the three plots ranged from 3.45 to 7.17 t/ha/yr. The values show a decreasing trend from PC 1 to PC 4 and then 6, and they are significantly different at P=0.05 using Duncan's multiple range test. Similar trend was observed for the leaf fraction which by itself ranged from 2.57 to 5.57 t/ha/yr. The trend for non-leaf fraction is slightly different in that the values for PC

4 and 1 are not significantly different. The leaf fraction accounts for 74-78% of the total aerial small litterfall. The ratios of leaf to non-leaf fraction (about 3:1) in the litterfall are similar to the results obtained for a freshwater swamp forest in Peninsular Malaysia (Furtado *et al.*,1980).

Small litterfall measurements done in alluvial forest, MDF, heath forest and limestone forest at Gunung Mulu National Park, Sarawak showed values ranging from 8.8 to 12.8 t/ha/yr (Proctor *et al.*,1983b). Studies on mangrove forests in Sarawak recorded an average small litter production of 8.60 t/ha/yr over a period of two years (Chai,1982). In a freshwater swamp forest in Peninsular Malaysia, litter production of 9.16 t/ha/yr was reported (Furtado *et al.*,1980). The highest litterfall value measured in lowland tropical forests is perhaps that of *Macrolobium* forest in Zaire where Laudelout and Meyer (1954) recorded 15.3 t/ha/yr. On the other hand, some African forest litterfall estimates were smaller at 5.3-8.3 t/ha/yr for eight sites in the Ivory Coast (Devineau,1976).

As none of the forests mentioned above is similar to the PSF of Sarawak, they can only serve as rough comparisons. The current values obtained for PC 1 and 4 are slightly lower than but similar to most of the other estimates, particularly those made within Malaysia. The value for PC 6 is very much smaller, being less than half of most of the recorded estimates. Many features of the vegetation in PC 6, including the leaf size and structure, resemble those of a tropical heath (Kerangas) forest (Anderson, 1961). Janzen (1974) speculated that heath forest leaves have evolved in adaptation to low nutrient availability and the relatively high nutrient cost of replacing leaves. The very low rate of litter production in PC 6 at the centre of the peat dome may therefore be a direct reflection of the very stunted and relatively sparse, shrub-like vegetation which has adapted similarly.

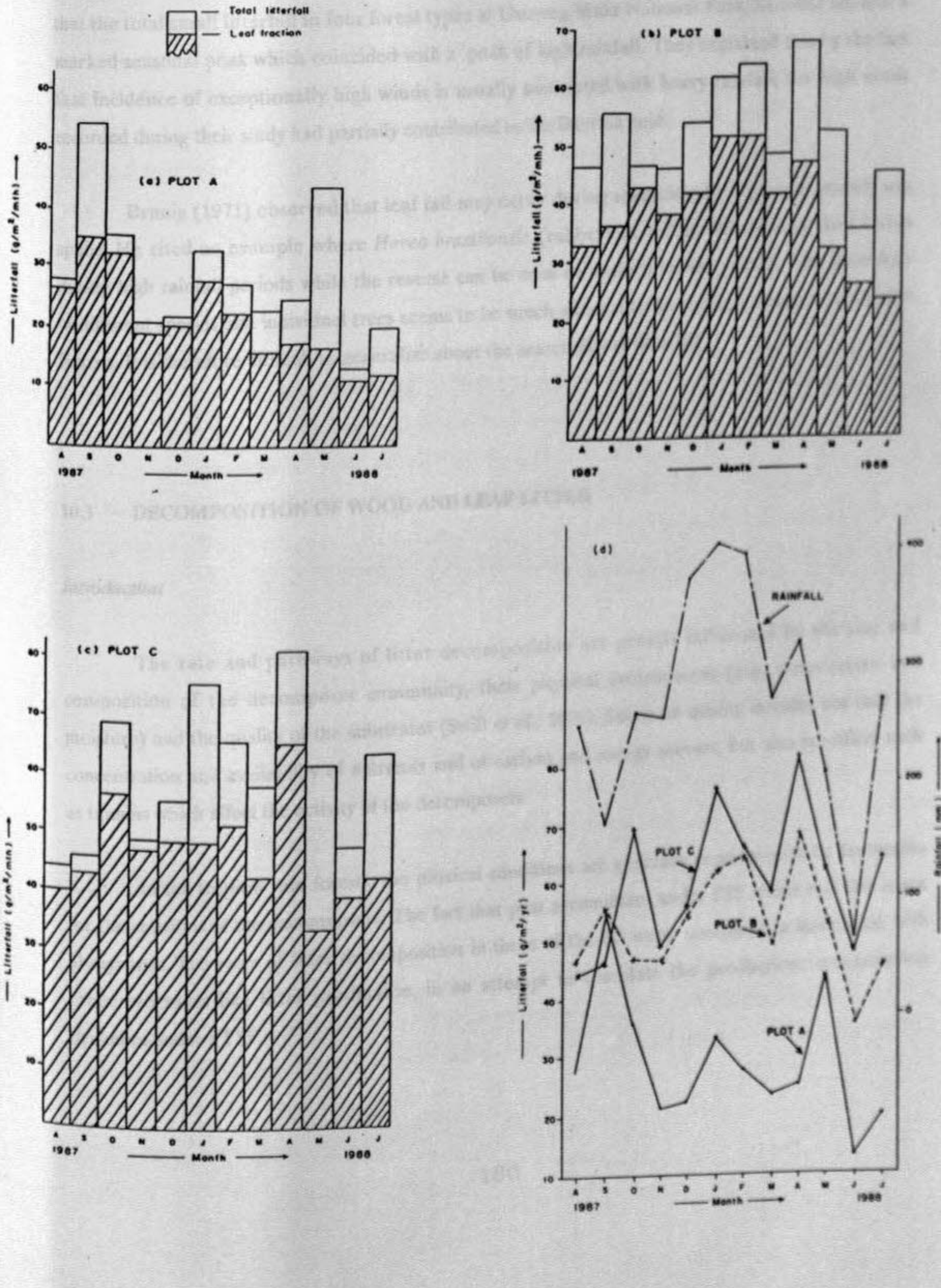
A striking feature of the present data is the high standard errors (SE) (see Table 10.2). The coefficients of variation (CV) of the leaf litterfall range from 15 to 54% and that of the non-leaf fraction is even higher with values of 34-124%. Litterfall measurements in tropical forests have been reviewed by Proctor (1983). He stipulated a minimum of twenty litter traps in a sample area and the intensity of sampling should aim at a SE of the mean of $\pm$ 5%. The use of nine 0.5-m^2 traps per plot in the present study was probably inadequate, resulting in the high SE. Determination of the leaf litterfall could have been improved by having more replicates. However, it is doubtful whether twenty or more traps would reduce the SE to $\pm$ 5% of the means for the non-leaf fraction. In the four lowland forests investigated by Proctor *et al.* (1983b), 35 traps (0.25-m^2) per plot gave results for small wood litterfall which had SE of 13-19% of the means.

The non-leaf fraction in the present study included small wood (<2 cm diameter), flowers, fruits and trash. The major component, especially in terms of weight, was the small wood which was mainly responsible for the large variations between traps. It was frequently observed during sampling that out of the nine traps in each plot, there were usually two or three traps without any woody fragments and one or two with several pieces which could weigh up to 50-60 g (o.d.). This sort of variation was the main source of high SE. Having more replicates may reduce the SE slightly but it will not solve the problem. As long as a few traps collect nothing and a few others have a lot, the range will be relatively large. The underlying factor seems to be the very scattered spatial distribution of the small wood litter. The use of larger traps would perhaps help to ensure that most, if not all, the traps would collect at least some wood litter so the range and consequently the SE would be reduced. On the other hand, too large a trap would be difficult to set up on the forest floor without having to disturb the undergrowth. Proctor *et al.* (1983b) had to use sub-plots of 5 x 5 m to monitor large wood (>2 cm - ≤10 cm diameter) litter; with ten replicates, the CV ranged from 18-66%.

The month of April gave the highest litterfall in Plots B and C (Fig.10.1) while Plot A had its highest monthly litterfall in September. The month of June which was the driest month during the sampling period recorded the lowest litterfall in Plots A and B, and the third lowest in Plot C. Figure 10.1.d shows that from October, 1987 to July, 1988, the monthly rainfall pattern was roughly mimicked by the trend of small litterfall in all the three forest types. Between August and October, 1987, however, lower rainfall in September corresponded to a rise in litterfall in Plots A and B; this increase in litterfall was not registered in Plot C until the following month of October. Therefore, it seems that a decrease in monthly rainfall can either produce a decrease (as in June, 1988) or an increase (as in September, 1987) in the small litterfall in these PSF. Higher litterfall during dry spells could be due to water stress but wet, windy periods could also result in higher litterfall by providing the mechanical impetus. The effect of the drier month of September, 1987 was not immediately felt in Plot C at the edge of the peat dome probably because it was receiving sub-surface through-flow from the higher ground.

It must be stressed that the litterfall was monitored for one year only. The data were therefore inadequate for firm conclusions about the seasonality of litterfall in these forests. Furtado *et*

FIGURE 10.1 MONTHLY LITTERFALL IN PLOTS A,B AND C AND MONTHLY RAINFALL AT MARUDI



al. (1980)
a three-ye
with the r
that the t
marked s
that incid
recorded

B
spells. He
during hig
of differen
factors. It

10.3 D

Introductio

Th
compositi
moisture)
concentrat
as tannins

In
for the acti
always tru
other proc
dynamics u

found no marked seasonality in litterfall in a freshwater swamp forest in West Malaysia for ear period. In many other studies, peak leaf fall has been related to a period of water stress maximum occurring during the dry season. On the other hand, Proctor *et al.* (1983b) found otal small litterfall in four forest types at Gunung Mulu National Park, Sarawak showed a easonal peak which coincided with a peak of high rainfall. They explained this by the fact ence of exceptionally high winds is usually associated with heavy rainfall; the high winds during their study had partially contributed to the litterfall peak.

Brunig (1971) observed that leaf fall may occur during exceptionally dry or excessively wet e cited an example where *Hevea brasiliensis* (rubber) on deltaic PS tends to shed leaves gh rainfall periods while the reverse can be seen on shallow humus podzols. The phenology at species and individual trees seems to be much affected by local micro-climate and edaphic is therefore difficult to generalize about the seasonality of litterfall.

ECOMPOSITION OF WOOD AND LEAF LITTER

on

he rate and pathways of litter decomposition are greatly influenced by the size and on of the decomposer community, their physical environment (esp. temperature and and the quality of the substrates (Swift *et al.*, 1979). Substrate quality includes not only the ion and availability of nutrients and of carbon and energy sources, but also modifiers such which affect the activity of the decomposers.

the tropical rain forests, the physical conditions are generally considered to be favourable ivities of the decomposers. The fact that peat accumulates under PSF shows that this is not e. The rates of litter decomposition in three of the PC were compared in association with cesses like litter production, in an attempt to elucidate the production: accumulation under a PSF.

The experiment was carried out in the same plots A, B and C which were used for monitoring litterfall; they were sited in PC 6, 4 and 1 respectively. Details of the methodology are given in Section 5.3.3 (p.64-68). The rates of decomposition of freshly fallen leaves, small wood (< 2 cm diameter) and large wood (12-15 cm diameter) were investigated. In the latter case, two different conditions were imposed : one set of samples was left exposed on the ground surface and the other buried at a depth of about 30 cm. Decomposition experiments of leaf and small wood samples were carried out in cages rather than litter bags of different mesh sizes so that the forest floor conditions could be simulated as closely as possible.

Results and Discussion

Remaining oven-dry weights of the samples, expressed as percentages of the original weights, are shown in Table 10.3 and Figure 10.2. In Table 10.3, Duncan's multiple range tests were done in sets of data where there were four replicates; where there were missing values or only two replicates, it was felt that the statistical test was not necessary. In cases where DMRT were done, remaining weights of almost all the samples in PC 1 are significantly lower than those in PC 4 and 6. There are no significant differences between the samples in PC 4 and 6 except for the leaf litter samples after 60 days.

Weight losses (100% - remaining weight) from mixed leaves in the litter cage after four months were 44.0, 23.2 and 14.0% for PC 1, 4 and 6 respectively (see Table 10.3). The corresponding weight losses from the small wood samples after a similar period of time were 18.8, 7.9 and 6.2%. It can be seen from these figures that small litter in PC 1 was decomposed at a significantly higher rate than that in both PC 4 and 6. Differences between PC 4 and 6 are not very distinct; while the leaf fraction in PC 4 was decomposed at a higher rate after an initial lapse of two months, there was no significant difference for the small wood fraction up to the fourth month.

In the case of large wood (12-15 cm diameter), the rate of decomposition was also significantly higher in PC 1 than PC 4 and 6 after the second month under both buried and exposed situations. There were no significant differences between PC 4 and 6 throughout the period of experimentation. It is interesting to note that significant termite activity was observed during field

TABLE 10.3. *REMAINING WEIGHTS AS PERCENTAGES OF ORIGINAL WEIGHTS IN DECOMPOSITION STUDY.*

(a) Leaf litter.

Time (days) \ Site	PC 1	PC 4	PC 6
0	100.0	100.0	100.0
30	85.6	90.4	97.7
60	75.6^{a}	86.4^{b}	95.5^{b}
90	66.1^{a}	81.8^{b}	91.5^{c}
120	56.0^{a}	76.8^{b}	86.0^{c}
150	51.7	74.0	83.5

(b) Small wood.

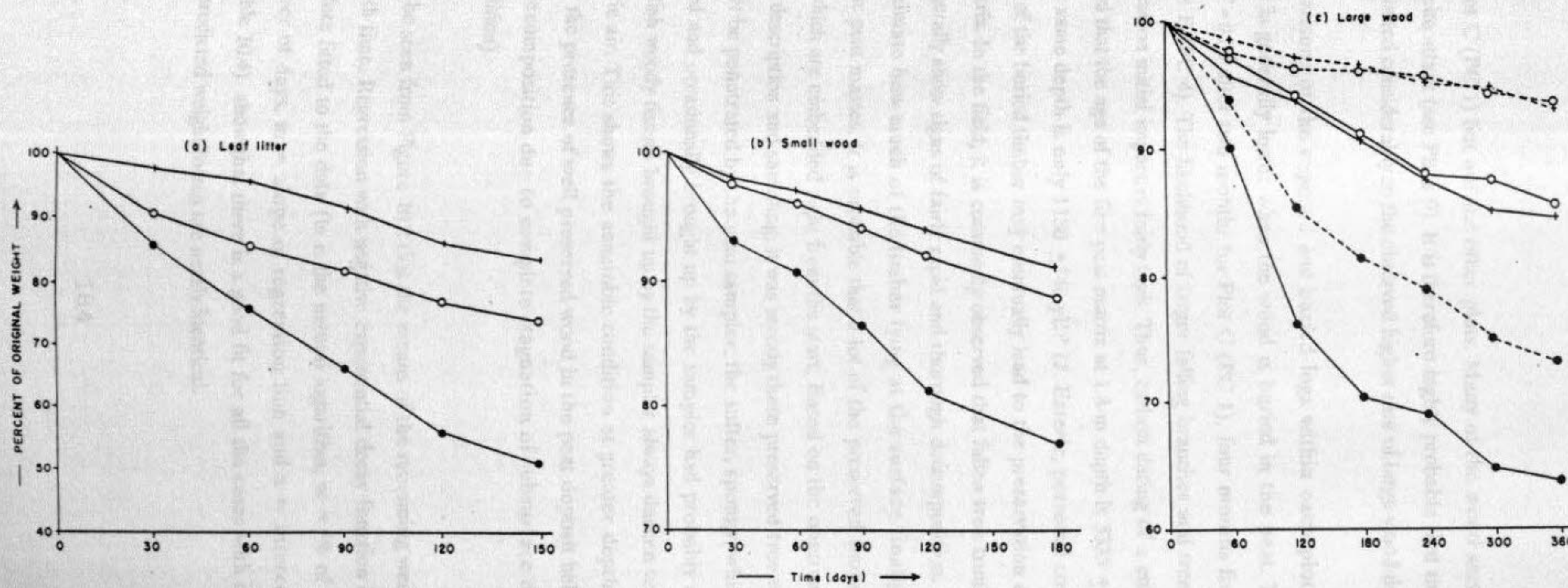
Time (days) \ Site	PC 1	PC 4	PC 6
0	100.0	100.0	100.0
30	93.0	97.5	98.0
60	90.6^{a}	96.0^{b}	97.0^{b}
90	86.4^{a}	94.1^{b}	95.5^{b}
120	81.2^{a}	92.1^{b}	93.8^{b}
180	77.0	88.6	91.0

(c) Large wood.

