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—Mini Review— Review of Soils on the 52 ha Long Term Ecological Research Plot in Mixed Dipterocarp Forest at Lambir, Sarawak, Malaysian Borneo

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ABSTRACT Much of the structural, floristic and dynamic variation in the hyperdiverse dipterocarp forest on the 52 ha long term ecological research plot at Lambir, Sarawak, is associated with soil differences, as indicated by topography, labile topsoil nutrients, and humus. This review expands the edaphic characterisation of the plot by collation of published and unpublished data on soil morphology, physical properties and non-labile nutrients. Topographically the plot consists of two dipslopes at different elevations with a steep and unstable intervening scarp. Sandstone underlies the main upper dipslope and shale the lower, and the scarp has mixed clastic sedimentary lithology. Most of the dipslope soils are moderately developed Red Yellow Podzolics (Acrisols/Udults). They are of medium depth, with thin topsoils and reddish yellow blocky subsoils that become redder, finer textured, firmer and blockier with depth. Textures vary with lithology, and range from loamy sand over sandy loam on sandstone to silty clay over clay on shale. The scarp has shallower, stonier and less horizonated Skeletal soils (Cambisols/Inceptisols). All of the soils are very acid, and have low contents of all labile nutrients. Contents of non-labile forms of P are low and those of Ca extremely low, but K and Mg are moderate. All nutrients are significantly lower in sandstone soils than on shale. The differences are more pronounced for non-labile than labile forms and in subsoils than topsoils. Ratios of mineral nutrient are stoichiometrically typical for Red Yellow Podzolics on clastic sediments, and differ from morphologically similar soils on other parent materials. The ecologically significant reserves of K and Mg are attributed to small but sustained replenishments by mica weathering.

Key words: dipterocarp forest, soils, stoichiometery, topography, Borneo

INTRODUCTION

The Mixed Dipterocarp Forest (MDF) on the long-term ecological research (LTER) plot at Lambir, northern Sarawak (Fig. 1), is located in the Bornean heartland of dipterocarp diversity (Ashton, 1989 and 1995), and was sited to include a range of forest and soil types (Ashton, 1978). The forest has the highest tree species richness so far documented in the paleotropics (Lee et al. 2002a). Much of the variation in forest floristics, structure and dynamics on the plot has been associated with an edaphic gradient from very dystrophic soils on sandstone to less dystrophic clays on shale (Davies, 2001; Davies et al. 1998 and 2005; Debski et al. 2002; Harrison et al. 2003; Itoh, 1997; Itoh et al. 2003; Lee et al. 2002a; Palmiotto, 1998; Palmiotto et al. 2004; Potts et al. 2004; Russo et al. 2005; Yamada et al. 1997 and 2000; Yamakura et al. 1996). This parallels associations between MDF and soils elsewhere in the Lambir area (Hirai et al. 1997; Ishizuka et al. 2001; Itoh, 1995; Itoh et al. 1995; Iwasaki et al. 1997; Nagamasu and Momose, 1997; Putz and Chai, 1987). Associations of MDF floristics and structure with soil lithology and reserve nutrients, especially those of P and Mg, have

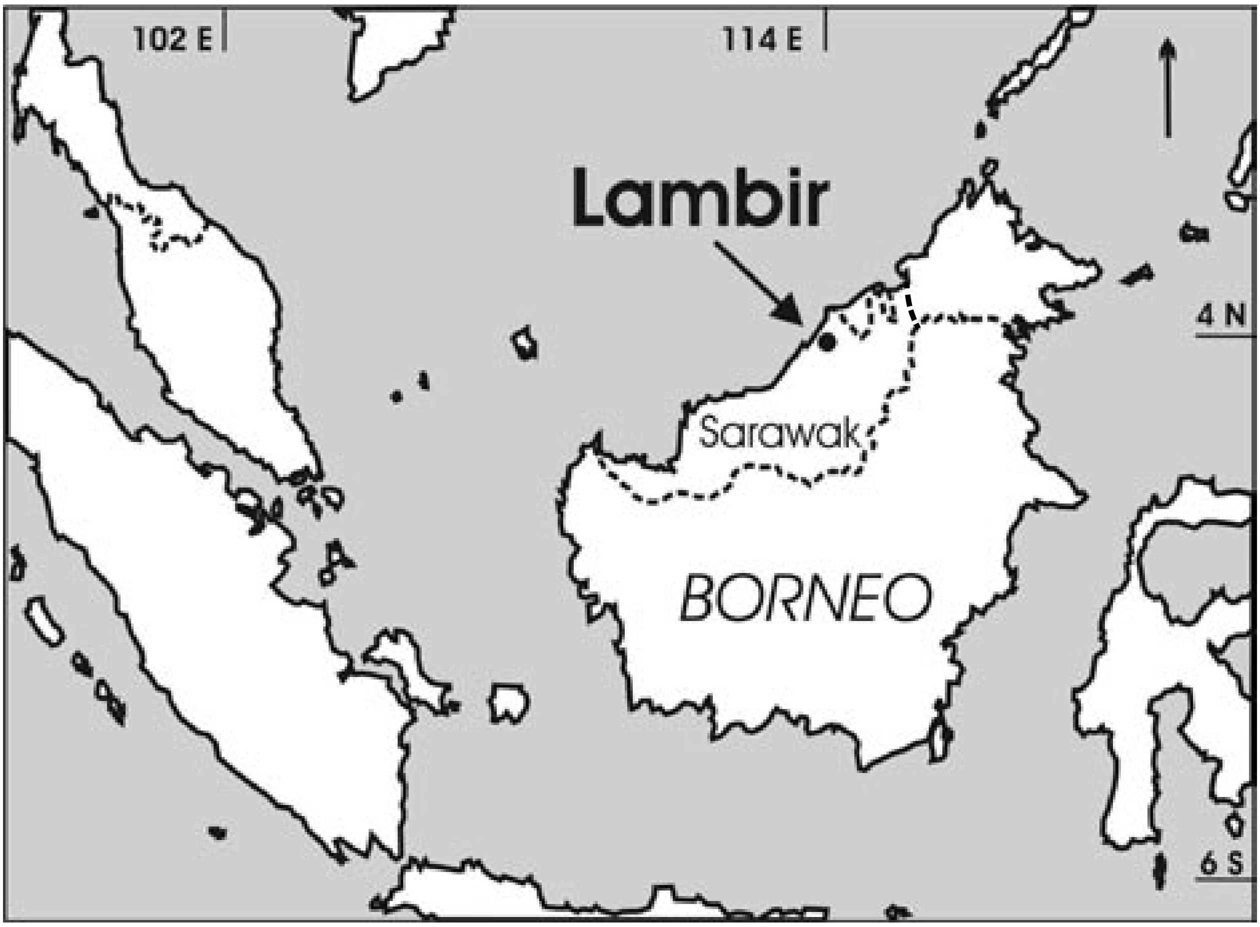

Fig. 1. Location of Lambir Hills National Park

been found on a range of rock types in other parts of Sarawak, (Ashton, 1973; Ashton and Hall, 1992; Baillie et al. 1987; Potts et al. 2002), and elsewhere in Borneo (Austin et al. 1972; Baltzer et al. 2005; M^cKinnon et al. 1997; Ohta et al. 1992; Webb and Peart, 2000). Soil differences are considered important enough to have been integrated into logging protocols for dipterocarp forests in Sabah (Glauner et al. 2003).