Time (days) \ Site	PC 1	PC 4	PC 6	PC 1	PC 4	PC 6
	Left on ground surface			Buried in peat		
0	100.0	100.0	100.0	100.0	100.0	100.0
60	90.2^{a}	96.7^{b}	95.6^{ab}	93.6^{ab}	97.5^{b}	98.5^{b}
120	76.2^{a}	94.0^{c}	93.5^{c}	85.4^{b}	96.0^{c}	97.0^{c}
180	70.2^{a}	91.0^{cd}	90.5^{c}	81.4^{b}	95.8^{cd}	96.4^{d}
240	69.0^{a}	88.0^{cd}	87.5^{c}	79.2^{b}	95.5^{e}	95.0^{de}
300	64.7^{a}	87.5^{c}	85.1^{c}	75.0^{b}	94.1^{d}	94.5^{d}
360	63.6	85.6	84.5	73.0	93.3	92.8

* *Figures with different superscripts in the same row are significantly different at* $P = 0.05$ *(DMRT).*

FIGURE 10.2 DECOMPOSITION OF LEAF LITTER, SMALL WOOD AND LARGE WOOD



Weight remaining in (a) leaf litter, (b) small wood and (c) large wood in PC 1 (●), PC 4 (o) and PC 6 (+) along Transect R.7 at Tanjung Pasir. Broken lines in (c) indicate that the wood sections were buried beneath the surface; solid lines are for samples which were left on the ground surface.

sampling in Plot C (PC 1) but not the other plots. Many of the wood sections in Plot C revealed substantial termite attack (see Plate 9). It is therefore highly probable that the termite activity in this plot had contributed considerably to the observed higher rate of large wood decomposition.

Comparisons of the exposed and buried logs within each plot show that the rate of decomposition is generally lower when the wood is buried in the peat. The differences became significant at P=0.05 after two months for Plot C (PC 1), four months for Plot A (PC 6) and six months for Plot B (PC 4). The likelihood of larger falling branches and tree trunks getting buried in the soft, wet peat on initial impact is fairly high. Thus, carbon dating of a core sample from Jambi in Sumatra showed that the age of the fine peat matrix at 1.8-m depth is 3335 $\pm$190 yBP while a piece of wood from the same depth is only 1180 $\pm$140 yBP (J. Esterle, personal comm.). The lower rate of decomposition of the buried timber may eventually lead to the preservation of large woody fragments in the peat matrix. In the field, it is commonly observed that fallen tree trunks and branches lying on the surface generally show signs of fairly rapid and thorough decomposition. At this juncture, it is not possible to estimate how much of the timber lying at the surface finally gets incorporated and preserved in the peat masses. It is probable that a lot of the preserved timber has been derived from the materials which are embedded right from the start. Based on the observations made while digging pits for profile description and sampling, it was mostly these preserved tree trunks and large branches which could not be penetrated by the peat sampler; the softer, spongy, whitish woody tissues which were penetrated and occasionally brought up by the sampler had probably originated from the dead roots. The whitish woody tissues brought up by the sampler always darken very rapidly on exposure to the atmospheric air. This shows the anaerobic condition at greater depths. Anderson (1961) also suggested that the presence of well preserved wood in the peat deposit below the surface indicates cessation of decomposition due to complete stagnation of subsurface drainage (and therefore anaerobic condition).

It can be seen from Figure 10.2 that the means of the remaining weights do not show a linear relationship with time. Regression with negative exponential decay function in the form : $ln(w) = a - mt$ were therefore fitted to the data (ln is the natural logarithm, w = % of original weight, t = time lapse in number of days, m = slope of regression line and a = intercept). The results of the regression (Table 10.4) show that there is a good fit for all the cases with r>0.95 and P<0.001. The observed and predicted weight losses are nearly identical.

TABLE 10.4 DECOMPOSITION OF LEAVES AND WOOD AT THREE SITES ALONG TRANSECT R.10, TANJUNG PASIR.

Litter Type	Mixed leaves			Small wood			Large wood			Large wood (buried)		
Site	PC 1	PC 4	PC 6	PC 1	PC 4	PC6	PC 1	PC 4	PC 6	PC 1	PC 4	PC 6
Observed % wt. loss after * mth.	48.3	26.0	16.5	23.0	11.4	9.0	35.3	12.5	14.9	25.0	5.9	5.5
Predicted % wt. loss after * mth.	49.6	27.0	16.2	24.1	11.5	9.0	35.3	13.0	14.3	24.8	5.9	5.9
# Slope (m) ($x -10^{-3}$)	4.482	1.952	1.264	1.444	0.666	0.516	1.263	0.436	0.479	0.871	0.169	0.195
# Intercept (a)	4.593	4.583	4.618	4.590	4.603	4.604	4.549	4.597	4.595	4.581	4.595	4.603
# Corr. Coef. (r)	0.997	0.990	0.985	0.989	0.999	0.998	0.952	0.988	0.990	0.983	0.957	0.993

** Observed and predicted percentages are after 5 months for leaves, 6 months for small wood (<2 cm dia.) and 10 months for large wood (12-15 cm dia.).*

 # Slope (m), intercept (a) and correlation coefficient (r) for the regression : $ln(w) = a - mt$ are shown; w is percentage of weight remaining after a time lapse of t days.

Based on the regression, predicted weight losses of mixed leaves after ten months would be 74.2, 45.6 and 30.6% for PC 1, 4 and 6 respectively. In a litter bag decomposition study done in Gunung Mulu, Anderson *et al.* (1983) found similar values of 41.3% (alluvial forest), 43.6% (MDF) and 54.8% (heath forest) from mixed leaves in fine-mesh bags after ten months. However, direct comparison between the two sets of data could not be made because the conditions of the studies were different.

Since the present study was carried out with the materials collected within their respective locality, the differences in the rate of decomposition could be attributed to the quality of the substrate, the quality and quantity of the decomposer community and the physical environment like the temperature and moisture regimes. A higher rate of decomposition could be due to the fact that the materials were more easily decomposed, the decomposers were more numerous and active, the physical environment was more conducive to decomposition, or a combination of these. The activity of termites in Plot C but not Plots A and B has been noted above. Apart from this, no other comments about the decomposer community can be made without further study on the litter-feeding macrofauna and micro-organisms.

Table 10.5 shows the nutrient contents of the leaf and non-leaf fractions of the fresh litterfall collected from the litter traps. The leaf litter of PC 1 consistently show significantly higher levels of N, K, Ca and Mg than those of PC 6; levels of these nutrients in the leaf litter of PC 4 are of intermediate values. The same pattern can be seen for the non-leaf fraction except that the level of Ca in PC 4 is anomalously high. Level of P is not significantly different between all the sites for both leaf and non-leaf fractions. Among the elements analysed, Na shows the lowest values; its pattern is similar to that of P.

The small litter of PC 1, therefore, seems to have the highest resource quality in terms of N, K, Ca and Mg. Between PC 4 and 6, only the level of Ca is significantly different. This difference in the resource quality of the substrate is probably a contributing factor to the observed rate of small litter decomposition in the order of PC 1 >> PC 4 > PC 6. Unfortunately, a full picture of the resource quality can not be obtained because other attributes like the availability of carbon sources and the concentrations of modifiers (e.g. tannins) were not determined. Further study on litter decomposition in PSF should take these factors into consideration.

TABLE 10.5 MEAN ELEMENT CONCENTRATIONS IN LITTERFALL COLLECTIONS.

Element	Plot C (PC 1)	Plot B (PC 4)	Plot A (PC 6)	HF#
Leaf litter:				
N (%)	1.19^{b}	0.74^{a}	0.55^{a}	0.57
P (%)	0.031^{a}	0.033^{a}	0.025^{a}	0.014
K (%)	0.27^{b}	0.19^{ab}	0.15^{a}	0.23
Ca (%)	0.65^{b}	0.69^{b}	0.56^{a}	0.88
Mg (%)	0.27^{b}	0.16^{a}	0.15^{a}	0.16
Na (ppm)	135^{b}	118^{ab}	87^{a}	90
Non-leaf:				
N (%)	0.82^{b}	0.55^{a}	0.49^{a}	-
P (%)	0.030^{a}	0.028^{a}	0.019^{a}	-
K (%)	0.18^{b}	0.10^{a}	0.08^{a}	-
Ca (%)	0.42^{a}	0.71^{b}	0.38^{a}	-
Mg (%)	0.13^{b}	0.08^{a}	0.07^{a}	-
Na (ppm)	98^{a}	74^{a}	79^{a}	-

* *Figures with different alphabets along the same row are significantly different at P=0.05 (DMRT).*
\# *Heath forest at Gunung Mulu. Source : Anderson et al. (1983).*

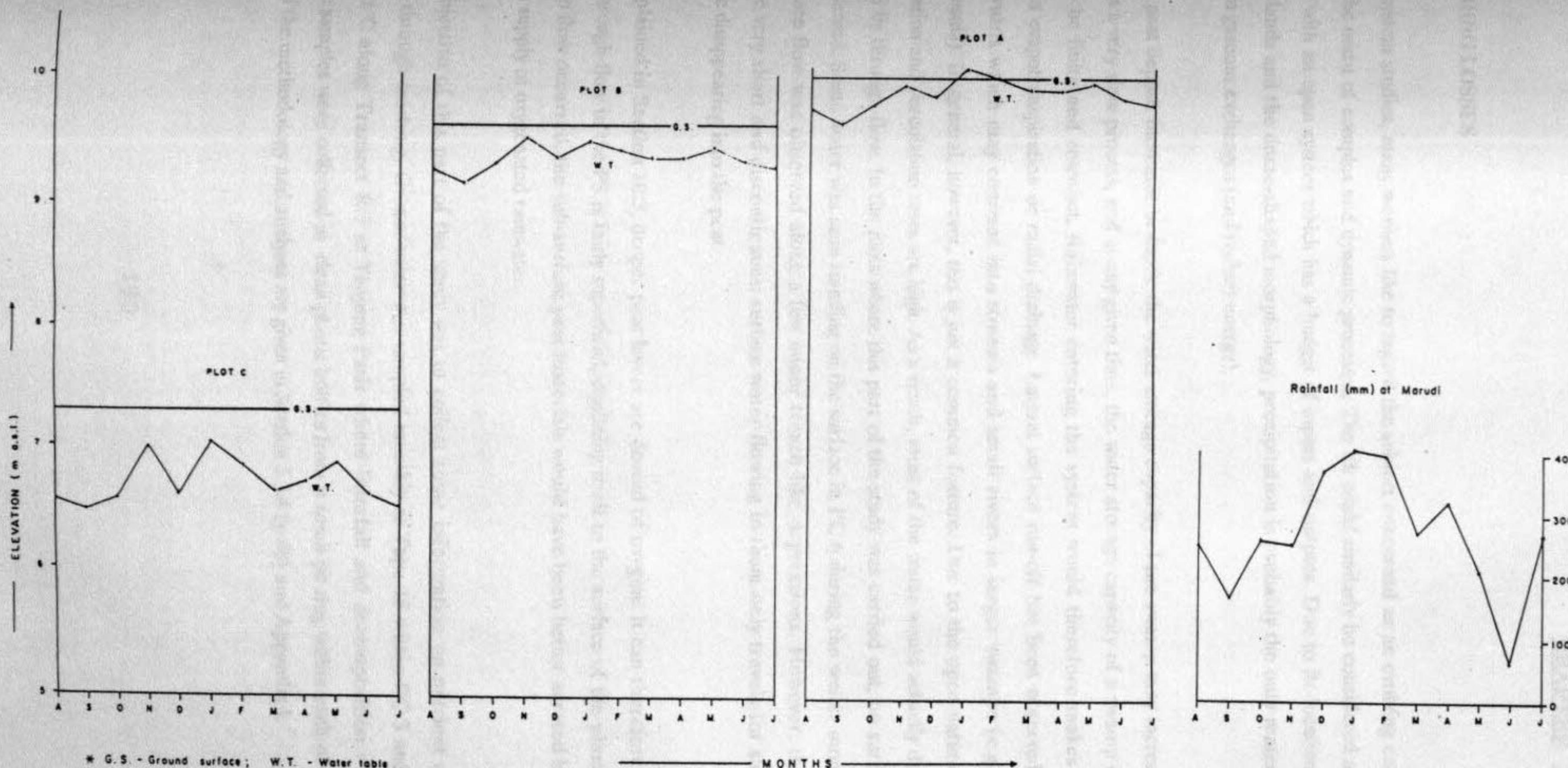
Many researchers have likened features of the vegetation of PC 6 to those of tropical heath (Kerangas) forest (e.g.Anderson, 1961). It is interesting to note (see Table 10.5) that the levels of chemical nutrients of the leaf litter from these two forest types are very similar. Analytical data of the leaf litter from heath forest (Anderson *et al.*, 1983) show that the levels of N (0.57%), Mg (0.16%) and Na (0.009%) are almost the same as those of PC 6. The level of P in PC 6 at 0.025% seems to be slightly higher than that in heath forest (0.014%), but the latter has slightly higher K (0.23%) and Ca (0.88%) contents.

Another rate determining factor which should be examined is the physical environment. Initially, it was very tempting to assume that the physical conditions like temperature and moisture regimes in the three plots were the same. However, monitoring of the groundwater table (see Section 5.3.4 for methodology) showed that throughout the period of experimentation, Plot C was better drained than Plots A and B (see Fig.10.3). In all the plots, the water table fluctuated in accordance with the rainfall. However, the water table in Plot C was consistently lower than the other plots. It was also observed in the field that the ground surface in Plot C was generally drier. The better drainage in Plot C followed by Plot B and then Plot A can be explained by radial drainage, and the flat centre and domed periphery of the surface (see Fig. 6.1.e). The more waterlogged nature of Plots A and B probably limits the rates of decomposition in these localities.

Although the temperature was not monitored, the much more open nature of the vegetation in PC 6 would suggest that the temperature regime of the soil surface here would probably have a wider range with higher maximum and lower minimum when compared to PC 1 and 4. To a certain extent, this was borne out by field experience when one could feel the heat during the day in PC 6 but not under the closed canopy in PC 1 and 4. During one of the trips along Transect R.10 at Tanjung Upar, exceptionally cold nights were also experienced while camping within PC 6. However, it is difficult to comment further without any empirical data.

To summarize, it can be reiterated that the rates of decomposition of small litter and large wood are not the same in PC 1, 4 and 6. The differences between PC 1 and the other sites are particularly significant. Such differences can be explained by the resource quality of the substrate in terms of nutrient elements like N, K, Ca and Mg, the activity of the decomposer community like termites, and the physical determinants like moisture regime. However, it must be emphasized here that one cannot extrapolate from the present negative exponential decay models derived from short-term measurements to arrive at an accurate figure for net organic matter accumulation under these forest types. For a start, one is not certain when the organic materials have reached a point whereby further decomposition has ceased and the residues have become peat. Furthermore, the rate of decomposition at the surface, as it has been shown here, is quite different from that in the soil profile at greater depths. All one can deduce for the moment are that the rate of decomposition of small litter and large wood is in the order of PC 1 >> PC 4 > PC 6, and that decomposition in the subsurface layers is slower and may cease altogether at greater depths.

FIGURE 10.3 MONTHLY VARIATIONS IN LEVEL OF GROUNDWATER TABLE ALONG TJ. PASIR TRANSECT (R.7) AND RAINFALL AT MARUDI (AUG.,1987 - JULY,1988).