Because of the apparent importance of site-forest associations in Bornean MDF, the soils of the LTER plot at Lambir have been investigated in some detail, but many of the data are unpublished and inaccessible. We collate them here with published findings in order to:

1) Clarify soil spatial patterns, especially the nature and intensity of the edaphic gradient;
2) Compare the soils of the plot with those of other tropical forests;
3) Avoid unnecessary soil sampling and analyses in the future

We concentrate on the plot's physiography and on the mineral and inorganic attributes of the soils, as Baillie et al. (2006) have already examined the morphology, dynamics and edaphic implications of the litter and humus.

We use 'labile' to refer to nutrients extracted by mild reagents, and include exchangeable cations leached by 1M NH_4OOCH_3 , extractable cations leached by 1M KCl and 1M NH_4Cl, and available P extracted with the Bray 2 reagent. Non-labile nutrients include reserves extracted with concentrated HCl and totals extracted with concentrated H_2SO_4 or $HClO_4$.

THE STUDY SITE

Location and access

The Lambir LTER plot was established in 1991 as part of the pantropical network of similar plots coordinated by the Center for Tropical Forest Science (CTFS) and, for Asia, the Arnold Arboretum of Harvard University. The plot is at 4° 11' N, 114° 01' E in Taman Negara Bukit Lambir (Lambir Hills National Park), Northern Sarawak, Malaysian Borneo (Fig.1). It measures 0.5 × 1.04 km, corrected for slope (Yamakura et al. 1995). There is a good path along the major axis, and the plot is accessible from the Miri-Sibu highway. Navigation within the plot is facilitated by pegs at the corners of the 1300 slope-corrected 20 × 20 m quadrats, and by the inclusion of quadrat numbers on the permanent metal tags on all monitored trees and saplings (Lee et al. 2002a; Yamakura et al. 1995)

Forest

The plot contains approximately 350 000 free-standing trees and saplings of > 1 cm diameter at reference height. These were inventoried in1992-3 for species, size and form, and permanently tagged according to standard CTFS procedures (Condit, 1998; Lee et al. 2002a), and re-measured in 1998-9 and 2002-3, with another recensus currently under way in 2007-8. The forest is structurally typical of Bornean MDF, with tall, slim-boled and high-buttressed trees, a dense irregular canopy at 40-50 m, with a few emergents exceeding 60 m. Basal areas are moderate, at 35-45 $m^2.ha^{-1}$, but the tall trees give a substantial above-ground biomass, estimated to average over 500 t. ha^{-1} (Lee et al. 2002a; Yamakura et al. 1986). The plot contains almost 1200 species of trees and saplings (Potts et al. 2004), with dipterocarps of eight genera and 87 species dominating the canopy and larger size classes (Lee et al. 2002b).

Climate

The climate is equatorial aseasonal. Monthly mean temperatures vary little, ranging from 26 to 28 ℃, and diurnal ranges are 8-10 ℃. The mean annual rainfall of 2500–3000 mm is distributed throughout the year, although heavier during the *landas* (north-eastern monsoon) in November-February (Watson, 1985). Because the plot is sited in a freestanding peri-coastal range of hills, it receives localised orographic rainfall, which may add 100–200 mm p.a. to the regional mean (Palmiotto, 1998; Sakai, et al. 1997). Soil reserves of available moisture are sufficient to permit uninterrupted transpiration though the drier months in most years (Hirai, et al. 1997; Kumagai, et al. 2004a, 2005) but ecologically significant droughts occur in ENSO years (Harrison, 2000; Ichie et al. 2004; Itioka and Yamanti, 2004; Nakagawa, 2000; Potts, 2003). Run-of-wind totals are low but brief and narrow-fronted squalls precede many rainfall events. However, Borneo is too near the equator for typhoons, except extremely rarely (Proctor et al. 2001).

Geology

The predominantly clastic sedimentary rocks of the Lambir Formation underlying the plot were deposited in deltaic and coastal environments during the Mio-Pliocene (Morley et al. 2003). They are underlain at depth by the continental basement of the Luconia block, a micro-terrane that moved southwards from South China in the early Tertiary (Hutchison, 1988). The main rock type is light grey, yellowish and pinkish yellow sandstone. It is mostly medium- and fine-grained but there are some coarser beds (Wilford, 1961). The sand grains are predominantly quartz, with subordinate fragments of mudstone and chert, set in a matrix of silt- and clay-sized quartz and subordinate ferruginous sesquioxides (Rubiah, 1994). The generally siliceous nature of the Lambir sandstone limits the quantities of clays and cationic nutrients generated by weathering (Hill et al. 1992).

The Lambir formation includes subordinate dark grey, weakly consolidated shales, which occur both as thin partings and thick beds. The thick beds are more frequent towards the base of the formation and in the south and east of the plot. The main shale minerals are micas, with subordinate fine-grained quartz and pyrites. Some of the shales are carbonaceous and almost black when fresh. Thin coal seams are reported in the lower parts of the formation (Noryati, 1995), although none were seen on the plot. There are also thin calcareous beds near the base (Wilford, 1961; Rubiah, 1994) but none were seen on the plot. Some of the shales are ferruginised, with indurated orange-rust brown interlayers of concentrated ferric sesquioxides up to 10 cm thick. These formed during sedimentation rather than after exhumation (Lim and Leman, 1994).

The Lambir formation is about 1 km thick and has been uplifted by at least half a kilometre since deposition (Banda, 1998). Satellite imagery shows linear breaks of slope at the base of the range, suggesting that it is a fault-defined horst (Caline and Huong, 1992). The uplift occurred spasmodically during the Pliocene and Pleistocene (Wilford, 1961; Wall, 1964), and concurrent tilting gave the beds their current 15-35 degrees dip down to the N-NW. The tectonic movements caused normal, reverse and transverse faults (Yasin, 1990). There is no current volcanic activity but limited seismicity indicates that, tectonically, the area is not completely inert.

Topography and hydrology

The plot is located on the southern slopes of the Lambir Hills, a low free-standing range rising out of the North Sarawak coastal lowlands. The range consists of cuestas (dip-controlled asymmetrical ridges) and steep hills. The cuestas dip NW, and dipslopes are best seen on the