10.4 LEACHING LOSSES

In ecosystem studies, many workers like to regard the subject concerned as an evolving entity maintained in the midst of complex and dynamic processes. The PS could similarly be considered as a changing entity with an open system which has a budget of inputs and outputs. Due to its location in the coastal lowlands and the dome-shaped morphology, precipitation is probably the only material input apart from gaseous exchanges (and radiant energy).

As the peat deposit increases in depth, the water storage capacity of the swamp may increase. However, this is a very slow process, and at any given time, the water storage capacity of a swamp can be assumed to be finite and constant. Rainwater entering the system would therefore makes its eventual exit via evapotranspiration or radial drainage. Lateral surface run-off has been observed to form minor rivulets which may combine into streams and small rivers in larger swamps (e.g. at Maludam Peninsula). In general, however, this is not a common feature. Due to the open nature of the peat, infiltration and percolation rates are high. As a result, most of the water would actually drain off from the PS by through-flow. In the plots where this part of the study was carried out, no surface run-off was observed. Some water was seen standing on the surface in PC 6 during the wetter months and some surface flow was observed along a few minor trench-like depressions. However, these depressions are very short and discontinuous; surface water flowing in them only travels for short distances before disappearing into the peat.

As explained in Section 10.3, deeper peat layers are devoid of oxygen. It can therefore be deduced that through-flow in the PS is fairly superficial, confining itself to the surface of the phreatic zone. Had deep flow occurred, the sub-surface peat materials would have been better aerated by a continual, fresh supply of oxygenated rainwater.

The objective of this part of the study was to collect some information on nutrient and material losses through leaching. Groundwater was sampled monthly at Tape 18 within PC 3 and at Plots A, B and C along Transect R.7 at Tanjung Pasir where litterfall and decomposition were monitored. The samples were collected in clean plastic bottles from a small pit dug within each of the plots. Details of the methodology and analyses are given in Section 5.3.4 (p.68) and Appendix I.

Total dissolved solids (TDS) and elements like K, Ca, Mg, Na and Cl were analyzed. The amount of suspended organic particles was not determined because the water samples collected from the pits, though colored, were observed to be very clear. As the surface groundwater flows through the peat masses, small bits and pieces of organic materials can be dislodged and get carried away in the through-flow. However, such particles would very likely be trapped by the matrix further down the line. While boating along Sg.Maludam which dissects a huge PS at Maludam Peninsula, it was observed that the water was very clear with relatively few suspended particles. The situation probably changes during or immediately after a heavy downpour when there may be some surface run-off and the through-flow is likely to be more turbulent. Unfortunately, such a situation was not encountered during the field work. No data are therefore available on the loss of materials carried out in suspension.

Under normal circumstances, the through-flow does not discharge directly into a river. Bordering the peat deposit, the levee and the fringe of imperfectly to poorly drained mineral (usually clayey) soils with very low permeability would also act like a sieve to trap any materials in suspension and thus minimize losses in this manner at the fringes of the swamp. Therefore, it seems that transportation of suspended organic particles out of the PS is more likely to occur via surface flow which is very limited. Where the river levee has been eroded and the peat deposit is directly exposed to the current, loss of peaty materials through erosion takes place. However, this is relatively rare and plays only a minor role in the normal development of a PS.

There is no meteorological record at Tanjung Pasir. However, it is only about 4 km away from Marudi where rainfall data are available. The mean annual rainfall at Marudi over a period of 45 years is 2749 mm (DID Hydrological Yearbook 1977 & 1978).

Some attempts have been made to directly measure the amount of evapotranspiration from vegetation (e.g. Black *et al.*,1970). In ecological studies, however, it is usually estimated indirectly from meteorological data, using equations such as Penman's (1948). Penman found that evaporation from a free water surface approximated that from damp soil or vegetation. Brunig (1971) wrote that evapotranspiration of tropical rain forests might approach the evaporation from open water surfaces as long as water supply was ample. This probably applies in the PS of Sarawak as the ground surface is always wet and the supply of water to the soil surface and the vegetation is very seldom, if ever, limited. Evaporation data have not been recorded at Marudi weather station. Such data are available at Sibu which is similarly located at about 38 km from the coast in the transition zone between the swamps and the low hills. Available records measured from evaporation pan installed at Sibu indicate that the mean total evaporation per year is about 1484 mm (DID Hydrological Yearbook 1977 & 1978).

Brunig (1971) estimated potential evapotranspiration (PET) of various forest types in Sarawak from average potential evaporation using Holdridge's assumed relationship between evaporativity and stand morphological features such as height and structure. For the PSF, he arrived at figures of 1800, 1600, 1400 and 1000 mm for PC 1 to 4 respectively. These give a means of 1450 mm, which is very close to the total annual evaporation of 1484 mm given above.

Taking Brunig's PET figures for various PC and an average rainfall of about 2750 mm for the study area at Tanjung Pasir, it can be calculated that the annual potential for through-flow, and therefore leaching, is approximately 950 mm for PC 1, 1350 mm for PC 3, and 1750 mm for PC 4. The average amount of water flushing through the peat deposit at PC 4, for example, would therefore be in the order of 17,500 m^3/ha/yr. Brunig had no estimate of PET for PC 5 and 6, but it can probably be assumed to be similar to that of PC 4.

Results of groundwater analyses are averaged and shown in Table 10.6. While there are no significant differences between the levels of Ca, Na, and Cl in the groundwater for all the three localities and between Plots A and B for other analyses, levels of K, Mg and TDS in the peat water from Plot C are significantly higher than those in the other two plots. The level of Ca in Plot C seems to be higher, but due to the high variance, the figure is not statistically different from the rest at 5% significance level.

Due to the dome-shaped morphology of the peat deposit, water drains out radially from the centre. The actual amount of water flushing through the outer fringes of the dome is the sum of the leaching potential and the water coming down from higher ground which can be regarded as the catchment area. The "leachate" can therefore be diluted or concentrated depending on the differences in their respective concentrations. In the following discussion, "leachate" for a locality is meant for that part of rainwater that has fallen directly onto the area and subsequently leaches the soils of that locality. For calculation purpose, this is considered separately from the water that has entered the area from higher ground. It is also assumed that the peat swamp forms a perfect circular dome with no surface irregularities which may act as hollows and spurs in converging and diverging through-flow respectively (Anderson and Burt,1978; Speight,1980). The divergent through-flow from the centre is therefore regarded as being dispersed uniformly over the whole dome.

TABLE 10.6 LEVELS OF NUTRIENT ELEMENTS AND DISSOLVED SOLIDS IN PEAT WATER AND RAINWATER (MARUDI).

Analysis (ppm)	Plot C (PC 1)	Tape 18 (PC 3)	Plot B (PC 4)	Plot A (PC 6)	Rainwater
K	0.30^{b}	-	0.19^{a}	0.18^{a}	0.15^{a}
Ca	2.25^{a}	-	1.79^{a}	1.75^{a}	1.46^{a}
Mg	0.09^{b}	-	0.05^{a}	0.04^{a}	0.04^{a}
Na	2.11^{a}	-	1.58^{a}	1.57^{a}	1.92^{a}
Cl	1.23^{a}	-	0.98^{a}	0.94^{a}	0.71^{a}
TDS	117^{d}	100^{c}	50^{b}	48^{b}	24^{a}

** Figures with different alphabets in the same row are significantly different at P=0.05 (LSD).*

Since the levels of nutrient elements and TDS in the groundwater of PC 4 and 6 are nearly identical, this dilution/concentration effect is not significantly felt at PC 4 (Plot B), and the concentration of the groundwater can be equated to that of the "leachate". Although Plot A (PC 6) was not sited right at the centre, no dilution/concentration effect is expected here because the environment from here to the centre (supposedly the highest point of the peat dome) is fairly homogeneous.

Though the "leachate" from PC 1 has actually been diluted by the influx of water from its catchment area, the levels of some nutrient elements and TDS in the groundwater of Plot C (PC 1) are still significantly higher than those of Plots A and B. This dilution effect complicates the estimation of the loss of dissolved materials from PC 1 because the level of TDS in the groundwater here is not equal to the actual amount of materials coming from PC 1. The higher levels of nutrient elements and TDS in the "leachate" from PC 1 may have resulted from a higher rate of nutrient release due to the higher rate of decomposition (see Section 10.3).

Taking the mid-point of PC 6 (1,500 m along R.7 from Baram River) as the centre of this peat dome (see Fig.5.2.c;p.53), it can be seen that Plot C (PC 1) is situated 1,300 m from the centre. It is also shown in Figure 5.4 (p.65) that PC 1 and 3 are adjacent to each other and PC 2 is not represented along this transect. If one takes a flow path with a width of 100 m entering PC 1 from PC 3 (A width of 100 m is taken arbitrarily to demonstrate the calculation; the argument holds for any width), the specific catchment area and the amount of through-flow above this imaginary line along the contour can be estimated as follows (refer to Fig.10.4):

(a). Catchment area within PC 4-6 (A1 m^2) = 0.5 x 81.8 m x 900 m.

(b). Catchment area within PC 3 (A2 m^2) = 0.5 x (81.8+100) m x 200 m.

(c). Quantity of through-flow from area A1 (F1 m^3/yr)
= A1 x 10^{-4} ha x 17,500 m^3/ha/yr.

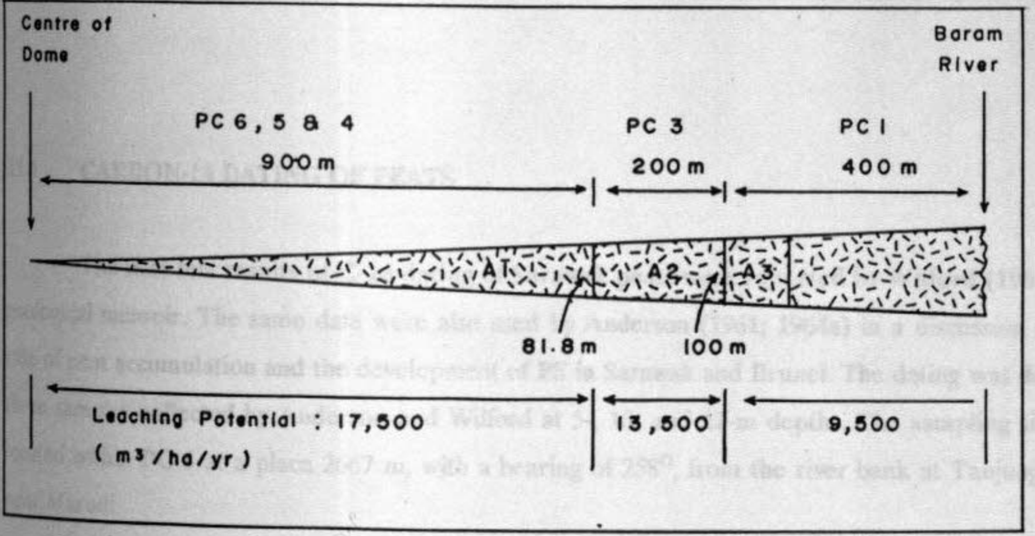
(d). Quantity of through-flow from area A2 (F2 m^3/yr)
= A2 x 10^{-4} ha x 13,500 m^3/ha/yr.

(e). An area of one hectare within PC1 (A3) directly below the line will generate by itself a leaching potential of 9,500 m^3/yr. Total amount of groundwater flushing through area A3 (F3) = F1 + F2 + 9,500 m^3/yr.

(f). $C_{G1} \times F3 = (C_{L1} \times 9{,}500) + \{C_{G3} \times (F1 + F2)\}$
where C_{G1} is the concentration of TDS in the groundwater (through-flow) within PC 1, C_{L1} the concentration of the "leachate" from PC 1, and C_{G3} the concentration of groundwater coming down from PC 3 into PC 1. Substituting the values of C_{G1} and C_{G3} from Table 10.6 into the equation, it can be calculated that C_{L1} is 276 ppm.

On the basis of the leaching potential and the concentration of TDS in the "leachate", it can be estimated that the loss of dissolved materials from PC 1, 4 and 6 is 2.62, 0.88 and 0.84 t/ha/yr respectively. Losses from PC 1 are substantially higher than those from PC 4 and PC 6.

FIGURE 10.4 SCHEMATIC DIAGRAM SHOWING THE CATCHMENT AREA OF A HYPOTHETICAL ONE-HECTARE PLOT AT PC 1/PC 3 BOUNDARY



The large amount of organic materials which dissolves and gets transported out in the groundwater is very much evident from the colour of the water draining out of the PS. This process helps to explain why the sub-surface layers of peats are always hemic to fibric in nature while the surface few centimetres of peats are usually sapric. As the sapric materials get buried under fresh materials, decomposition becomes slower and may even cease altogether. On the other hand, the buried, well decomposed materials, now under water most of the time, are slowly leached out leaving behind the coarser, less decomposed materials. The degree of decomposition of the sub-surface peat masses as manifested by the remaining materials is therefore no longer sapric.

As 36% of the rainfall entering PC 4 and 6 is lost through evapotranspiration, the nutrient levels in the remaining volume of water should in fact be concentrated by an equal proportion. It is interesting to note (see Table 10.6) that the concentrations of the nutrient elements in the rainwater does not differ significantly from those in the peat water of PC 4 and 6. This can only be explained by the fact that there is a considerable "harvesting" of these nutrients which enter the system through precipitation. The figures also show that those elements which are mineralized upon the decomposition of the litter are very efficiently taken up by the roots of the standing vegetation. Such efficiency of nutrient cycling in the humid tropical rain forests has been well recognized and frequently reported in the literature (e.g. Jordan, 1985). It minimizes nutrient loss and helps to enable native forests to survive under nutrient-poor environment.

CHAPTER 11. DEVELOPMENT OF PEAT SWAMPS

11.1 CARBON-14 DATING OF PEATS

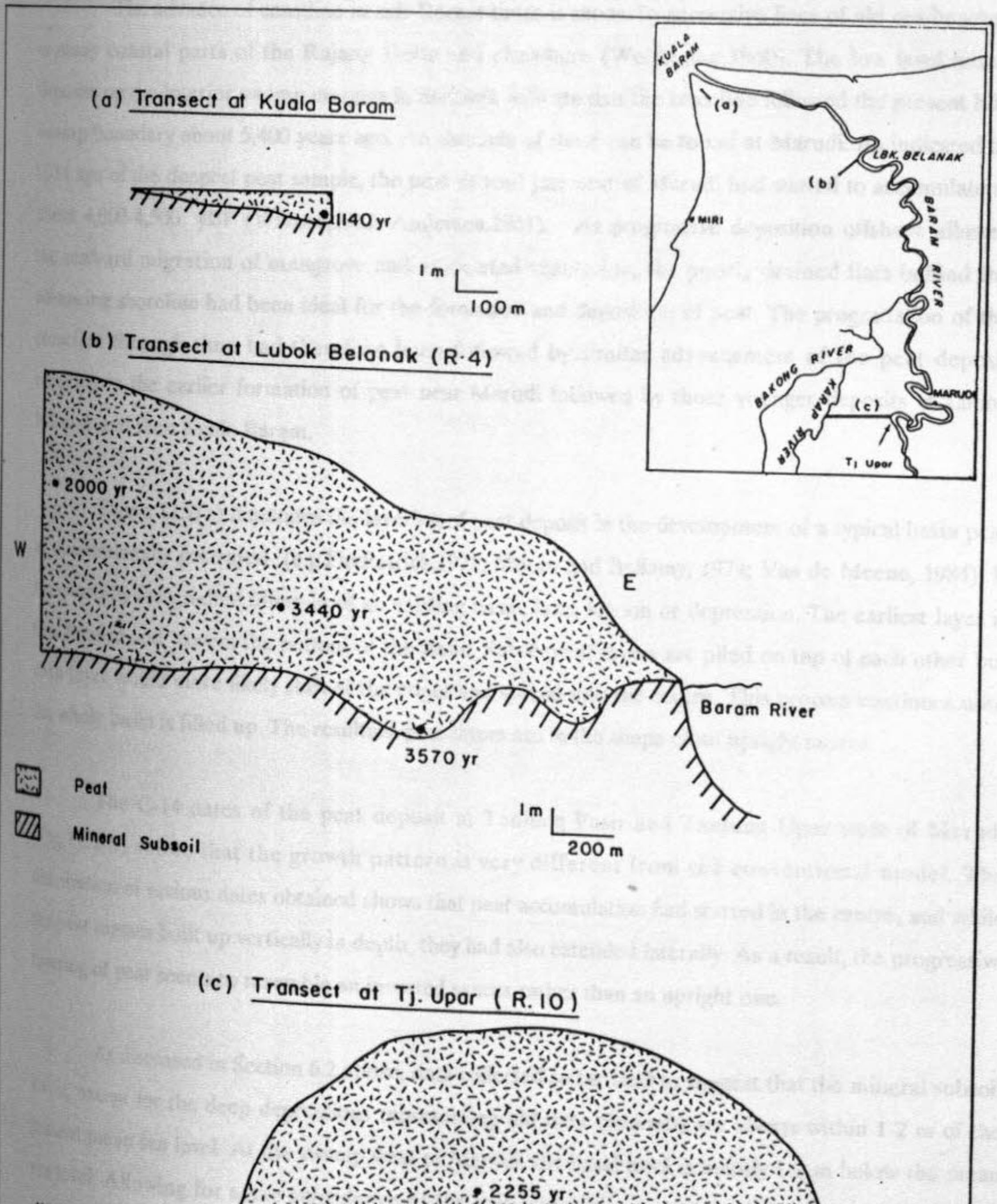
The first few results of C-14 dating of Sarawak peats were reported by Wilford (1961) in a geological memoir. The same data were also used by Anderson (1961; 1964a) in a discussion on the rate of peat accumulation and the development of PS in Sarawak and Brunei. The dating was done on three samples collected by Anderson and Wilford at 5-, 10- and 12-m depths. The sampling site was located within PC 6 at a place 2667 m, with a bearing of 258^{0}, from the river bank at Tanjung Pasir near Marudi.

In this part of the study, six more peat samples were dated by Krueger Enterprises Inc., Massachusetts, USA. The background and detail of the analysis are given in Section 5.3.5. The samples were collected from the PS along Batang Baram : two along Transect R.10 at Tanjung Upar, three from Lubok Belanak along R.4 and one at the coast near Kuala Baram.

The results are shown diagrammatically in Figure 11.1. Although Wilford (1961) and Anderson's (1961) samples were not sited along R.10, they were taken from the middle of the same peat dome within a distance of about 4 km from the mid-point of R.10. The forest type (PC 6) and the total peat depth are similar at these two locations. While Wilford (1961) reported that the peat depth at their site ranged from 10.7 to 12.2 m, the peat at the mid-point of R.10 was found to be 12 m deep. It was therefore decided to make use of the old data which were also plotted in the cross-section along R.10 (see Fig.11.1) but spatially they were located about 4 km to the north.

The chronological seaward extension of the peat deposit is clearly shown in Figure 11.1. While the bottom peat sample collected from the middle of the peat dome to the west of Marudi was formed at about 4,300 yBP, similar samples from Lubok Belanak further down river and from Kuala Baram just behind the present coastline were dated 3,570 and 1,140 yBP respectively.

FIGURE 11.1 C-14 DATES (YEARS BP) OF PEAT SAMPLES FROM PEAT SWAMPS ALONG BARAM RIVER



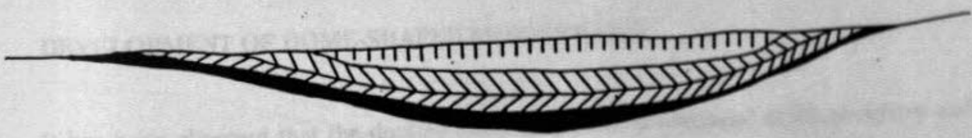
The advance of coastline in sub-Recent times is shown by successive lines of old sea-beaches in many coastal parts of the Rajang Delta and elsewhere (Wolfenden,1960). The low level beach deposits on the interior swamp margins in Sarawak indicate that the coastline followed the present hill-swamp boundary about 5,400 years ago. An example of these can be found at Marudi. As indicated by C-14 age of the deepest peat sample, the peat deposit just west of Marudi had started to accumulate at about 4,000-4,500 yBP (Wilford,1961; Anderson,1961). As progressive deposition offshore allowed the seaward migration of mangrove and associated vegetation, the poorly drained flats behind the advancing shoreline had been ideal for the formation and deposition of peat. The progradation of the coastline through time had therefore been followed by similar advancement of the peat deposit resulting in the earlier formation of peat near Marudi followed by those younger deposits at Lubok Belanak and then Kuala Baram.

Figure 11.2(a) illustrates the layering of peat deposit in the development of a typical basin peat as conventionally portrayed (e.g.FitzPatrick,1971; Moore and Bellamy, 1974; Van de Meene, 1984). It is formed by the gradual filling-in of an existing basin, lake, lagoon or depression. The earliest layer is first formed and covers the bottom of the basin. Subsequent layers are piled on top of each other but each layer would more likely start at the edges and spread into the centre. This process continues until the whole basin is filled up. The resultant peat layers are in the shape of an upright saucer.

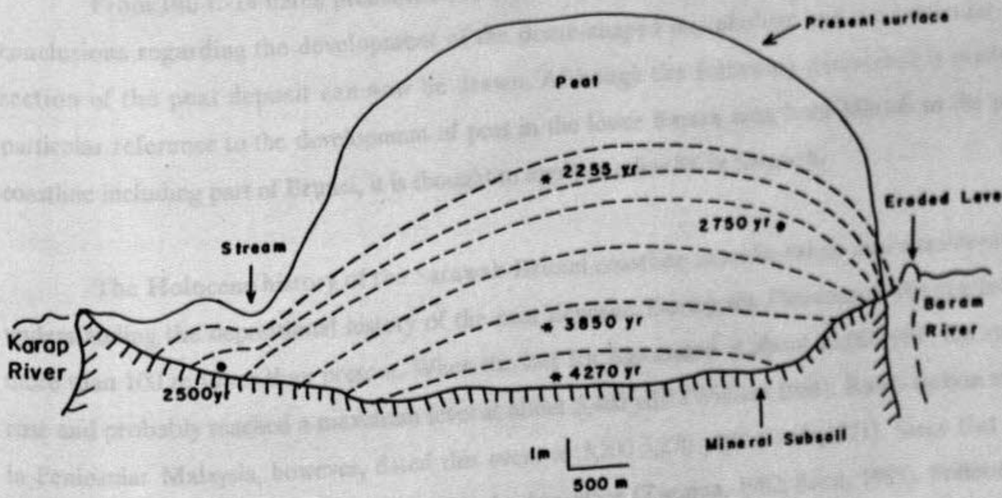
The C-14 dates of the peat deposit at Tanjung Pasir and Tanjung Upar west of Marudi (Fig.11.2.b) shows that the growth pattern is very different from the conventional model. The distribution of various dates obtained shows that peat accumulation had started in the centre, and while the peat masses built up vertically in depth, they had also extended laterally. As a result, the progressive layering of peat seems to resemble an inverted saucer rather than an upright one.

As discussed in Section 6.2 above, data collected so far tend to suggest that the mineral subsoil levels, except for the deep depressions representing old river channels, are always within 1-2 m of the present mean sea level. At the swamp west of Marudi, the basal level is mainly 1-2 m below the mean sea level. Allowing for some subsidence of the soft estuarine or coastal sediments and the recent stability of sea level, it seems that the original ground surface prior to the deposition of peat was very close to the sea level. The initial formation of peat therefore took place under a low-lying, poorly drained but largely terrestrial conditions rather than in an aquatic environment such as a pond, lake or lagoon. This deduction is supported by pollen analyses which show that the initial phase of peat

FIGURE 11.2 STAGES IN THE FORMATION OF PEAT



(a). A typical illustration of the layering of a peat deposit filling up a basin or lake (e.g. Van de Meene, 1984)



(b). Schematic diagram showing the development of the peat dome at Tanjung Upar near Marudi formation was associated with mangrove type of vegetation rather than aquatic reeds (Anderson,1961; Anderson and Muller,1975). A recent survey of a coastal peat research station at Sesang, south of Rajang Delta (Tie, 1990) has also come across clear evidence of nipah (*Nypa fruticans*) roots in the second lowest layer of peat deposit. Both mangrove trees and nipah palms are hydrophilous but not aquatic plants thus ruling out the initial existence of a large permanent open water body.

11.2 DEVELOPMENT OF DOME-SHAPED MORPHOLOGY

It has been observed that the doming effect gets more pronounced at the periphery and the central bog plain flattens and extends radially as the PS gets older (see Sections 4.3.2 and 6.2). Anderson (1961) explained that for the bogs to evolve from the almost perfect convex-topped forms found near the coast to the flat-topped structures with relatively steep margins typical of the advanced PS, the rate of accumulation at the margins must increase or the rate at the centre must decrease. This explanation given by Anderson is very attractive but it is not directly supported by any data. Furthermore, it does not say why in the first place the centre of a PS is higher than the outer fringes.

From the C-14 dates presented above and the data discussed in Chapter 10, some overall conclusions regarding the development of the dome-shaped morphology and the lenticular cross-section of the peat deposit can now be drawn. Although the following discussion is made with particular reference to the development of peat in the lower Baram area from Marudi to the present coastline including part of Brunei, it is thought to apply to other PS in Sarawak.

The Holocene history of the Sarawak-Brunei coastline must be taken into consideration in understanding the depositional history of the peat deposits. During the Pleistocene, the sea level was more than 100 m lower than present. When the last Ice Age ended at about 11,000 yBP, the sea level rose and probably reached a maximum level at about 5,400 yBP (Wilford,1961). Radio-carbon analyses in Peninsular Malaysia, however, dated this event at 5,200-5,270 yBP (Haile,1971). Since that period (5,000-5,500 yBP), a slight fall in sea level had taken place (Zuraina, 1982; Scott, 1985). Following this slight recession, sea level has been relatively stable at the present datum and this condition has allowed extensive silting of the previous offshore areas forming deltas and floodplains.

In the lower Baram area, for example, an on-lap complex of marine deposits was formed during the rise in sea level in early Holocene (Lallanne de Haut, 1965). Another typical deltaic off-lap sequence was deposited seawards of the Rasau-Ensalai Shoal in late Holocene (Fig. 11.3). The shoreline at about 5,400 yBP extended from Seria to Marudi and from Marudi to Miri as shown by the remnants of marine terraces (Fig. 11.4). During the regressive stage after 5,400 yBP, the infilled bay was covered by clay and later peat. In contrast, the off-lap sequence was mainly topped by sands similar to the present day beach sands and finally covered by peat. An approximate rate of regression was estimated to be 9 m/yr by assuming the shoreline to be near Marudi 5,400 years ago (Lallanne de Haut, 1965). The present C-14 dates of the bottom peat sample from Tanjung Pasir near Marudi (4,270 yBP) and from Lubok Belanak (3,570 yBP) just behind the buried Rasau-Ensalai Shoal suggest that the initial on-lap in-fill phase had proceeded much more rapidly. The regression should have reached Lubok Belanak by 3,570 yBP for the peat to be deposited on top of the marine alluvium. As the distance from Marudi to Lubok Belanak is about 37 km, it is estimated that the rate of regression during the early on-lap in-fill stage would be about 20 m/yr. The sheltered nature of the embayment behind the Rasau-Ensalai Shoal and the sand spit at Seria had probably helped to increase the rate of regression by promoting rapid deposition. Apart from this, the regression had probably been enhanced by the slight fall in sea level mentioned above.

Radio-carbon dating of the peat samples has shown that some of the oldest peat deposit started to form at about 4,000-4,500 yBP. As the coastline migrated seawards, mangrove became established on the marine deposits. Progressive deposition offshore allowed the extension of the mangrove front but in the poorly drained flats behind the coastal belt, the initial, strongly saline conditions were progressively replaced by a brackish and then a fresh water environment. At the same time, the mangrove communities were succeeded by nipah (*Nypa fruticans*), "nibong" (*Oncosperma filamentosa*) and then PSF associations. Such a transition of vegetation from the coastline to the PS is commonly observed in Sarawak today. The continued seaward extension of mangrove colonizing new marine deposits, to be replaced in its turn by PSF, was possible as long as the offshore conditions were conducive to the build-up of alluvium irrespective of the presence or absence of a sand bar or headland.

The C-14 dates of peat samples at a highly developed PS just west of Marudi show that the growth pattern had been very different from the typical infilling-of-a-basin situation often seen in literature (see Fig. 11.1). From a nucleus of peat deposit at the bottom of a poorly drained, low-lying

FIGURE II.3 SCHEMATIC CROSS-SECTION OF BARAM DELTA
(Source : Lallanné de Huat, 1965)

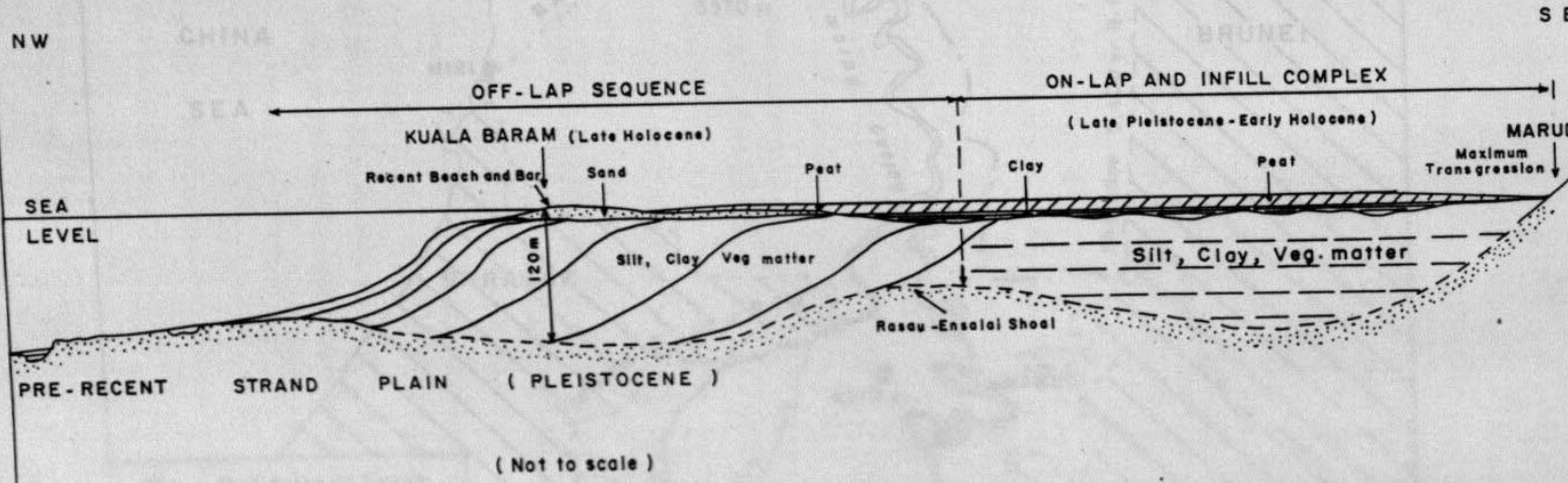
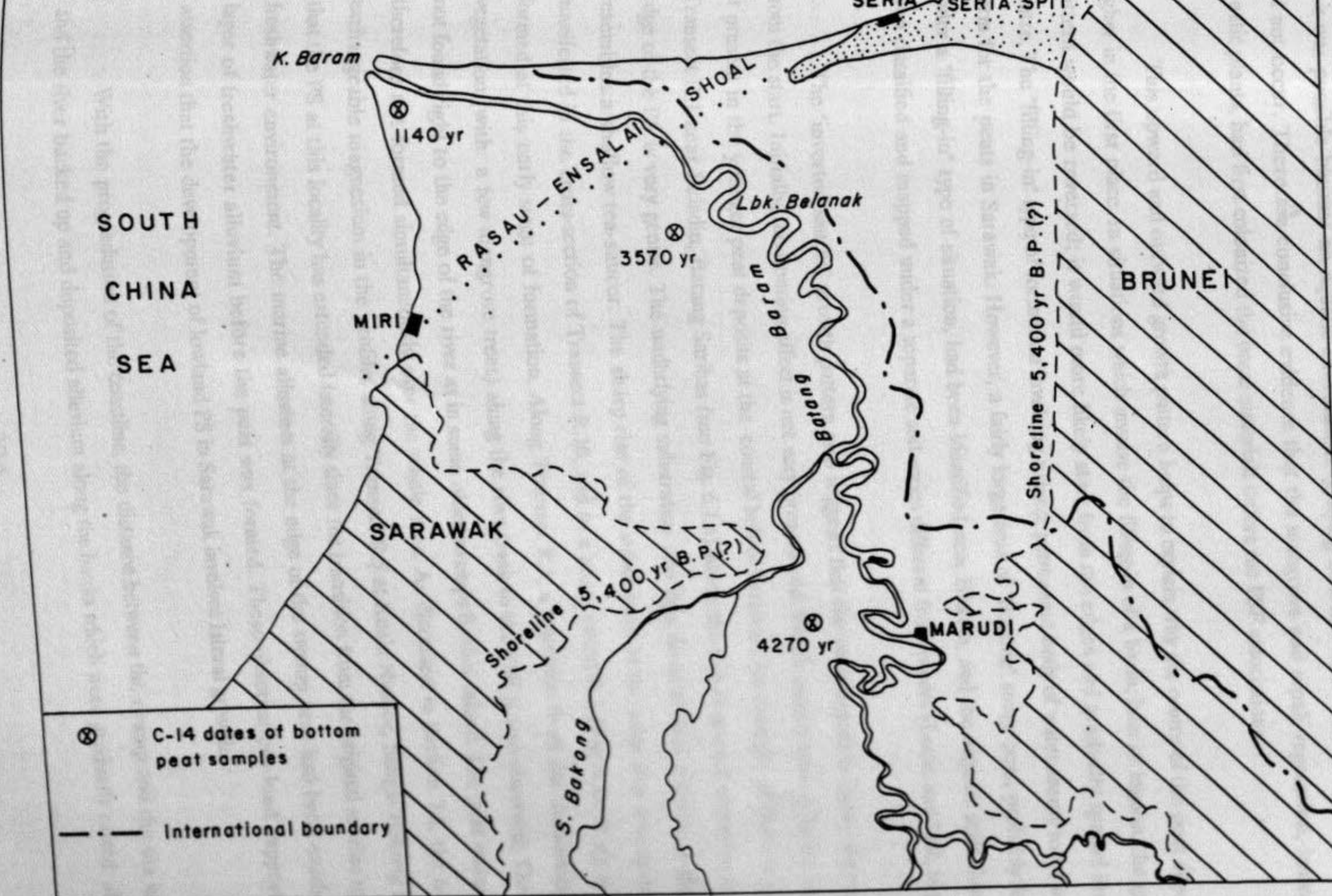