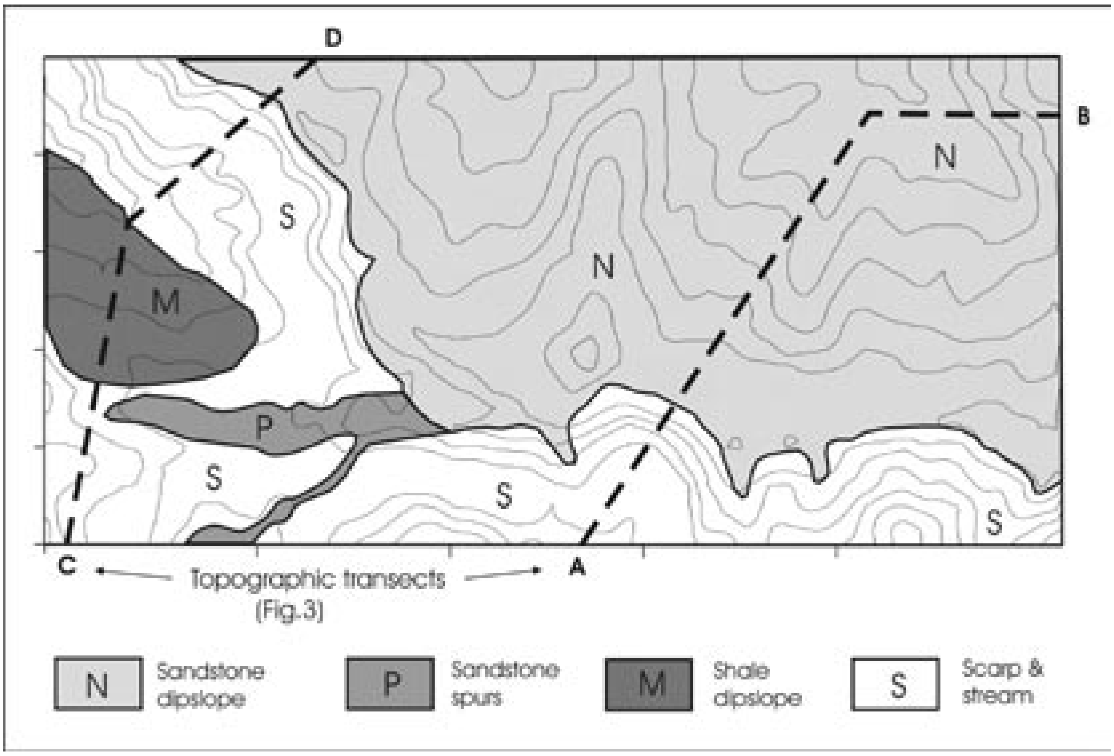

Fig. 2. Landforms of Lambir LTER Plot
Contours after Yamakura et al. 1995; soil types based on I.C. Baillie, J.D. Mamit and S. Tan unpublished data, 1971 - 2003.

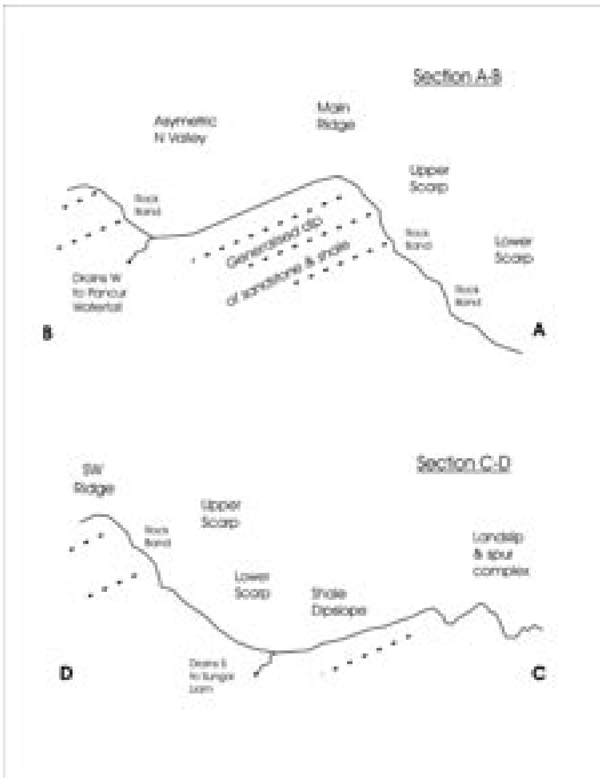

Fig. 3. Topographic sections of Lambir LTER Plot
Based on I.C. Baillie, J.D. Mamit, M. Tani, T Yamakura and S. Tan unpublished data, 1971 - 2003; and Yamakura et al. (1995).

northern slopes (Wall, 1964; Watson, 1985). The plot is located in the more broken terrain on the southern side.

Yamakura et al. (1995) derived a contour map for the plot (Fig. 2) and estimated slope gradients and indices of vertical convexity/concavity from detailed levelling surveys. I.C. Baillie and S. Tan (unpublished data, 2003) assessed site drainage, microrelief and plan convergence/divergence on 245 quadrats.

Although at low altitude (< 250 m a.s.l.), the terrain is rugged, and the plot has internal relief of 140 m and many slopes steeper than 50% (Yamakura et al. 1995). The main topographic elements are an extensive elevated NW-sloping cuesta dipslope on sandstone, a cuesta scarp complex of steep slopes and streambeds on mixed lithology, and a smaller and lower NW-dipping cuesta on shale (Figs 2 and 3). The asymmetry of the cuestas is attributed to the shallow dip of the beds and relatively higher competence of the sandstones.

Westward-flowing headwaters of Sungai Liam have incised two shallow asymmetrical valleys in the upper main sandstone dipslope. Within these valleys, the south-bank streams have cut through the sandstone and their shallow channels run over smooth, ferruginised, case-hardened, shallow dipping shale beds. The north bank streams have narrower, steeper and less regular beds, with alternating small cascades over sandstone bands and pools hollowed out in the shales. The dip-aligned interfluve slopes on the south banks are moderately graded and rectilinear, whilst north bank slopes are steep and stepped meso-scarps with minor sandstone bluffs (Section A-B in Figs 2 and 3).

The main scarp is a complex of steep, irregular, unstable slopes and streambeds. The upper slopes are steeply convex, with discontinuous transverse sandstone bluffs. The lower slopes are steep and irregularly concave, and mantled with debris, which is unconsolidated and unvegetated when fresh, and vulnerable to surface wash and gullying (Dyke, 1996). There are some wide landslip scars, which were probably initiated by the exceptional rains of 1963 (Watson, 1985), but have since been patchily reactivated. Other slips have narrow tracks, with run-out deposits confined between steep spurs. The scarp complex is interrupted in the southeast by a substantial sandstone spur with an irregular plunging crest and symmetrical, steep side slopes.

The smaller and lower cuesta on shale in the south of the plot has a more or less undissected NW low angle dipslope (Section C-D in Figs 2 and 3), and an insignificant scarp on its eastern edge

The plot is drained to the east and west by low order streams. In the landas of late 2003, surface wash scoured fresh runnels into thick forest litter and exposed well-established shallow root mats. Surface runoff appears be infrquent, and infiltration adsorbs most throughfall and stemflow. Root and microbial uptakes of soil moisture are substantial (Kumagai, et al. 2004b), but there is sufficient remaining to give runoff and steam flow throughout the year (Kumagai et al. 2005). On shales a high proportion of the outflow from the soils is diverted laterally as shallow throughflow and contributes to stream storm- and quickflows, whilst on sandstone a higher proportion leaches deeply and feeds baseflows (Baillie, 1975 and1996; Pullen et al. 2004).

Regolith

The saprolites on the dipslopes are stable, and the soils are formed in residua and colluvia. Soil pits dug in 1971 show the stability of the dipslope regolith, as 57 out of 60 were still visible in 2003, and 45 were still moderately deep, with extant free faces of 80-100 cm. Infill has been mainly by spalling from friable upper subsoils, leaving the more competent, root-bound topsoils as slight overhangs (Baillie, Mamit and Tan, unpublished data, 1971-2003; Baillie, 1978).

The regoliths on the scarp are unstable. They tend to be truncated, and shallow on the upper slopes. The overnight collapse of an upper scarp trench intended for throughflow monitoring in the landas of late 2003 highlighted the instability. Throughflow was the main destabilising process in this instance, with the friable upper subsoil caving in and retreating upslope by about 25 cm after 18 hours of heavy rain, leaving a 15 cm overhang of more stable, well-rooted topsoil. The lower scarp regoliths are deep mixtures of allochthonous colluvium, landslip debris and gully wash.