FIGURE 11.4 BARAM DELTA



area, the peat masses built up vertically in depth and at the same time extended laterally. As a result, the successive layers of peat seem to resemble an inverted saucer (or plate) rather than an upright one. This was possible because an aquatic environment typifying an initial lacustrine or lagoonal situation did not occur. There ~~are~~ is conclusive evidence that the mangrove and nipah vegetation, instead of aquatic plants, had first colonized the basal materials before the PSF associations.

This upward and outward growth pattern helps to explain why the centre of the peat deposit is higher in the first place. In situations which involve the filling-in of a basin, lake or lagoon, the growth pattern would be reversed; it would more likely start from the edges and gradually spread into the centre. The "filling-in" type of formation involving a deep, permanent body of water seems to be not the norm for the peats in Sarawak. However, a fairly large area of "floating" sedge peat, probably formed under a "filling-in" type of situation, had been identified near Bintulu, and the organic soils there had been classified and mapped under a separate soil series different from others (Louie and Lah, in prep).

The "inverted-saucer" growth pattern also suggests that the peat deposit is dome-shaped right from the start. Initially, the doming effect is not very pronounced. This is exactly what is being observed at present in the younger peat deposits at the coastal belt of Sarawak. An example of these is given by Transect R.1 near Beladin, Batang Saribas (see Fig. 6.1.a) where the rise in ground elevation from the edge of the PS is very gentle. The underlying substratum also dips down at such a gentle angle that it resembles a shallow tea-saucer. The sharp rise of the substratum at the edge like a soup-plate, as manifested in the cross-section of Transect R.10, and to a lesser extent R.5 (Fig. 6.1.c & e), is not yet formed at this early stage of formation. Along Transect R.1, a transition from the dominantly nipah vegetation (with a few mangrove trees) along the river bank to the PSF is also observed. The PSF is not found right to the edge of the river as in some older swamps further inland. The peat materials are therefore not formed simultaneously over the whole area. As discussed in Section 7.3, the trends of exchangeable magnesium in the profiles along Transect R.5 at Kuala Nyabor, Sungai Bakong indicate that the PS at this locality has extended laterally since the transition from the original marine to a later freshwater environment. The marine alluvium at the edge of the swamp here had been overlain by a layer of freshwater alluvium before the peat was formed. These observations lend support to the assertion that the development of lowland PS in Sarawak involves lateral growth.

With the progradation of the coastline, the distance between the swamp and the sea increased and the river backed up and deposited alluvium along the banks which were gradually raised above the original level of the subsoil. This is how the characteristic plate-shaped foundations of PS in Sarawak evolved (Anderson,1961). As the river level rose, the waterlogged condition in the swamp behind the rising levee was maintained, and this allowed the accumulation of peat to continue and reach the great depths (up to 21 m) commonly encountered today. Therefore, the present day plate-shaped basin found underlying the advanced peat deposit was not antecedent to the peat itself; the basin and the peat evolved together.

From the results of C-14 dating of peat samples, Anderson (1961; 1964a) showed that the rate of peat accumulation decreased towards the surface. At an average of 4.76 mm per year at the early phase, the rate decreased to 3.14 and then to 2.22 mm per year in the later stages. The difference would have been greater if increased compaction of peat masses at lower depths had been allowed for in these calculations. Anderson (1964a) suggested that the high sulphur and salt contents at the base might have retarded the microbial activities and therefore increased the initial rate of peat accumulation. However, these two factors are probably not significant; otherwise, coastal peat deposits would be much more widespread.

A more likely cause is the higher rate of organic matter production at the earlier stages of development. At the initial topogenous stage when the plants can still tap the nutrient source of the relatively fertile marine alluvium and there is a continuous influx of nutrients from the flood water, the primary production of the vegetation and consequently the production of litter are relatively high. At the ombrogenous phase of development when the ecosystem receives no further influx of nutrients from outside (apart from the small amounts brought in by the rain) but is losing them through leaching, the production of organic matter decreases and the growth rate of the peat masses diminishes.

The present litterfall data, in comparison with those of the mangrove vegetation, seem to support this hypothesis. Chai (1982) found that small litter production in a Sarawak mangrove forest with 70% *Rhizophora apiculata* was 8.60 t/ha/yr. He also cited values up to 15.7 t/ha/yr for *Rhizophora* forests from other studies. These are higher than the values obtained for PC 1 (7.17 t/ha/yr), PC 4 (6.23 t/ha/yr) and PC 6 (3.45 t/ha/yr) in the present study. Although these sets of values are not directly comparable statistically, a decreasing trend of litter production from the initial mangrove vegetation through mixed PS forest to Padang Alan and Padang Paya Forests is apparent.

As outlined by Driessen and Subagjo (1975), net accumulation of organic matter would be the difference between production and losses through decomposition, leaching and burning. Although compaction does not cause a real loss of materials, a compaction factor would have to be taken into account if accumulation is assessed in terms of depth instead of weight. Compaction of fresh organic materials is probably very small because the loading factor at the surface is rather low. Driessen and Subagjo (1975) estimated annual compaction of undrained forest peat to be in the order of 0.1 mm, which is about 3% of the 3.0 mm of gross annual organic matter accumulation.

In the following discussion, production and losses are considered on weight basis. Although there have been recent (1982-83) cases of forest fire spreading into PS areas in Sarawak and Indonesia during unusually dry weather, losses of peat through burning under the natural waterlogged conditions are generally insignificant. Table 11.1 shows a partial budget for organic matter production and losses through decomposition and leaching in PC 1, 4 and 6. It is not the full picture because not all the factors have been taken into account. On the production side, only small litter has been considered; other components like large wood litter, tree fall and rate of root growth and death are left out. However, it is probably fair to assume that as a comparison, small litterfall can be taken as an index of the actual total production, and that the comparative rates of production for other components are proportional to that of the small litter. For decomposition and leaching losses, similar assumptions can be made. However, another problem arises here because there is a certain degree of overlap between losses through decomposition and losses through leaching. When the fresh litter decomposes, certain amounts of materials are mineralized and these get into the water and are subsequently leached out. Such losses are therefore double-counted. Leaching losses, however, cannot be left out completely because some of the materials so lost are washed out of wholly or partially decomposed materials.

Weight losses of leaf litter and small wood are calculated from the negative exponential decay functions presented in Table 10.4. Although production and decomposition processes are uninterrupted, calculations are done on a monthly basis. Weight losses are then summed over the 12 months to give an annual figure; the materials left over from the previous year's budget are not considered. Leaching loss and rainwater input are estimated from annual rainfall, potential evaporation and concentrations of total dissolved solids in the peat water and rainwater (see Section 10.4).

The picture portrayed by Table 11.1 may be over-simplified. However, the semi-quantitative data do provide some evidence to partially support Anderson's (1961) suggestion that for a bog to evolve to a flat-top structure with relatively steep margins, the rate of accumulation at the periphery must increase or the rate at the centre must decrease.

TABLE 11.1 A PARTIAL BUDGET FOR ANNUAL PRODUCTION AND LOSSES OF ORGANIC MATTER IN THREE PC

Item (t/ha/yr)	PC 1	PC 4	PC 6
ADDITIONS :			
Production of small litter	7.17	6.23	3.45
Rainwater input	0.66	0.66	0.66
LOSSES :			
Cumulative wt. loss of leaf litter	3.02	1.47	0.52
Cumulative wt. loss of small wood	0.40	0.19	0.08
Leaching loss	2.62	0.88	0.84
Balance	1.79	4.35	2.67

As the PS evolves, the vegetation changes. At the same time, the rate of litter production and the type of materials getting into the peat also change. The differences in the parent materials are indicated by the decreasing trend of particle densities of the surface peats from PC 1 to PC 6 (see Section 9.4). Profile R.6/T41 sampled within PC 6 also shows a similar trend of decreasing particle densities vertically down the profile, with an average value of 1.406 g/cm^3 in the top 100 cm decreasing to 1.374, 1.349, 1.345 and 1.341 g/cm^3 at 100-200, 200-300, 300-400 and 400-500 cm depths respectively. Unfortunately, only one set of such data was available; more samples are required to confirm whether the spatial variation of particle densities across the peat dome is also reflected in the vertical trend. As the parent material *inter alia* changes, the dynamics of peat decomposition also alter. All these factors act concurrently to shape the morphology of the peat deposit that is observed today.

Although PC 1 has the highest production in terms of small litterfall (see Table 11.1), the rates of decomposition and leaching are also higher; the balance at the end of the year is the lowest among the three forest types examined. This situation results in a slower peat growth and the ground surface is kept low. PC 6 has lower production but also lower decomposition and leaching losses. The net result in PC 6 seems to be a positive gain of materials, thereby suggesting that a state of stasis has not been reached. PC 4 has a slightly lower production than PC 1 but its rates of decomposition and leaching are only slightly higher than or similar to those of PC 6. As a result, the net figure for PC 4 at the end of the year is the highest among the three forest types. These show that as the peat gets deeper and the surface vegetation evolves to the stage of Padang Paya Forest (PC 6), the rate of peat accumulation decreases. In the intermediate stages like the Padang Alan Forest (PC 4), the net rate of peat accumulation remains relatively high thus allowing the ground elevation here to gradually catch up with that of Padang Paya Forest. At the edges of the PS where Mixed Peat Swamp Forest (PC 1) occurs, the higher rate of decomposition, probably as a result of better drainage due to the convex shape, counteracts the higher rate of production. The net rate of peat accumulation is slower than that of PC 4, and the difference between them slowly causes the margins to get steeper. If this situation should proceed unchecked, PC 4 would eventually become higher than PC 1 and 6. This does not happen because as the peat in PC 4 gets deeper, the vegetation will evolve to become PC 5 and 6, and the rate of peat accumulation will also decrease concurrently. The overall effect is therefore the evolution from a gentle convex-topped structure to one with a flat top and relatively steep margins.

The steepness between two points on a sloping surface is a function of the height difference and the horizontal distance between them. The steepening effect at the edges due to an increased difference in elevation as a result of different accumulation rates will be reduced by lateral expansion of the margins of the peat deposit. However, this lateral growth is not unlimited. A common sequence of soils or catena from the river bank to the PS usually comprises well to moderately well drained alluvial mineral soils on the river levee, followed by poorly drained gleyed mineral soils which slowly grade into shallow peats and then deep peats on the low-lying area behind the levee. Laterally expanding peat deposit may encroach onto the gley soils and even the river levee but further growth will be limited by the river. Transects R.4 (Lubok Belanak), R.7 (Tanjung Pasir) and R.10 (Tanjung Upar) have relatively steep margins (see Fig. 6.1). Lateral growth at these localities had been limited by the river and this must have contributed to the development of the steep margins. Indeed, the reverse process is currently occurring at the edges in these localities: the river meanders are cutting into the peat margins causing gradual loss of materials through erosion.

Although the peat deposits at Kampung Nyabor (R.5) and Lubok Belanak (R.4) have formed at about the same time, the margin at Transect R.5 is not so steep. This is probably because lateral expansion of the peat deposit at Kampung Nyabor area is still possible (see Fig.6.1) and so the steepening effect at the periphery due to the differences in vertical growth is very much subdued. Figure 6.1(c) seems to show that the ground surface along Transect R.5 steepens suddenly at the boundary between PC 1 and 2. It would be interesting to find out whether this has been caused by the differences in the rates of peat accumulation between these two forest types.

As the periphery gets steeper, the groundwater will be drained off more easily. This effect has already been noted in PC 1 along Transect R.7 (Plot C) which is situated at the steep margin (see Fig.5.4) and where the rate of decomposition is relatively high (see Section 10.3). Therefore, as the domed morphology gets more pronounced, the net rate of peat accumulation at the edges will probably decrease. If this process continues, a situation will arise when the rate of decomposition at the steep, outer margin exceeds that of accumulation and the system begins to collapse. However, this may not occur because the vegetation at the centre and the intermediate zones may degenerate further, thus decreasing the rate of organic matter accumulation. A no-growth situation may be attained in the central parts of the swamp so that the outer margins will not steepen further. Eventually, an equilibrium may therefore be reached whereby the growth of the whole swamp ceases and production of organic matter by the climax vegetation then is exactly balanced by losses through decomposition and leaching.

Although the present study did not measure the absolute rates of peat accumulation under various PC, the partial budget of additions and losses (see Table 11.1) suggests that the peats under PC 1, 4 and 6 are still growing slowly with positive rates of accumulation. In Indonesia where similar zonation of PSF has been observed, large tracts of "Padang Forest" equivalent to PC 6 have also been described (Anderson,1976). It appears that PC 6 is the most advanced stage of vegetation succession in the current stage of PS development in the Malesia, and that a state of stasis has not been reached even under the most stunted vegetation of PC 6 which is likely to degenerate further.

11.3 GENERAL DISCUSSION AND RECOMMENDATIONS

Scientific Findings

REFERENCES

Afifi, A.A. and Clark, V. 1984. Computer-Aided Multivariate Analysis. Lifetime Learning Publications, California.

Ahmed, M.I. and Ng, T. T. 1973. Nutrient status assessment of a Sarawak deep peat. The Sarawak Gazette, Vol. XCIV, No. 1380, mp. 16-18.

Anderson, J.A.R. 1961. The ecology and forest types of the peat swamp forests of Sarawak and Brunei in relation to their silviculture. Ph. D. Thesis, Univ. of Edinburgh, U.K.

Anderson, J.A.R. 1963. The flora of the peat swamp forests of Sarawak and Brunei, including a catalogue of all recorded species of flowering plants, ferns and fern allies. Gardens' Bulletin, Vol. XX, Part II: 131-228.

Anderson, J.A.R. 1964a. The structure and development of the peat swamps of Sarawak and Brunei. J. of Tropical Geography, 18:7-16.

Anderson, J.A.R. 1964b. Observationson climatic damage in peat swamp forest in Sarawak. Commonwealth For Review 48:145-158.

Anderson, J.A.R. 1973. An introduction to the ecology of the peat swamps of Sarawak and Brunei. Proc. IPS Symposium on "Classification of Peat and Peatlands", Glasgow, Pp. 44-51.

Anderson, J.A.R. 1976. Observations on the ecology of five peat swamp forests in Sumatra and Kalimantan. Soil Research Institute, Bogor, Bull 3, 45-55.

Anderson, J.A.R. 1983. The tropical peat swamps of Western Malesia. In "Ecosystems of the world, Vol. 4B, Mires: Swamp, Bog. Fen and Moor", Ed. A.J.P. Gore. Elsevier Scientific Pub. Co., Amsterdam. Ch. 6:181-199.

Anderson, J.A.R. and Muller, J. 1975. Palynological study of a Holocene peat and a Miocene coal deposit from NW Borneo. Rev. Palaeobot. Palynol., 19:291-351.

Anderson, M.G. and Burt, T.P. 1978. The role of topography in controlling throughflow generation. Earth Surface Processes, 3:331-344.

Andrews, D.F., Gnanadesikan.R, and Warner,J.L.1973. Methods of assessing multivariate normality. In:*Multivariate Analyses III.* ed.P.R. Krishnaiah. Academis Press, New York.

Andriesse, J.P. 1972. The soils of West Sarawak (East Malaysia). Memoir I. Gov't printing office, Sarawak.

Andriesse, J.P. 1974. Tropical lowland peats in South-East Asia. Communication 64, Royal Tropical Institute, Amsterdam.

Ashton, P.S. 1964. Ecological studies in the Mixed Dipterocarp Forests of Brunei State. Oxford Forest Mem. 25.

REFERENCES

Ashton, P.S. 1971. The plants and vegetation of Bako National Park, Malayan Nature J. 24:151-162.

Ashton, P.S. 1973. Report on research undertaken during the years 1963-1967 on the ecology of the Mixed Dipterocarp Forests in Sarawak. MS, Botany Dept., Univ. of Aberdeen,U.K.

Atmawidjaja, R., Manan, S. and Soepangkat, S. 1987. The peat swamp forest ecosystem in Indonesia and its conservation and management. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Aubert, G. 1954. The hydromorphic soils of French West Africa. Trans. 5th Int. Congr. Soil Sci. 4:447-450.

Austin, M.P., Ashton, P.S. and Greig-Smith, P. 1972. The application of quantitative methods to vegetation survey III. A re-examination of rain forest data from Brunei. J. of Ecology, 60:305-324.

Bailey, H.H. 1950. Peat formation in the Tropics and subtropics. Proc. Soil Sci. Soc. Amer., 15:283-4.

Baillie, I.C. 1976. Further studies on drought in Sarawak, East Malaysia. J. Tropical Geography 41:9-15.

Baillie, I.C. 1978. Studies of site-forest relationships in the Mixed Dipterocarp Forest of Sarawak. Ph. D. Thesis, Univ. of Aberdeen, U.K.

Baillie, I.C. and Ahmed, M.I. 1984. The variability of Red Yellow Podzolic Soils under Mixed Diptercarp Forest in Sarawak, Malaysia. Malaysian J. of Trop. Geog. 9:1-13.

Beccari, O. 1904. Wanderings in the Great Forests of Borneo. Reprinted in 1986 by Oxford University Press. 424 pp.

Beveridge, A.E. 1953. The Menchali Forest Reserve. Malay. For., 16:3.

Black, T.A., Tanner, C.B. and Gardner, W.R. 1970. Evapo transpiration from a snap bean crop. Agron. J.62:66-69.

Blackburn, G. and Baker, R.M. 1958. A soil survey of part of Brunei, British Borneo. CSIRO (Australia) Soils Land Use Ser. No. 25, pp. 84.

Browne, F.C. 1952. The Kerangas lands of Sarawak. Malay. Forest. 15(2):61-73.

Brunig, E.F. 1961. Regional management plan for Bintulu peat swamp forest. Forest Dept., Sarawak.

Brunig, E.F. 1964. A study of damage attributed to lightning in two areas of *Shorea albida* forest in Sarawak. Empire For. Review 43:134-144.

Brunig, E.F. 1971. On the ecological significance of drought in the Equitorial wet evergreen (rain) forest of Sarawak (Borneo). In "The Water Relations of Malesian Forets", ed. by J.R. Flenley, Univ. of Hull,U.K. Misc.Series No.11, p.66-88.

REFERENCES

Brunig, E.F. 1974. Ecological studies in the Kerangas Forest of Sarawak and Brunei. Borneo Literature Bureau, Kuching, 237 pp.

Buol, S.W., Hole, F.D. and McCracken, R.J. 1973. Soil genesis and classification. The Iowa University Press, Ames. 360 pp.

Cattell, R.B. 1966. The meaning and strategic use of factor analysis. In *Handbook of Multivariate Experimental Psychology*, ed.R.B.Cattell. Rand McNally, Chicago.

Chai, P.P.K. 1982. Ecological studies of mangrove forests in Sarawak. Ph. D. Thesis, Univ. of Malaya, K.L.

Chan, F. and Purba, P. 1987. Oil palm on peat soils in North Sumatra. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Charin Samati 1987. Net primary production of *Melaleuca leucadendron* stands in swamp forest of Narathiwas Province. Presented at IPS Symposium on "Tropical Peat and Peatlands for development", Indonesia.

Chenery, E.M. 1953. A digest of the chemistry of dead swamps in Kigezi District, S.W. Uganda, Repr. Rep. Hydro. Surv. Dep., Uganda, pp.6.

Chew, W.Y. 1970. Effects of length of growing season and NPK fertilizers on the yield of five varieties of sweet-potatoes (*Ipomoea batatas*) on peat. Mal. Agric. J. 47:453-464.

Chew, W.Y. 1977. Assesssment of Cassava as an industrial crop on Malaysian Peat. Report No. 57, MARDI, KL.

Chew, W.Y. and Yeong, N.H. 1974. An observation on the yield of some vegetables grown on Malaysian Peat. Mal. Agric. J. 49:433-436.

Chin Siew-Phin, 1986. A laboratory manual of methods of soil analysis. Research Branch, DOA, Sarawak.

Chin Siew-Phin, 1987. A laboratory manual of methods of plant analysis. Research Branch, DOA, Sarawak.

Clarke, E.C. 1968. Silvicultural practice in Sarawak 1960-9. Malayan Forester 3(4):305-309.

Clayton, W.D. 1958. A tropical moor forest in Nigeria. J.W. African Sci. Assoc. 4.

Clayton, J.S. Ehrlich, W.A., Caun, D.B., Day, J.H. and Marshall, I.B. 1977. Soils of Canada, Research Branch, Canada Dept. of Agriculture.

Coulter, J.K. 1950. Peat formations in Malaya. Malayan Agricultlural J., 33:63-81.

Coulter, J.K. 1955. Soil Survey of jungle swamps for padi cultivation. Int. Rice comm. News-letters No. 15, 11-14.

REFERENCES

Coulter, J.K. 1956. Soil Survey reports No. 4, Kuala Langat (North) Forest Reserve, Malayan Agricultural J., 39.

Coulter, J.K. 1957. Development of the peat soils in Malaya. Malaya Agricultural J., 40:188-199.

Coulter, J.K., McWalter, A.R. and Arnott, G.W. 1956. Soil Survey reports No. 3, the Trans-Perak swamp. Malayan Agricultural J., 39:99-120.

Dachnowski-Stokes, A.P. and Roberts, R.C. 1934. Saline peat profiles of Puerto Rico. J. Washington Acad. Sci. 24:175-182.

Dames, T.W.G. 1962. Soil research in the economic development of Sarawak. Report no. 1512, FAO, Rome.

Daultrey, S. 1976. Principal component analysis. Concepts and Techniques in Modern Geography No.8, Geo Abstracts Ltd., University of East Anglia, Norwich.

Davis, J.C. 1973. Statistics and Data Analysis in Geology. J. Wiley &Sons, New York. 550pp.

Davis, J.H. 1946. The peat deposits of Florida, their occurrence, development and uses. Florida Geol. Surv. Bull. 30.

Day, J.H., Rennie, P.J., Stanek, W. and Raymond G.P. 1979. Peat testing Manual. Tech. Memo. no. 125, National Research Council, Canada.

Dent, D. 1986. Acid Sulphate Soils: A Baseline for Research and Development. ILRI Publication No.39. ILRI, Wageningen, The Netherlands.

Driessen, P.M. 1977. Peat soils. Proc. of IRRI Symposium on "Soil and Rice", IRRI, Philippines.

Driessen, P.M. and Rochimah, L. 1976. The physical properties of lowland peats from Kalimantan. Soil Research Institute, Bogor, Bull. 3, 56-73.

Driessen, P.M. and Subagjo, 1975. Growth and subsidence of tropical ombrogenous peats - a semi-quantitative approach. Proc. 3rd Asean Soil Conference.

Driessen, P.M. and Sudewo, P. 1977. A review of crops and crop performance on Southeast Asian lowland peats. Soil Research Institute, Bogor, Bull 4, pp. 94.

Driessen, P.M. and Sudjadi, J. 1976. On the defective grain formation of Sawah rice on peat. Soil Research Institute., Bogor, Bull 3, 20-44.

Driesssen, P.M. and Sudjadi, J. 1981. Soil and specific soil problems of tidal swamps. Int. workshop on Research Priorities in Tidal Swamp Rice (Manuscript).

Durgnat, P.A. 1952. Swamp forests in Lower Perak. Malay. Forester 15.

Ehrencron, V.K.R. 1949. Preliminary pot experiments with acid peat from Borneo. Comm. Gen. Agr. Res. Sta. Bogor, Java No. 90.

Eilers, R.G. and Loi Kuong Soon 1982. The soils of northern interior Sarawak (East Malaysia). Memoir 3. National Printing Dept., Sarawak.

Eiumnoh, A. 1987. Peatland development and characterization in Southern Thailand. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Endert, F.H. 1920. De woudboom flora van Palembang. Tectona, 13.

Esterle, J.S., Ferm, J.C., Durig, D.T. and Supardi 1987. Physical and chemical properties of peat near Jambi, Sumatra, Indonesia. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

F.A.O. 1974. Soil map of the world. Volume I - Legend. FAO - Unesco, Paris.

Farnham, R.S. and Finney, H.R. 1965. Classification and properties of organic soils. Advances in Agronomy, 17, 115-162.

Fitch, F.H. 1952. The geology and mineral resources of the neighbourhood of Kuantan, Pahang, Geol. Scien. Dept. (Ipoh), Fed. of Malaya, Memoir 6.

Fitch, F.H. 1953. Fuel value of peat near Papar. In Annual Report of the Geological Survey Department for 1953, F.W. Roe (ed.). Gov't Printing Office, Sarawak.

Fitzatrick, E.A. 1971. Pedology - A Systemic Approach to Soil Science. Oliver & Boyd, Edinburgh.

Furtado, J.I., Verghese, S., Liew, K.S. and Lee T.H. 1980. Litter production in a freshwater swamp forest, Tasek Bera, Malaysia. Tropical Ecology and Development, 815-822.

Guinazu, J.R. 1934. The peat deposits of the region of Fuego. Publ. No. 10, Direc. Minoas y Geol., Buenos Aires.

Haeruman, H. Js. 1987. Peat swamps utilization and its environment impacts. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Haile, N.S. 1971. Quaternary shorelines in West Malaysia and adjacent parts of the Sunda Shelf. Quarternaria XV:333-343.

Hand, D.J.1981. Discriminant and Classification. John Wiley & Sons, Chichester. 218pp.

Hardjonigeno, S. and Selari, M. 1987. Suitability of peat soils in Sumatra for agricultural development. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Hardy, F. 1936. Some aspects of tropical soils. Trans. 3rd Int. Congr. Soil Sci., 2:150-163.

Harman, H.H. 1967. Modern Factor Analysis. 2nd ed. University of Chicago Press.

Harris, W.F. 1968. Peat classification by pedological methods, applied to peats of Western Wellington, New Zealand. Bulletin 189, Dept. of Scientific and Industrial Research, N.Z.

Hashim, Mohd. Yusof 1984. Potential and problem of kpeat for agriculture in Malaysia. Proc. of workshop on "Classification and Management of Peat in Malaysia", Malaysian Society of Soil Science, K.L. P. 3-10.

Heincelman, M.L. 1963. Ecol. Monographs 33:327-374.

Hewitt, B.R. 1967. The occurrence, origin and vegetation of lowland peat in Malaya. Proc. Linn. Soc. N.S.W.92:58-66.

Hull, C.H. and Nie, N.H. 1981. SPSS Update 7-9:New Procedures and Facilities for Release 7-9. McGraw-Hill Book Co., New York.

Ismail Abu Bakar 1984. Characterisation of lowland organic soils in Peninsular Malaysia. Proc. of Workshop on "Classification and Management of Peat in Malaysia", KL. P. 109-126.

Jordan, C.F. 1985. Nutrient Cycling in Tropical Forest Ecosystems: Principles and Their Application in Management and Conservation. John Wiley & Sons, Chichester. 190 pp.

Joseph, K.T., Chew W.Y. and Tay T.H. 1974. Potential of peat for agriculture. Report No. 16, MARDI, KL.

Kamal, A.J.M., Othman Yaacob and Nik Mokhtar Nik Wan. 1987. The potential of peatland for oil palm. Presented at IPS Symposium on "Tropical Peat and Peatlands for Developments", Indonesia.

Kanapathy, K. 1978. Planting oil palms on peat. Perak Planters' Assoc. J. 101-107.

Kawaguchi, K. and Kyuma, K. 1977. Peddy soils in Tropical Asia - Their material nature and fertility. Monograph of the centre for SE. Asian Studies, Kyoto University.

Kim, J.O. and Mueller, C.W. 1978. Introduction to Factor Analysis. Sage Press, Beverly Hills.

Koopmans T. Th. and Andriesse, J.P. 1982. Baseline study - Monitoring project of nutrient cycling in shifting cultivation. Progress Rep. No. 1, Royal Tropical Institute, Amsterdam.

Korpijaakko, E.O. 1987. On the peat resources of Senegal. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Kostermans, A.J.G.H. 1958. Note on lowland vegetation in equitorial Borneo. Study of Tropical Vegetation. Proc. of the Kandy Symposium. UNESCO.

Kueh, Hong Siong, Elone, R., Tie Yiu Liong, Ung Chin Min and Jaman Hj. Osman 1987. Mukah sago plantation feasibility study. Lembaga Pembangunan dan Lindungan Tanah, Sarawak.

Kueh, Hong Siong and Wong, Siu Hieng 1983. Pilot project proposal for peat development in Nonok (Asajaya) Scheme (memeo.).

Kyuma, K. and Pairinta, C. 1983. Shifting cultivation - An experiment at Nam Phrom, Northeast Thailand and its implications for upland farming in the Monsoon Tropics.

REFERENCES

Lallanne de Haut, J.P.Y.M. 1965. Depositional history of the recent Baram Delta. Borneo Reg.Malaysia Geol.Survey Ann. Rep., p.168-172.

Lappalainen, E. 1987. The usefulness of peat in Sri Lanka. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Laudelout, H. and Meyer, J. 1954. Les cycles d'elements minereaux et de matiere organique en foret equatoriale congolaise. Trans. of the 5th Int. Congr. of Soil Sci., 2, 267-272.

Lee, Hua Seng, 1972. Regeneration of Mixed Swamp Forests after exploitation. Forest Dept. Conference, Sarawak.

Lim, Chin Pang, 1975. Notes on Soil Classification in Sarawak. SSD, DOA, Sarawak.