SOIL DATA COLLECTION

The earliest known soils work on the plot was by P.S. Ashton during the setting up of a network of 105 × 0.6 ha ecological research plots in Sarawak MDF during the 1960's (Ashton, 1973). He established six plots at Lambir, of which four were permanent forest dynamics plots. These were re-measured at intervals until about 1990 (Ashton and Hall, 1992) and then incorporated into the 52 ha LTER plot in 1991. All four permanent plots were sited on dipslopes, three on sandstone and one on shale. The profiles of three soil pits on each plot were described for Munsell hue and texture, sampled at 0-22 cm and 22-75 cm, and the samples bulked to give one topsoil and one subsoil composite per plot. These were analysed at the Sarawak Agricultural Research Centre, Semongok for disturbed bulk density, granulometry, pH, and total nitrogen. Reserve nutrients and non-crystalline sesquioxides of Fe and Al were extracted by digestion with concentrated HCl and assayed by flame emission spectrophotometery for K and Na, and by titration for Ca, Mg, Fe and Mg. Reserve nutrients were preferred to more labile forms, because they correlate better with fertiliser responses in Sarawak, especially for tree crops (Bailey, 1964 and 1967).

In 1971 Baillie and Mamit edaphically characterised Ashton's four permanent plots in more detail, with 15 profile pits per plot After description and topsoil and subsoil sampling, the pit faces were cut back in layers to give horizontal surfaces for triplicate determinations of topsoil and subsoil undisturbed bulk density by sand pouring. Topsoil bulk densities were determined and samples collected at four additional points around each pit. The coefficient of linear expansion (COLE) was determined in silicone-coated copper troughs (Dumbleton, 1975) for the soil excavated for each bulk density determination. Particle specific gravity was determined by pycnometer. The 75 topsoil and 15 subsoil samples from each plot were bulked to give three composites for each depth (Baillie, 1978). These were analysed at Semongok for pH, organic carbon, total nitrogen, reserve nutrients and Fe and Al non-crystalline sesquioxides, using the same methods as above.

P.A. Palmiotto measured the thickness of surface litter and depth of rooting and determined field textures at 5-15 cm in all quadrats in 1994-5 (Palmiotto, 1995 and 1998; Palmiotto et al. 2004). He bulked ten subsamples from the top- and sub-soils at each of six sites on sandstone within the plot and three on shale, and the composites were analysed at Yale University for organic carbon, total nitrogen, and particle size, and extracted with NH_4Cl for extractable cations, Bray 2 solution for available P, and concentrated H_2SO_4 for total nutrients. All extracts were assayed by inductively coupled plasma (ICP) spectrophotometery.

S. Tan collected 501 samples at 5-15 cm to characterise soil nutrients and their spatial variation on the plot in 2001. The samples were analysed at Semongok by extraction with 1M NH_4OOCH_3 for exchangeable cations, Bray 2 for available P, and $HClO_4$ for total P. All extracts were assayed by ICP (Chin, 2002).

In 2003 I.C. Baillie and S. Tan described the soils on 245 quadrats by augering to one metre. Topsoil (A_1 horizon, 0-10 cm) and subsoil (B_t horizon, 45-55 cm) samples from 60 augerings were analysed at Semongok by extraction with NH_4OOCH_3 for exchangeable cations, Bray 2 for available P, and digestion with concentrated HCl for reserve nutrients. All extracts were assayed by ICP (Chin, 2002).

Collation of soils data from various laboratories over long periods is complicated by methodological differences and drift. Fortunately, most of the soil data reviewed here come from the Semongok laboratory, which has ISO accreditation and participates in national and international inter-laboratory quality control programmes (Chin, 1996; Chin and Sim, 1990).

All statistical analyses used SPSS version 12.0. Significances of differences between means were estimated by t-tests and Tukey HSD analyses of variance. The spatial correspondence between Mantel habitats derived from the 2001 topsoil data and the 2003 soil series and (Fig 4 and Table 11) was tested with chi^2. In order to identify underlying trends within the data, principal components were extracted from the 2003 data.

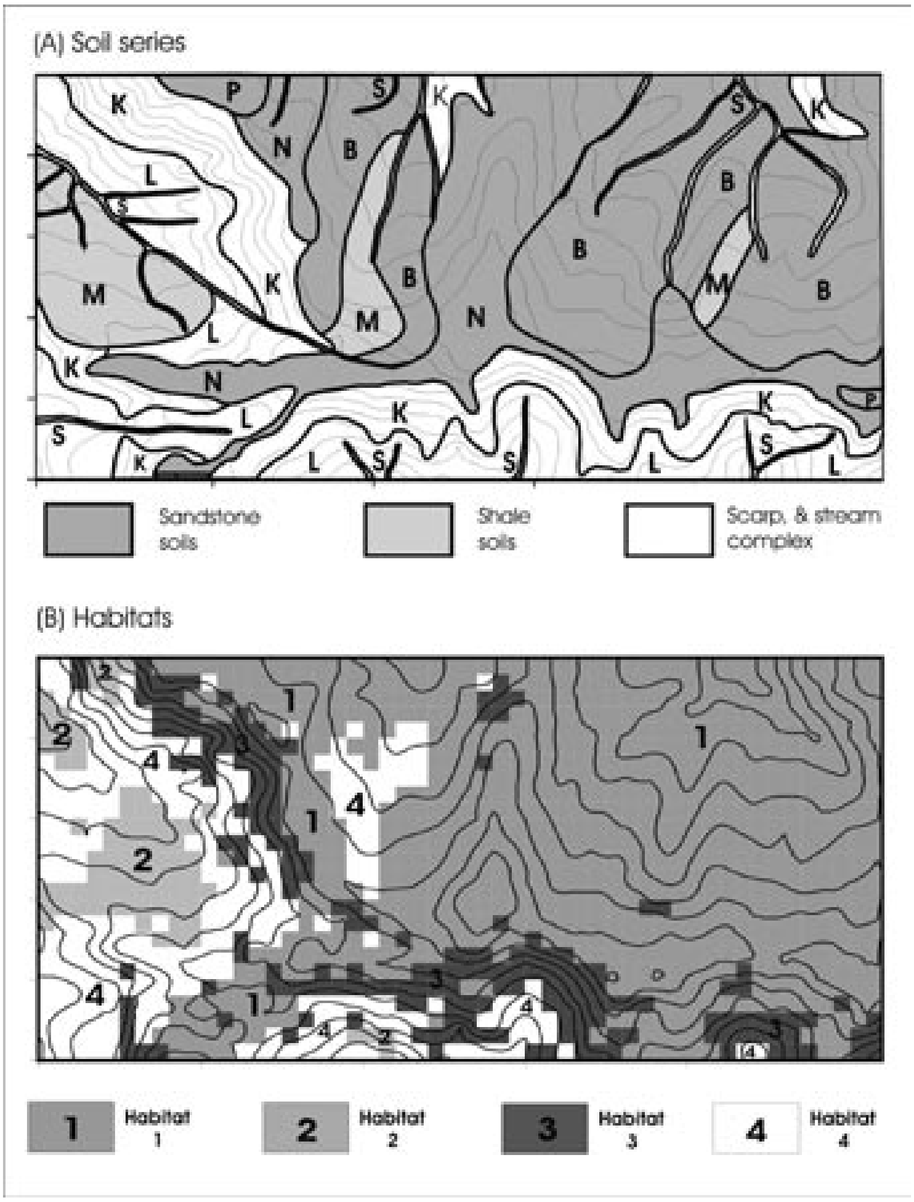

Fig. 4. Soil series and Mantel Habitats of Lambir LTER plot

(A) Soil series

Sandstone series: B, Bekenu; N Nyalau; P, Peninjau. *Shale series:* M, Merit. *Scarp and stream complex*: K, Kapit family; L, landslip; S, streambed.

Based on I.C. Baillie, J.D. Mamit and S. Tan unpublished data, 1971 - 2003.

(B) Habitats. Defined by Mantel analysis of 2001 topsoil data (after Potts et al. 2004)

RESULTS: SOILS OF THE LAMBIR 52 HA LTER PLOT

Although each of the soil data sets for the plot (Table 1) has limitations, collectively they give a clear general overview, which is amplified by the findings from soil surveys of nearby areas (Baillie, 1970, 1971; Baillie and Ahmed, 1984; Danida/SWMPI, 2003; Ishizuka et al. 1998, 2001; Lim, 1970a, 1970b; Lim and Rosli, 1971; Sakurai, 1999; Soepadmo et al. 1984; Wall, 1962, 1964, 1965).

Soil classification and mapping

We considered using the one or both of the international systems, i.e. World Reference Base (WRB) for Soil Resources (FAO, 2006) and Soil Taxonomy (ST) of the USDA (Soil Survey Staff, 1999 and 2006), for the primary classification of the plot's soils. However, we aopted the Sarawak system (Teng, 1996) because it uses locally appropriate criteria and its taxa can be related to Sarawak agronomic results. Also its taxa are relatively stable, whereas new data can lead to substantial reclassification in the international systems (Schwendenmann et al. 2003;). Furthermore, WRB is explicitly intended for use in conjunction with, not instead of, local classifications (Deckers et al. 2005).

The Sarawak Soil Classification (Table 2) is a hierarchical divisive system, the main levels of which are soil group, family and series. The taxa are defined on non-

Table 1. Soil data sets for Lambir LTER plot and National Park

Data collected by:	Type of study	Area	Sites with topographic and soil morphological data	Number of analysed soil samples	Analyses	Reference
52 ha LTER plot						
Ashton	Edaphic characterisation of Sarawak MDF permanent ecological plots	4 × 0.6 ha	11 × pit descriptions (+ 1 just outside)	11 × topsoil and subsoil (+ 1 just outside)	pH, HCl extractable reserve P, Ca, Mg, K, and Fe + Al sesquioxides	Ashton, 1973
Baillie and Mamit	More detailed characterisation of Ashton's plots	Same 4 × 0.6 ha	57 × full profile descriptions; and 456 × in situ bulk density and porosity (+ 3 and 24 just outside)	11 × bulked topsoil + subsoil (+ 1 just outside)	Particle specific gravity, COLE,, pH,, HCl extractable reserve P, Ca, Mg, K, and Fe + Al sesquioxides	Baillie, 1978
Palmiotto	Soil characterisation as background for nutrient cycling and experimental studies	52 ha	1278 × surface organic matter and shallow auger descriptions	9 × bulked topsoil + shallow subsoil (+ 6 outside)	NH_4Cl extractable bases, Bray 2 available P, H_2SO_4 extractable total bases, Fe, Mn, Al and P	Palmiotto, 1995 and 1998; Palmiotto et al. 2004
Tan and Chin	Topsoil available nutrient fertility survey	52 ha	-	501 topsoil	pH, NH_4COOH_3 exchangeable Ca, Mg, K, CEC; available (Bray 2) and total ($HClO_4$)P	Potts et al. 2004
Baillie, Tan and Chin	Soil mapping and nutrient study	52 ha	242 × descriptions of site, surface organic matter and augerings.	60 × topsoil + subsoil	pH, NH_4COOH_3 exchangeable Ca, Mg, K; Available (Bray 2) P, , HCl extractable reserve Ca, Mg, K and P	This study
Elsewhere in Bukit Lambir National Park						
Hirai et al.	Soil and site associations with distributions of *Dryobalanops* spp		8		NH_4COOH_3 exchangeable cations, 1M KCl extractable Al and H; hydraulic conductivity and available moisture capacity, tensiometers at 10 and 30 cm depths	Hirai et al. 1997
Ishizuka et al.	Characterisation of soil texture and consistence		2			Ishizuka et al. 1998
Sakurai	Characterisation of soils for *Dryobalanops* habitats				Includes oxalate and dithionite extractable Si and Fe, Al sesquioxides	Sakurai, 1999

Table 2. Morphology, classification and mapping, of the soils of the LTER plot, Lambir

Map unit symbol (Fig. 4a)	Topography	Position	Sarawak soil classification* Group	Family	Series	Main morphological features	Depth	Textural profile	Surface organic matter
P	Sandstone dipslope	Knolls on main ridge	Arenaceous	Peninjau	Peninjau	Deep, yellow (10YR), sandy, very friable and permeable subsoil	> 100 cm to weathered sandstone, mostly > 150 cm	Loamy sand / sandy loam to > 100 cm	Thick litter and continuous rooted humus mat
N		Main ridge and spurs	Red Yellow Podzolic	Nyalau	Nyalau	Yellowish (10YR) coarse topsoil over redder (7.5YR) loam subsoil, moderately friable subsoil	> 50 cm to weathered sandstone, mostly > 100 cm	Sandy loam, over sandy clay loam within 100 cm	
B		Slopes of N and W valleys		Bekenu	Bekenu	Yellowish (10YR) loam topsoil over redder (7.5YR) and fine loam subsoil, moderately friable subsoil	> 50 cm to weathered sandstone/ shale, mostly > 100 cm	Sandy loam / sandy clay loam, over sandy clay within 100 cm	Moderate litter and patchy rooted humus mat
M	Shale cuesta	Undissected dipslope		Merit	Merit	Yellowish (10YR) fine loam topsoil over redder (7.5YR) firm clay subsoil	> 50 cm to weathered shale	Clay loam / silty clay loam, over clay / silty clay within 100 cm	Thin and patchy litter. Occasional non- humic root mat
K	Upper scarp slope	Cliffs and rock bands	Skeletal	Meluan	Meluan #1	Bare rock, +/- thin soil cover	< 25 cm to hard rock	Variable over rock	Variable litter, with patchy humus root mat
		Convex steep upper slopes		Kapit	Kapit	Yellowish (10YR) stony loam topsoil over thin (7.5YR) stony fine loam subsoil, over shallow saprolite	< 50 cm to weathered rock	Variable over weathered rock	Variable litter, with patchy humus root mat
L	Concave lower scarp	Irregular runout deposits		Tutoh	Tutoh	Patchy thin topsoil over deep, mixed 10YR and 7.5YR stony loam subsoil	< 50 cm to > 50% stones	Variable over stony	Variable litter, but no humus root mat
S	Streams	Streambeds and toe slopes	Gley	Semadoh	Tumau	Dark mucky topsoil over grey mixed texture and, +/- mottles and stones	Variable	Variable	No litter or humus root mat

Based on Baillie, Mamit and Tan, unpublished data, 1971 – 2003, Palmiotto (1998) and Baillie et al. (2006)
* Adapted from Teng (1996).

ephemeral morphological and physical features, especially texture, depth and drainage (Teng, 1996; Tie, 1982). For the more mature soils on the dipslopes we differentiate soil series, but in some scarp areas with very heterogeneous soils we generalise at family and group levels. Although chemical attributes are not definitive, mineral nutrients are affected by parent material lithology and reflected in soil textures, and Sarawak soil series differ somewhat with respect to nutrient fertility.