Lim, Chin Pang, 1972. Report on a semi-detailed soil survey of the Benawa Area. Report No. 172, SSD, DOA, Sarawak.

Louie, R.H. and Lah Jau Uyo (in prep.). The soils of Central Interior Sarawak, Soil Memoir No. 4, Soils Division, DOA, Sarawak.

Lucas, R.E. 1982. Organic soils (Histosols): Formation, distribution, physical and chemical properties and management for crop production. Research report 435, Michigan State University.

Lucas, R.E. and Davis, J.F. 1961. Relationships between pH of organic soils and availabilities of 12 plant nutrients. Soil Sci. 92:177-182.

Lynn, W.C. Mckinzie, W.E. and Grossman, R.B. 1974. Field laboratory tests for characterization of Histosols. In "Histosols: Their characteristics, classification and use", SSSA Special Publication Series No. 6, Wisconsin, USA.

Maas, E.F., Tie Yiu Liong and Lim Chin Pang 1986. Sarawak land capability classification and evaluation for agricultural crops (2nd edition). Technical paper No. 5, SD, DOA, Sarawak.

Maher, W. 1980. The contribution of Irish bogs to Ireland's energy requirements in the 1980s. Proc. of 6th International Peat Congress, Duluth, Minnesota, U.S.A. P.251-256.

Mclellan, J.K. and Rock, C.A. 1986. The application of peat in environmental pollution control: A review. Int. Peat Journal, 1:1-14.

Miller, R.W.R. 1949. Sarawak's peat swamps. Annual Report, DOA, Sarawak. P. 57-59.

Miller, A.A. 1953. Climatology. Methuen, London (8th Edition).

Mohr, E.C.J., Van Baren, F.A. and Van Schuylenborgh, J.1972. Tropical Soils. Mouton, The Hague.

Moore, P.D. and Bellamy, D.J. 1974, Peatlands. Elek Science, London.

REFERENCES

Newbery, D. McC, and Proctor, J. 1984. Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak. IV. Association between tree distribution and soil factors. J. of Ecology, 72:475-493.

Nie,N.H., Hull,C.H., Jenkins,J.G., Steinbrenner,K. and Bent, D.H. 1975. SPSS - Statistical Package for the Social Sciences. 2nd ed. McGraw-Hill Book Co., New York.

Norusis, M.J. 1986. SPSS/PC+ Advanced Statictics V.2.0 for the IBM PC/XT/AT and PS/2. SPSS Inc., Chicago.

Nye, P.H. and Greenland, D.J. 1960. The soil under shifting cultivation. Tech. Comm. No. 51, Commonwealth Bureau of soils, Harpenden.

Oldeman, L.R. and Frere, M. 1982. A study of the agroclimatology of the humid tropics of Southeast Asia, FAO, Rome.

Ooi, Ho Seng, 1985a. Studies on mechanical clearing of undecomposed wood in peat soil. Report No. 95, MARDI, KL.

Ooi, Ho Seng, 1985b. Evaluation of a mini-excavator for maintenance work on peat soil. Report No. 96, MARDI, KL.

Ottow, J.C.G., Prade,K., Benckiser,G. Jacq,V., Bertenbreit er, W., and Djakasutami, S. 1987. Alleviation of iron toxicity with wetland rice (*Oryza sativa* L.) on snady and peaty soils of Asia and Africa. Presented at IPS Symposium on "Tropical Peat and Peatland for Development", Indonesia.

Parbery, D.B. and Venkatachalam, R.M. 1964. Chemical analysis of South Malayan peat soil. J. Tropical Geog., 18:124-133.

Paul, H. 1953. The trace element status of peat soils in British Guiana. Proc. Int. Soc. Sugar Cane Tech. 209-214.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. A., 190:120-145.

Pillai, T.R.N. and Subrahmanyan, V. 1931. The origin and nature of the peaty soils of Travancore. J. Indian Inst. Sci. 14A, Pt. VII, 99-117.

Polak, B. 1941. Peat investigation in the Netherlands Indies: an outline of the problems. Landbouw 17:1033-1062.

Polak, B. 1946. Peat research in the Netherlands Indies. Natuurw. Tijdschcrift voor Nederlandsch Indie 102:63-73.

Polak, B. 1950. Occurrence and fertility of tropical peat soils in Indonesia. Proc. 4th Int. Congress of Soil Sci., Vol. II: 183-185.

Ponnamperuma,F.N. 1972. The chemistry of submerged soils. Advances in Agronomy, Vol. 24:29-96.

Pons, L.J. and Driessen, P.M. 1976. Waste land areas of oligotrophic peat and acid sulphate soils in Indonesia.

Potenie, H. and Kooders, S.H. 1909. Sumpfflachmoornatur der Moore des Produktiven Karbons. Jahrb. Kon. Prcusz. Geol. Landesanstalty Berlin.

Proctor, J. 1983. Tropical forest litterfall I. Problems of data comparison. Tropical Rain Forest: Ecology and Management, Special Publication No. 2 of British Ecological Society, p. 267-273.

Proctor, J., Anderson, J.M., Chai, P. and Vallack, H.W. 1983a. Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak. I. Forest environment, structure and floristics. J. of Ecology, 71:237-260.

Proctor, J., Anderson, J.M., Fogden, S.C.L. and Vallack, H.W. 1983b. Ecological studies in four contrasting lowland rain forests in Gunung Mulu National Park, Sarawak. II. Litterfall, litter standing crop and preliminary observations on herbivory. J. of Ecology, 71:261-283.

Quijano, C.C. and Neue, H.U. 1987. Role of varietal tolerance in rice production on peat soil. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Ramirez, A., Thayer, G., Cohen, A.D., Raymond, R.Jr.,and Allen, A. 1987. Peat deposit in Panama : Their potential for use in energy applications. Presented at IPS Symposium on "Tropical Peat and Peatlands for Developed, Indonesia.

Reifenberg, A. and Moshiky, S. 1941. Palestine peat in relation to other peats. Soil Sci. 51:173-180.

Richards, P.W. 1952. Tropical Rain Forest. Cambridge Univ. Press.

Richards, P.W. 1961. The types of vegetation in the humid tropics in relation to the Soil. Proc. Symp. on Tropical Soils and Vegetation, Abidjan. UNESCO, Paris. PP. 15-24.

Ripado, M.F.B. 1954. Peat soils of Southern Mozambique. Proc. 2nd Int. African Soils Conf. 2:927-32.

Schimper, A.F.W. 1903. Plant-geography upon a physiological basis. O.U.P. Oxford.

Schmidt, F.H. and Fergusen, J.H.A. 1951. Rainfall types based on wet and dry period ratios for Indonesia with Western New Guinea. Kementarian Perhubungan Djawatan Meteorologi dan Geofisik, Jakarta, Verhandelingen 42.

Scott, I.M. 1973. A draft reclassification of soils in Central and North Sarawak. Technical paper No. 3, Research Branch, DOA, Sarawak.

Scott, I.M. 1985. The soils of Central Sarawak Lowlands, East Malaysia. Memoir 2. National Printing Dept., Sarawak.

Sewandono, M. 1938. Peat areas of Bengkalis (Sumatra). Tectona 31:99-135.

Sieffermann, G., Kristijono, A. Parhadimulyo, S.A., Triutomo, S. and Sadelman, M.T. 1987. Peat genesis in the lowlands of Central Kalimantan province: the respective influence of podzolisation and bad drainage. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Sieffermann, G. and Sasitiwarih, A. 1987. Remote sensing in peat survey: contribution to soil mapping of Central Kalimantan province using computer analysis of data. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Sillanpaa, M. 1972. Distribution of trace elements in peat profiles. Proc. 4th Int. Peat Cong., Finland. Vol. V: 185.

Sinaga, V.M. 1987. The role of peat as a seedling medium in supporting a successful reforestation. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Sjors, H. 1961. Endeavour 20:217-224.

Smythies, B.E. 1950. Survey of peat swamp forests of Lower Rajang. Forest Dept., Sarawak (Unpubl.).

Smythies, B.E. 1951. Survey of peat swamp forests of the Oya-Mukah area. Forest Dept., Sarawak (Unpubl.).

Soepardi, G., Surowinoto, S. and Djajakirana, G. 1987. Inland peat as agricultural land. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Soepraptohardjo, M. and Driessen, P.M. 1976. The lowland peats of Indonesia, a challenge for the future. In : Peat and Podzolic soils and their potential for agriculture in Indonesia, Bulletin 3, Soil Research Institute, Bogor. P. 11-19.

Soil Survey Staff 1966. A classification of Sarawak soils. Technical Paper No. 2, Research Branch, DOA, Sarawak.

Soil Survey Staff 1975. Soil Taxonomy. Agriculture Handbook No. 436, USDA.

Soil Survey Staff 1981. Soil Survey Manual (Revised). Soil Conservation Service, (Mimeo.).

Speight, J.G. 1980. The role of topography in controlling throughflow generation: A discussion. Earth Surface Processes, 5:187-191.

Steward, J.M. and Reader, R. 1970. Some considerations of production:accumulation dynamic in organic terrain. In Proc. of 4th Int. Peat Congress, Finland, Vol. 1, 247-258.

Subramoney, N. 1951. Fertility investigation on the acid peats (Kari) of Travancore. I. Descriptive features and general considerations. Bull. Cent. Res. Inst. Univ. Travanscore 2A:1-16.

Suhardjo, H. and Widjaja-Adhi, IPG. 1976. Chemical charac teristics of the upper 30 cm of peat soils from Riau. Soil Research Institute, Boger, Bull. 3, 74-94.

Swift, M.J., Heal, O.W. and Anderson, J.M. 1979. Decomposition in Terrestrial Ecosystems. Blackwell Scientific Publications, Oxford.

Tay, T.H. 1972. Crop production on West Malaysian Peat. Proc. 4th Int. Peat Congress, Finland, Vol. 3, 75-88.

Tay, T.H. and Wee, Y.C. 1972. Liming of peat soils and its effect on pineapple. Malaysian pineapple 2:53-59.

Taylor,J.A. 1964. Distribution and development of the world's peat deposits. Nature,Vol.201: 454-456.

Tie, Yiu Liong, 1977. Properties of organic soils. Proc. of Seminar on Water Management for Agricultural Devel opment. Ministry of Agriculture and Community Development, Sarawak.

Tie, Yiu Liong, 1982. Soil classification in Sarawak. Technical paper no. 6, Soils Division, DOA, Sarawak.

Tie, Yiu Liong 1988a. A report on the semi-detailed soil survey of Sibu-Bintangor deep peat areas. Report No. 260, Soils Division, DOA, Sarawak.

Tie, Yiu Liong 1988b. A rport on the detailed soil survey of Lebaan-Bawang Assan NSSIP area, Sibu Division. Report No. 262, Soils Division, DOA, Sarawak.

Tie, Yiu Liong, and Lim, Chin Pang, 1976. Peat soils for sago growing in Sarawak. Presented at the First International Sago Symposium, Sarawak.

Tie, Yiu Liong, Baillie, I.C., Phang, Min Sen and Lim, Chin Pang, 1979. Soils of Gunong Mulu National Park, Soil Survey Division, DOA, Sarawak.

Tie, Yiu Liong (In Preparation). A report on the detailed soil surveys of Peat Research stations and Bareo peat areas. Report No. 271, Soils Division, DOA, Sarawak.

Tie, Yiu Liong and Kueh, Hong Siong, 1979. A review of lowland organic soils of Sarawak. Technical Paper No. 4, Research Branch, DOA, Sarawak, Malaysia.

Todorov, A.V. 1980. Soil temperature in Malaysia, MARDI Report No. 69.

UNESCO 1958. Study of tropical vegetation. Proc. of the KANDY Symposium, 1956.

Van de Meene, E.A. 1984. Geological aspects of peat formation in the Indonesian-Malaysian lowlands. Bull. Geol. Res. and Dev. Centre, No. 9, Bangkok.

Van der Veen, R. 1938. Peat soils in Besuki. Meded. Besoek, Proefsta. 61:24-39.

Van Steenis, C.G.G.J. 1950. Flora Malesiana, Series 1, Vol. 1.

Van Steenis, C.G.G.J. 1958. Commentary on the Vegetation Map of Malaysia, UNESCO.

Van Wijk, C.L. 1951. Soil survey of the tidal swamps of South Borneo in connection with the agricultural possibilities. Contr. Gen. Agric. Res. Sta. Bogor No. 123, pp. 49.

Viraraghaven, T. and Rana, S.M. 1987. Utilization of peat in onsite wastewater disposal systems. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Wade, B. and Blackwood, N. 1987. Peat and peatland utilization options in Jamaica. Presented at IPS Symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Wahl, P.W. and Kronmal,R.A. 1977. Discriminant functions when covariances are unequal and sample sizes are moderate. Biometrics, 33:479-484.

Waksman, S.A. 1942. The peats of New Jersey and their utilization. Geologic series, Bulletin 55, Dept. of Conservation and Development, New Jersey.

Wall, J.R.D. 1966. The Bekenu-Niah-Suai Area, Sarawak, Malaysia: An analysis of the environment, a detailed appraisal of the soils and the technique of soil mapping, and an assessment of the agricultural potential. Ph. D. Thesis, Univ. of Reading, U.K.

Walsh, R.P.D. 1982. Climate. Gunung Mulu National Park, Special Issue No. 2. The Sarawak Museum Journal, Vol. XXX, No. 51:29-67.

Wang, C. 1982. Application of transect method to soil survey problems. LRRI contribution No. 82-02, Research Branch, Agriculture Canada.

Weber, C.A. 1903. Uber tort, humus and moor. Adhandl. Naturw. Ver Bremen 17:465-484.

Wee, Y.C. 1972. Weed infestation of peat areas under pine- apple cultivation in West Malaysia. Proc. 4th Int. Peat Congress. Vol. 3, 165-174.

White, Sir B., Wolfe B. and Partners 1956. Development report with project plans and estimates for the Nonok Peninsular, Sarawak, Vol. 1, 2 and 3.

White, Sir B., Wolfe, B. and Partners 1957a. Report on Maludam Peninsular, Sarawak (Unpub.).

White, Sir B., Wolfe, B. and Partners 1957b. Report on Baram-Tinjar Area, Sarawak (Unpub.).

Whitmore, T.C. 1975. Tropical Rain Forests of the Far East, Clarendon Press, Oxford, 281 pp.

Whittaker, R.H. and Marks,P.L. 1975. Methods of assessing terrestrial productivity. In *Primary Productivity of the Biosphere*, ed. by H. Lieth and R.H. Whittaker, Springer-Verlag, New York Inc. Pp.55-118.

Wilford, G.E. 1961. The geology and mineral resources of Brunei and adjacent parts of Sarawak. Memoir 10, Geol. Surv. Dept., Brit. Territories in Borneo, 319 pp.

Wiraatmadja, Suhaldi 1987. Present status and prospects of peat soil for the promotion of food crop production. Presented at IPS symposium on "Tropical Peat and Peatlands for Development", Indonesia.

Wolfenden, E.B. 1960. The geology and mineral resources of the Lower Rajang Valley and adjoining areas, Sarawak. Govt Printing Office, Kuching, Sarawak.

Wyatt-Smith, J. 1959. Peat swamp forest in Malaya. Malay. Forester 22.

Yim, K.M., Tay, C.S., Mohd. Puat Yahaya, Mohd. Tayeb Dolmat and Ariffin Ismail 1984. Early performance of oil palm on deep peat in RISDA Mini Estate, Parit Seraya, West Johore Integrated Agricultural Development Project. Proc. of Workshop on "Classification and Management of Peat in Malaysia", K.L. p. 19-41.

Zuraina Majid, 1982. The West Mouth, Niah, in the Prehisto- ry of Southeast Asia. The Sarawak Museum Journal, Vol. XXXI, No. 52 (Ch. III, p. 31-34).

PLATE 1. High groundwater table - Under the natural conditions, peat soils in Sarawak have a groundwater table at or near the surface most of the year round.

PLATE 2. Groundwater had to be bailed constantly for pit description and sampling.

PLATE 3. Macaulay peat sampler, with one-metre extension rod, and Edelman auger.