The dipslope soil mapping units (Fig.4a) are consociations, with one series predominant and others as minor inclusions. The spatial variability of the scarp and streambeds necessitates mapping of soil complexes, with several taxa co-dominant.

Soil morphology

Most of the dipslope soils are well-drained mature soils of the Red Yellow Podzolic (RYP) group in the Sarawak system (= Acrisols in WRB and Udults in ST). The coarsest textured soils are morphologically similar but

Table 3. Physical data for soils of Lambir LTER Plot

Data reference	Soil series	Depth	n	Stones	Sand	Silt	Clay	Bulk density	Total Pores	COLE
		cm			%			$g.ml^{-1}$	%	
Ashton (1973)	Nyalau (12 of 15 quadrats of Plot L4)	0-22	1	nd	58	20	22	1.54	nd	
		22-75	1		63	14	23	1.82		
Baillie and Mamit (Baillie, 1978)		0-15	2	0 (n=60)	62	17	19	0.9 (n=60)	66 (n=60)	6.5 (n=60)
		Bt	2	5 (n=36)	57	16	27	1.6 (n=36)	41 (n=36)	13.7 (n=36)
Ashton (1973)	Bekenu (Plots L3 and L5))	0-22	2	nd	60	19	21	1.52	nd	
		22-75	2		65	16	19	1.8		
Baillie and Mamit (Baillie, 1978)		0-15	6	0 (n=150)	69	14	17	1.00 (n=150)	62 (n=150)	6.6 (n=150)
		Bt	6	5 (n=90)	64	14	22	1.5 (n=90)	41 (n=90)	9.5 (n=90)
Ashton (1973)	Merit, (Plot L2)	0-22	1	nd	27	43	30	1.6	nd	
		22-75	1		14	44	42	1.66		
Baillie and Mamit (Baillie, 1978)		0-15	3	0 (n=75)	47	28	24	1.04 (n=75)	61 (n=75)	9.0 (n=75)
		Bt	3	7 (n=45)	36	28	35	1.43 (n=45)	46 (n=45)	13.0 (n=45)
Palmiotto (1998)	'Humult' (=sandstone soils)	0-15	6	nd	69	17	13	0.8	nd	
		15-30	6		66	14	17	nd		
	'Udult' (=Merit series)	0-15	3		43	35	22	1.0		
		15-30	3		36	33	31	nd		

Based on Ashton, Baillie, Mamit, and Palmiotto, unpublished data, 1966 – 2003; Palmiotto, 1998

are separated in the Arenaceous group (Teng, 1996).

The mineral topsoils of these soils are thin, moderately darkened, and have friable, porous crumb structures. By 10-15 cm they grade to reddish yellow and moderately porous blocky subsoils, which become redder and finer textured with depth. Subsoil consistence is firm, and Ishizuka et al. (1998) found drop cone penetrometer resistance to be moderate. The subsoils overlie patchy red, white and yellow soft weathered rock (saprolite) at depths of 0.5-2.5 m, and there are variable contents of saprolitic fragments above the main paralithic contact. The RYP/Arenaceous soils on the plot form a textural gradient from Peninjau series (Arenosol/Paleudult, sandy), through Nyalau (Acrisol/Paleudult, coarse loamy), Bekenu (Acrisol/Hapludult, fine loamy) to Merit series (Acrisol/Hapludult, clay) (Table 2).

The coarse textured Peninjau and Nyalau series occur on sandstone-dominated regoliths on the ridge and upper slopes of the main dipslope. They are the deepest and most weathered soils on the plot, with sola often more than 2 m deep. Relatively deep RYP are common on sandstone ridges elsewhere in Sarawak (Wall, 1964; Baillie et al. 1987), but not at Belalong in adjacent Brunei, where the sandstone ridge soils are shallow and stony (Ross and Dyke, 1996). The subsoils of Peninjau series are porous, friable and no finer than sandy loam within the top metre, whereas subsoils in Nyalau series grade to slightly firm sandy clay loam. Although clay contents increase with depth, subsoil contents are still low and clayskins are absent or weak. These soils have almost continuous mats of dark reddish brown humus, which are mostly less than 10 cm thick but are densely rooted and can be lifted off the surface like a carpet (Baillie et al. 2006). The humus is mor or dysmoder (Ponge et al. 2002), with little faunal mixing into the underlying mineral soil.

The soils of Bekenu series are the most extensive on the plot and cover much of the main dipslope (Fig. 4a). They are of intermediate texture and depth, and form on sandstone with some shale. Some of the soils of Bekenu series have thin and discontinuous humus root mats. Clay content increases in with depth, from sandy loam topsoil to sandy clay within the top metre. The bright reddish yellow and slightly mottled subsoils have firm, blocky structures with low porosities and moderate clayskins. Soils of Bekenu series are moderately deep, mostly 1-1.5 m to the paralithic contact.

Merit series are the finest textured RYP's on the plot. They develop on shales, especially on the dipslope of the lower southern cuesta. Small areas also occur on the main dipslope, where dissection has cut through the capping sandstone into subjacent shale. These soils are well horizonated and apparently mature, but are shallower than the coarser-textured RYP series, with the paralithic contact often about 1 m. The litter normally lies directly on the mineral topsoil, with no humus mat (Baillie et al. 2006). Textures are (silty) clay loam in the topsoils, over (silty) clay subsoils. The bright reddish yellow and moderately mottled subsoils have moderate blocky structures, continuous clayskins, firm consistence, and few visible pores.

Most soils on the convex upper scarp are less than 1 m deep to hard rock or saprolite. Many are weakly developed versions of the RYP series, with reddish yellow subsoils and increased reddening and clay content with depth. Soils less than 50 cm deep to the lithic/paralithic contact or very stony layers qualify for the Skeletal group in the Sarawak system (Teng, 1996). Those over saprolite belong to Kapit family (Skeletic Cambisol/ Typic Dystrudept) and those over hard rock to Meluan family (Leptic Cambisol/ Lithic Dystrudept). The deep, stony, and erratically textured soils on fresh or recent wash and slip deposits downslope are in Tutoh family (Skeletic Regosol/ Typic Udorthent).

Many of the stream are steep and bare rocky beds, but there are intermittent narrow stretches with gullywash and alluvium. Some of the shallow and stony soils are freely or imperfectly drained, but mnay have greyish matrix colours and bright orange and rust brown mottles, indicating persistently impeded drainage.

Soil physical properties

The limited granulometric data differentiate Merit series from the other RYP's, but not between the sandstone series (Table 3), possibly because of clay dispersion problems. Undisturbed bulk density in topsoils increases with clay content from 0.85-0.9 in Nyalau series to 1.0-1.05 in Merit (I.C Baillie and J.D. Mamit, unpublished data, 1971). Subsoil bulk densities are about 1.6 in Nyalau series and 1.4 in Merit. The bulk density contrast between top- and subsoils decreases with clay content, being almost double in Nyalau series but increasing by only one third in Merit. Ashton's bulk density data are for disturbed samples but show similar trends.

The pattern for total porosity complements that of bulk density, with Nyalau series having the highest topsoil and lowest subsoil values, and sharpest decrease with depth. Ishizuka et al. (1998) found total porosities of 60-70% in a Nyalau series topsoil on an upper slope elsewhere at Lambir, compared to 50% in a lower slope soil of Peninjau series, but the subsoils were similar, with total porosities of 40-45%. Particle specific gravity values are not tabulated because they vary over such a narrow range, from 2.5 to 2.65. They are consistent with a predominantly quartz and mica mineralogy.

Coefficients of linear expansion (COLE) are moderate. They accord with the presence of some expansible clay minerals, such as illites and hydrated inter-layered vermiculites, but not smectites, reported elsewhere at Lambir (Ishizuka et al. 1998). COLE's vary between series but do not show the expected systematic increase with clay content.

Total porosity values (Table 3) do not indicate the proportions of different sized pores, the balance of which is crucial for drainage, aeration and the bio-availability of soil water. Subsoil matrix Munsell hues of 10YR or redder, and chromas and values of 5 or higher indicate that most soils are freely drained and have effective macro- and meso-pore systems. There are varicoloured mottles in some subsoils in Bekenu series and many in Merit series, but few are grey or ochreous and they look as much like incomplete weathering as hydromorphism. The pale patches in the saprolites are also mostly attributed to incomplete weathering. Some sandstone soils had very wet but bright and almost unmottled reddish yellow subsoils when augered in the 2003 *landas* (NE monsoon). The wetness was diffuse in a few soils but concentrated as a distinct layer in most, with drier soil beneath as well as above.

Moisture tensions have been traced in coarse textured soils elsewhere at Lambir (Ishizuka et al. 1998). In the drier part of the year topsoil tensions were measured as high as pF 4.0 (1 MPa) in a soil of Nyalau series on an upper slope, but only up to pF 3.2 (0.15 MPa) in a coarser textured soil of Peninjau series downslope, perhaps because of lateral recharge by throughflow. However, both soils dried to permanent wilting and no measurements were possible for about one month during a severe drought. Although the sandstone soils are drier than those on shale (S. E. Russo, unpublished data, 2005), Kumagai et al. (2005) concluded that forest evapotranspiration in non-ENSO years at Lambir is determined more by radiation than soil moisture deficits.

Soil chemical properties

The analyses of samples collected in the 1960's and 1970's indicated that HCl-extractable reserves in the mature RYP soils on the plot are moderate for K and Mg, low for P, very low for Ca, and increase with clay content for all nutrients. Similar trends are apparent in the 1990's data for H_2SO_4-extractable totals (Table 4)

The RYP's on the plot are intensively leached, very

Table 4. Pre-2000 data for non-labile nutrients in soils of Lambir LTER plot

Data reference	Soil series	Depth	n	P	Ca	Mg	K	Group III oxides		
		cm			mg.kg^{-1}			%		
Reserve (conc. HCl)										
Ashton 1966	Nyalau (Plot L4)	0-22	1	70	213	575	1613	4.6		
		22-75	1	69	Tr	317	1178	8.0		
Baillie and Mamit 1971		0-15	2	72	95	636	1495	nd		
		Bt	2	61	152	1116	1968			
Ashton 1966	Bekenu (Plots L3 and L5)	0-22	2	60	159	507	2088	3.9		
		22-75	2	85	136	782	2574	9.0		
Baillie and Mamit 1971		0-15	6	71	87	549	1516	nd		
		Bt	6	57	99	821	2247			
Ashton 1966	Merit (Plot L2)	0-22	1	133	111	1272	4226	7.9		
		22-75	1	116	Tr	1842	5530	10.3		
Baillie and Mamit 1971		0-15	3	136	187	1141	2511	nd		
		Bt	3	98	192	1876	3718			
Total (conc. H_2SO_4)										
Palmiotto (1998)				**P**	**Ca**	**Mg**	**K**	**Mn**	**Al**	**Fe**
						mg.kg^{-1}			%	
	'Humult' (=sandstone soils)	0-15	9	75^b	19^b	538^b	2404^b	4^b	1.46^b	0.65^b
		15-30	9	63^b	15^b	435^b	2732^b	2^b	1.27^b	0.59^b
	'Udult' (=Merit series)	0-15	6	131^a	106^a	1574^a	7180^a	123^a	2.69^a	1.45^a
		15-30	6	121^a	38^{ab}	1735^a	9328^a	45^a	3.03^a	1.52^a

Based on Ashton Baillie and Mamit, unpublished data, 1966 – 1971; Baillie, 1978
Different letter superscripts indicate differences are significant ($p < 0.05$)

Table 5. NH_4Cl-extractable nutrients in soils of Lambir LTER plot

Soil series	Depth (cm)	Org.C	Total N	C:N ratio	Extractable (NH_4Cl)						
					P	Ca	Mg	K	Mn	Al	Fe
		%			mg.kg^{-1}			cmol$^+$.kg^{-1}			
'Humult' (= sandstone soils)	0-15	1.9^b	0.14^a	14^a	3^a	0.06^b	0.18^a	0.10^a	0.01^b	3.83^a	0.31^a
	15-30	0.61^c	0.07^c	10^b	1^b	0.01^c	0.07^a	0.07^a	tr^d	2.36^a	0.10^b
Udult (= Merit series)	0-15	1.4^a	0.12^a	12^b	2^a	0.35^a	0.59^a	0.11^a	0.21^a	3.26^a	0.19^{ab}
	15-30	0.56^c	0.09^b	7^c	tr^b	0.07^b	0.46^a	0.08^a	0.06^b	3.72^a	0.10^b

Based on Palmiotto, 1998
Different letter superscripts indicate differences are significant (Tukey HSD, < 0.05).
*Converted from mg.kg^{-1}, assuming valencies of Mn^{4+} and Fe^{3+} in freely drained soils

Table 6. Means of 2001 data for topsoil nutrients in soils of Lambir LTER plot

2003 Soil Map Unit (see Figure 4a)	Depth	n	pH (H_2O)	Org C	Total N	C:N	Total P	Avail. P	Exchangeable (neutral NH_4OOCCH_3) Ca	Mg	K	Na	TEB	CEC	BS
				%			mg.kg^{-1}		cmol$_c$.kg^{-1} (= me%)						%
P	Top	6	4.8^{a}	1.2^{a}	0.09	13^{c}	27^{a}	2	0.23^{ab}	0.12^{ab}	0.08^{a}	0.13	0.55^{ab}	5.72^{a}	10^{ab}
N		61	4.6^{abc}	1.1^{ab}	0.10	11^{b}	57^{bc}	1	0.20^{a}	0.11^{a}	0.11^{ab}	0.06	0.48^{a}	7.28^{b}	6^{a}
B		113	4.6^{ab}	1.0^{ab}	0.10	10^{ab}	46^{ab}	1	0.23^{ab}	0.14^{ab}	0.12^{ab}	0.06	0.55^{ab}	7.64^{b}	8^{ab}
M		51	4.4^{cde}	1.0^{b}	0.10	10^{ab}	108^{d}	1	0.36^{c}	0.26^{c}	0.14^{b}	0.08	0.83^{c}	7.21^{ab}	12^{b}
K		120	4.4^{de}	0.9^{b}	0.10	10^{ab}	64^{bc}	2	0.25^{ab}	0.15^{ab}	0.13^{b}	0.08	0.61^{abc}	6.96^{ab}	9^{ab}
L		121	4.3^{e}	0.9^{b}	0.10	9^{a}	78^{c}	2	0.30^{bc}	0.26^{c}	0.14^{b}	0.08	0.77^{bc}	6.82^{ab}	12^{b}
S		28	4.3^{bcd}	0.9^{b}	0.10	9^{a}	73^{c}	2	0.28^{abc}	0.21^{bc}	0.13^{b}	0.08	0.71^{abc}	7.53^{b}	13^{b}
Overall mean		487 -500	4.46	1.0	0.10	9.65	67	1.6	0.26	0.18	0.13	0.07	0.65	7.23	8.9
p of ANOVA F ratio for SMU means			0.00	0.00	0.05 (ns)	0.00	0.00	0.02 (ns)	0.00	0.00	0.00	0.34 (ns)	0.00	0.00	0.00