PLATE 4. Cage for decomposition study - Samples of freshly fallen leaves and small wood were placed inside the cage.

PLATE 5. One batch of large wood samples to be buried for decomposition study.

PLATE 6. Piezometer for water table. monitoring

PLATE 7. An uprooted tree showing the shallow rooting system.

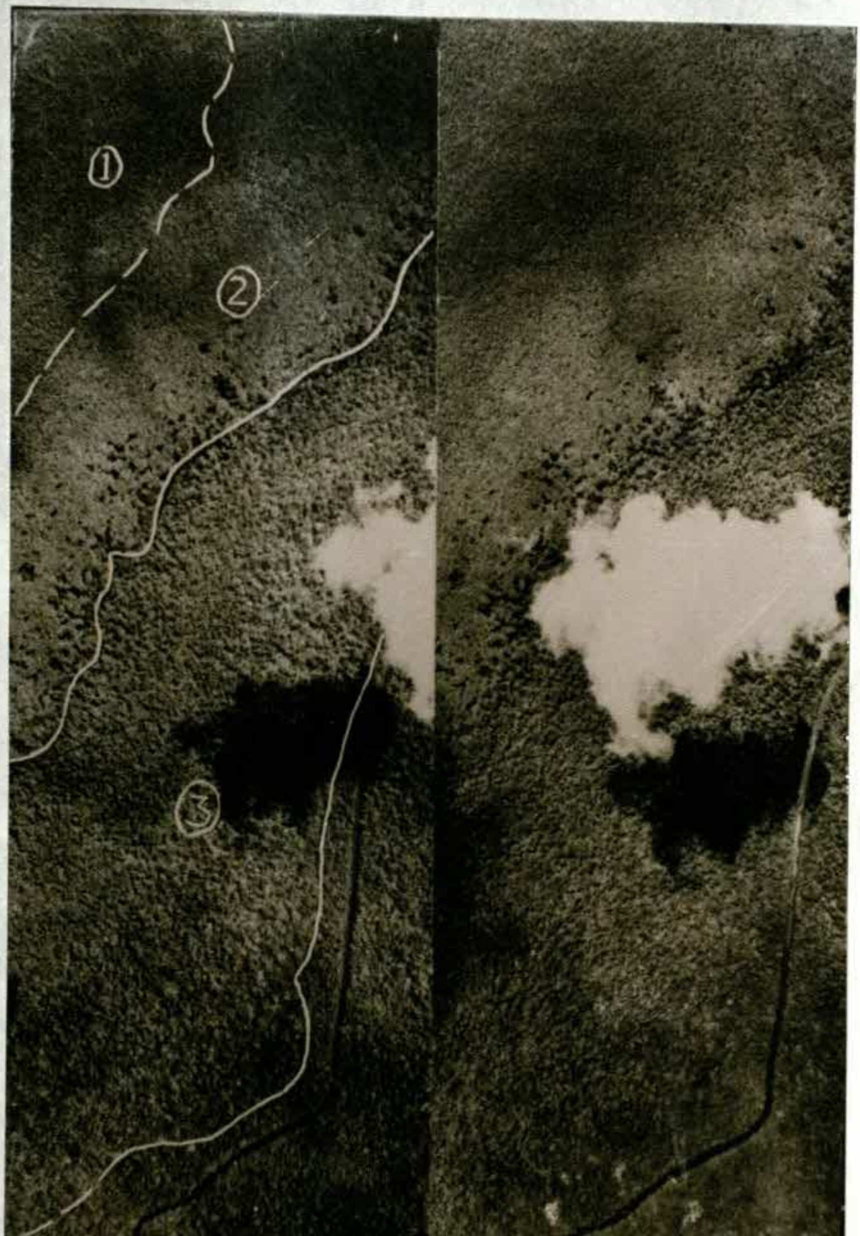


PLATE 8. The zonation of forest types across a peat dome can be easily identified on conventional monochrome air-photograph (stereo pair). 1= Padang Alan Forest (PC 4); 2= Alan Bunga Forest (PC 3); 3= Mixed Swamp Forest (PC 1); and 4= Riparian Forest.

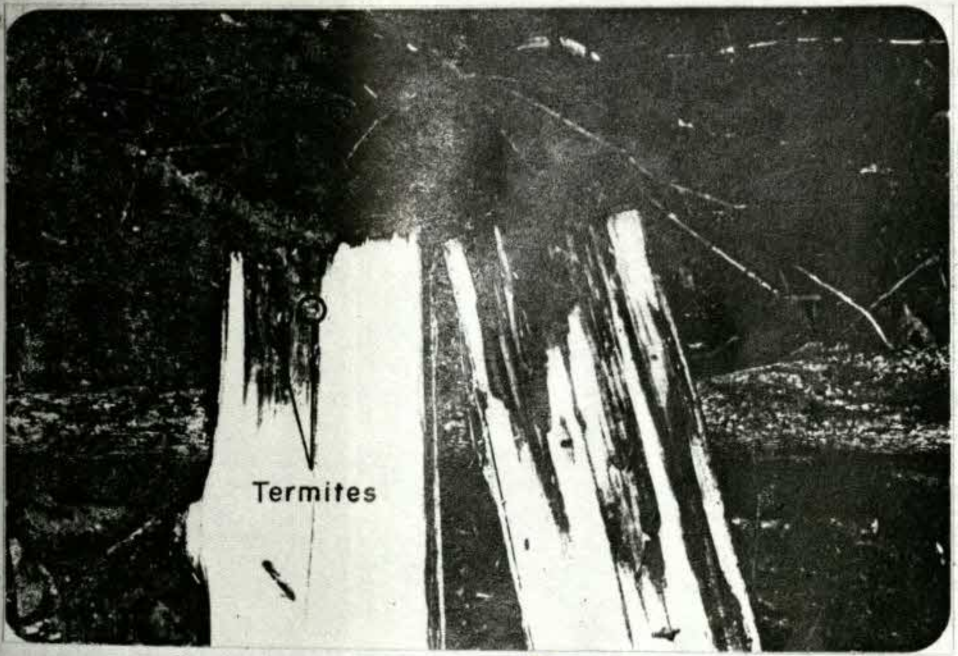


PLATE 9. In Plot C within PC 1, the large wood sample was attacked by termites.

PLATE 10. In some localities, river bank erosion has cut into and exposed the peat deposit.

APPENDIX 1. LABORATORY ANALYSES

1.1 ANALYSES OF SOIL SAMPLES

All the chemical analyses except pH and TS were carried out in the Chemistry Laboratory of Agricultural Research Centre at Semongok. Soil pH and physical analyses like bulk density, fibre content, PCI and shrinkage were done at the office of Soils Division, Department of Agriculture, Kuching. TS was done in the University of Kentucky,USA in collaboration with a PhD student, J.Esterle. The methods of all these analyses are described in detail by Day *et al.*(1979) and Chin (1986). A brief summary of these methods are given below.

Soil pH - pH(H_2O) was measured with a pH meter in a 1:2.5 soil:water suspension after 2 hours of equilibration. Fresh(moist/wet) soil samples were used. For the first batch of samples, pH(KCl) and pH($CaCl_2$) were also determined using 1N KCl and 0.01M CaCl solutions respectively.

Loss on ignition (LI) was determined by igniting a sample of oven-dried soil at 800^{0}C for one hour. Hundred percent subtracted by LI gave the ash (or mineral) content.

Organic carbon (OC) was measured by oxidising the organic matter with acidified potassium dichromate and then titrating for the unused dichromate with ammonium ferrous sulphate solution (Walkley and Black method).

Total nitrogen (N) was determined by a semi-micro kjeldahl method of acid digestion, steam distillation after adding caustic soda and titration of evolved ammonia against hydrochloric acid.

Exchangeable bases (ECa, EMg, EK and ENa) were extracted by leaching the soil with 1M ammonium acetate buffered at pH 7.0. K and Na in the extract were determined by flame photometry and Ca and Mg by atomic absorption spectrophotometry. The leached soil was then used to determine the **cation exchange capacity (CEC)** by replacing the exchangeable ammonium, distilling the leachate after adding MgO powder and then titrating the distilled ammonia against HCl.

Available P (AP) was measured by shaking the soil with Bray II solution (0.03N NH_4F and 0.1N HCl) for one minute at 1:20 soil: extractant ratio. After filtration, the extracted P was determined colorimetrically by auto-analyser.

Total analyses (TCa,TMg,TK,TP,TFe,TMn,TCu and TZn) - The ground soil sample was ashed, moistened with conc.HCl and baked. The residue was then dissolved in 2N HNO_3 and the solution brought to volume with distilled water.Ca, Mg, Fe, Mn, Cu and Zn in the extract were determined by atomic absorption spectrophotometry, K by flame photometry and P colorimetrically by auto-analyser.

Total S (TS) - between 0.2-0.5g of pulverized, oven-dried sample was combusted in an oxygen atmosphere in Leco SC32 analysis system which typed out the percent S value automatically and was calibrated every 15 or so samples.

Shrinkage was determined by measuring the dimensions of the ring sample after air-drying, after re-saturation and then after it was oven-dried. The change in volume, each time, was expressed as a percentage of the volume of the moist sample.

Bulk density (BD) was determined by oven-drying the ring sample or undistributed sample with known volume to constant weight at 105^{o}C.

Particle density (PD) was measured by kerosene displacement with a pycnometer.

Fibre content before rubbing(FBR) was determined by rinsing a fresh sample with water while it was placed on a 200-mesh sieve and measuring the volume of the sample left by the use of a modified graduated plastic hypodermic syringe. The residue was then rubbed lightly between the thumb and fingers while it was again rinsed over the sieve. The volume of the remaining sample was again determined to give the **fibre content after rubbing (FAR)**.

Sodium pyrophosphate colour index (PCI) was determined by soaking soil sample in a pyrophosphate solution overnight and then dipping a strip of chromatographic paper into the suspension. The colour of the chromatographic paper was then compared with a Munsell Soil Colour Chart. The result was expressed as the difference between value and chroma ratings.

Pyrophosphate solubility (of organic matter) index (PSI) - The soil sample was extracted for 18 hours with pyrophosphate solution at room temperature. The colour intensity of the extract after filtration and 5-fold dilution was then measured with a spectrophotometer at 550 nm.

Granulometric composition of the mineral subsoil was determined by the pipette method, after soil pretreatment with hydrogen peroxide. Dispersion was achieved by adding Calgon solution (50 g of a commercial mixture of sod. hexametaphosphate and sod. carbonate in one litre of water) and stirring with a high-speed stirrer. The pipetting intervals used gave the upper and lower silt-size limits of 0.05 and 0.002 mm.

1.2. WATER ANALYSES

pH was measured with a pH meter.

Electrical conductivity(EC) was measured with a conductivity meter and the reading was standardised at 25°C.

N, Ca, Mg, Na, K and Cl were determined after filtering off the suspended particles. Ca and Mg were measured by atomic absorption spectrophotometry, K and Na by flame photometry and N by distillation and titration of evolved ammonia against HCl. Cl was determined by titration against standard silver nitrate solution.

Total dissolved solids (TDS) was determined gravimetrically by evaporating an aliquot of filtered water sample.

1.3. ANALYSES OF LITTERFALL

Sample preparation - Oven-dried leaf and small wood samples were ground separately in a Wiley mill.

Total N - About 50 mg of ground sample were digested by Kjeldahl method. The content after digestion was transferred to a 100-ml flask and made up to volume with distilled water. N in the extract was determined colorimetrically by Technicon Autoanalyser II (Chin, 1987).

Total P, K, Ca, Mg and Na - About 1 g of oven-dried ground sample was ashed at 550°C for 5-6 hours. The ash was then baked with 1:1 HCl over a water bath. The residue was taken up with dilute HCl, filtered and made up to 100 ml with distilled water. P and K in the extract were determined colorimetrically by Technicon Autoanalyser II; Ca and Mg by atomic absorption spectrophotometry; and Na by flame photometry (Chin, 1987).

---ooo000ooo---

APPENDIX 2. LIST OF SCIENTIFIC AND COMMON NAMES

The following list includes the species mentioned in the text and tables of this thesis. Common vernacular names are given where they have been used in the text or where appropriate. Scientific nomenclature of the forest vegetation is mainly taken from Anderson(1980).

Alangium havilandii Bloemb.	**Jandam Paya**
Alocasia beccarii Engl.	**Herbaceous plant**
Asplenium nidus L.	**An epiphytic fern**
Blumeodendron tokbrai (Bl.) Kurz.	**Merbulan, Empungan**
Campnosperma macrophyllum HK.f.	**Terentang**
Casuarina sp. nov.(*Gymnostoma nobile* Johnson(msc.)	**Rhu Ronang**

Cephalomappa paludicola Airy Shaw.	Arau Paya
Combretocarpus rotundatus (Miq.) Danser	Keruntum
Copaifera palustris (Sym.) De Wit	Sepetir Paya
Cratoxylum arborescens (Vahl.) Bl.	Geronggang
Cyathea glabra (Bl.) Copel.	Terrestrial fern
Dacrydium pectinatum de Laub.	Sempilor Paya
Dactylocladus stenostachys Oliv.	Jonkong
Diospyros evena Bakh.	Merpinang Daun Kechil
D. maingayi (Hiern) Bakh.	Merpinang Daun Besar
Drynaria involuta v.A.v.R.	An epiphytic fern
Dryobalanops oblongifloia Dyer	Kapur Kelansan
D. rappa Becc.	Kapur Paya
Dyera polyphylla (Miq.) Ashton (ined.)	Jelutong Paya
Eleodoxa conferta (formerly *Zalacca conferta*)	Assam Paya
Eugenia leucoxylon (Korsh.) Miq. var. phaeophyllum	Ubah Merah
Eusideroxylon zwageri Teijsm & Binn.	Belian
Ficus callicarpides Corner.	A small climber
Ganua coriacea Pierre ex Dubard	Ketiau Merah
G. curtisii (K. & G.) H.J. Lam	Ketiau Badas
Ganua pierrei v.d. Assem	Ketiau Puteh
Garcinia cuneifolia Pierre.	Kandis Padang
Gonystylus bancanus (Miq.) Kurz.	Ramin
Hevea brasiliensis (Willd. ex A.juss) M.A.	Rubber
Ilex hypoglauca (Miq.) Loes.	Kerdam Mungkulat
Lecananthus erubescens Jack.	A small climber
Licuala sp.	A palm
Lithocarpus andersonii soepadmo	Empenit Jangkar
Litsea crassifolia (Bl.) Boerl.	Medang Padang
Melaleuca leucadendron L.	Gelam
Metroxylon spp.	Sago
Neoscortechinia Kingii (Hook.f.)Pax. et Hoffm.	Bantas Paya

Nepenthes ampullaria Jack.	Pitcher plant
N. bicalcarata Hook.f.	Pitcher plant
N. gracilis Korth.	Pitcher plant
Nypa fruticans Wurmb.	Nipah; apong
Oncosperma filamentosa	Nibong
Oryza sativa L.	Rice; Padi
Palaquium ridleyi King et Gamble	Nyatoh Jelutong
Pandanus andersonii H. St. John	Pandan
P. molleyanus	Pandan
P. ridleyi Martelli	Pandan
Parastemon spicatum Ridl.	Ngilas Padang
Parishia maingayi Hook. f.	Upi Paya
Ploiarium alternifolium (Vahl) Melch.	Somah
Rhizophora apiculata Bl.	Bakau Minyak
Shorea albida Sym.	Alan; Red Meranti
S. quadrinervis V. Sl.	Meranti Sudu
S. rugosa Heim.	Meranti Buaya Hantu
S. teysmanniana Dyer.	Meranti Lilin
Stemonurus umbellatus Becc.	Semburok
Tectractomia holttumii Ridley.	Rawang
Tectractomia parviflora Ridl.	Rawang Paya
Thorachostachyum bancanus (Miq.)Kurz.	A type of sedge
Tristania obovata R. Br.	Selunsor
Uncaria ovalifolia Roxb.	A large climber
Vittaria elongata Sw.	A terrestrial fern
Xanthophyllum amoenum Chod.	Nyalin
X. racemosum	Nyalin