Based on Tan and Chin, unpublished data, 2001
Different letter superscripts for significantly different means (Tukey HSD, < 0.05)

Table 7. Means of 2003 data for labile nutrients in soils of Lambir LTER plot

Soil map unit (see Fig. 4a)	Depth	n	pH (H_2O)	Org. C	Total N	C:N	Avail P	Exchangeable (neutral NH_4OOCCH_3) Ca	Mg	K	Na	TEB
	cm			%			ppm	cmol$_c$.kg^{-1} (=me%)				
Topsoil												
P	0 - 10	3	4.4	2.4	0.15	16^{a}	5	0.36	0.12	0.14	0.08	0.7
N		15	4.5	2	0.13	14^{ab}	5	0.43	0.21	0.15	0.1	0.89
B		20	4.5	1.8	0.14	13^{ab}	4	0.46	0.25	0.15	0.11	0.97
M		8	4.5	1.2	0.12	10^{b}	4	0.6	0.62	0.19	0.15	1.56
K		11	4.3	1.6	0.13	12^{ab}	5	0.53	0.3	0.15	0.08	1.07
L + S		3	4.2	1.3	0.13	10^{b}	5	0.34	0.18	0.16	0.08	0.76
Overall mean		60	4.42	1.74	0.132	12.7	4.5	0.47	0.29	0.16	0.1	1.02
p of F ratio			0.33 (ns)	0.16 (ns)	0.06 (ns)	0.002	0.62 (ns)	0.53 (ns)	0.1 (ns)	0.82 (ns)	0.16 (ns)	0.09 (ns)
Subsoil												
P	45 - 55	3	4.8^{a}	nd	nd	nd	4	0.18	0.06	0.08	0.05	0.37^{a}
N		15	4.7^{ab}				2	0.17	0.13	0.09	0.08	0.47^{a}
B		20	4.6^{ab}				3	0.24	0.18	0.12	0.13	0.66^{ab}
M		8	4.7^{ab}				3	0.27	0.71	0.16	0.18	1.33^{b}
K		11	4.3^{b}				4	0.18	0.16	0.1	0.08	0.52^{a}
L + S		3	4.7^{ab}				3	0.24	0.22	0.1	0.19	0.75^{ab}
Overall mean		60	4.6				3	0.21	0.23	0.11	0.11	0.67
p of F ratio			0.005				0.34 (ns)	0.28 (ns)	0.02 (ns)	0.07 (ns)	0.07 (ns)	0.001

Based on Baillie, Tan and Chin, unpublished data for 60 auger profiles, 2003.
Different letter superscripts indicate means are significantly different (Tukey HSD, < 0.05).

acid, and deficient in NH_4Cl-extractable P and bases, and Al is the dominant labile cation (Table 5). Labile forms of all of the main mineral nutrients increase from coarse to fine textured soils, but levels are still low. The 2001 data (S. Tan, unpublished) confirm that topsoils are very acid, and show that they all have low contents of NH_4OOCH_3-exchangeable cations (Table 6), with few significant differences between Peninjau, Nyalau and Bekenu series, but the clays of Merit series have significantly better exchangeable base status. Bray 2 available P contents are low throughout and vary little between series, but $HClO_4$-extracted total P increases significantly with clay content.

The 2003 data (I.C. Baillie and S. Tan, unpublished) also indicate that subsoils are very acid and have low contents of exchangeable cations and Bray 2 available P (Table 7). Series means increase with clay content, but not significantly. When individual sites are grouped by field texture, most labile nutrients increase systematically from sand to clay. However, the increases in topsoils are significant ($p < 0.05$) only for C:N, exchangeable Mg, and total exchangeable bases (TEB). Significance levels are higher in subsoils than topsoils but are very significant ($p < 0.01$) only for subsoil exchangeable K, Mg and TEB.

The 2003 data confirm that HCl-extractable reserves are moderate for K and Mg, low for P, and very low for Ca (Table 8). The differences between series are clearer for

Table 8. Means of 2003 data for reserve (HCl) nutrients in soils of Lambir LTER plot

Soil Map Unit (see Fig 4a)	Depth *cm*	n	Reserve (conc.HCl) P	K	Ca	Mg	Mn	Cu	Zn	B	Fe
			mg.kg^{-1}								%
Topsoil											
P	0 - 10	3	102	1864[a]	94	574[a]	1	1	15[ab]	19[a]	0.88[a]
N		15	91	2228[a]	141	685[a]	4	1	10[a]	17[a]	0.79[a]
B		20	88	2526[ab]	133	792[ab]	6	2	10[a]	19[a]	0.76[a]
M		8	129	4231[b]	170	1421[b]	88	3	23[b]	33[b]	1.46[b]
K		11	100	3276[ab]	158	874[ab]	9	2	12[a]	23[ab]	0.99[a]
L + S		3	121	3291[ab]	124	967[ab]	11	1	12[a]	20[ab]	0.84[a]
Overall mean		60	99	2822	142	862	17	2	12	21	0.91
p of F ratio			0.10 (ns)	0.008	0.38 (ns)	0.000	0.05 (ns)	0.02 (ns)	0.000	0.001	0.000
Subsoil											
P	45 - 55	3	78	1782[a]	111	579[a]	1	1	7[a]	21[a]	0.96[a]
N		15	78	2499[ab]	129	796[a]	2	2	12	21[a]	0.94[a]
B		20	78	3078[abc]	139	967[ab]	3	2	12[a]	23[a]	1.04[a]
M		8	123	4630[c]	127	1667[b]	68	3	25[b]	38[b]	1.60[b]
K		11	88	3867[bc]	124	997[ab]	5	3	13[a]	28[ab]	1.18[ab]
L + S		3	102	3423[bc]	117	1188[ab]	4	3	14[a]	26[ab]	1.10[ab]
Overall mean		60	87	3237	130	1014	12	2	14	25	1.11
p of F ratio			0.03 (ns)	0.001	0.32 (ns)	0.001	0.05 (ns)	0.08 (ns)	0.000	0.000	0.001

Based on Baillie, Tan and Chin, unpublished data, 2003.
Different letter superscripts indicate means are significantly different (Tukey HSD, < 0.05)

Table 9(a). Principal Components in data for auger profiles (n = 60)

	Principal Component 1	2	3	4
Eigenvalue	12.94	3.83	2.82	2.44
% Total variance	37	11	8	7

Based on Baillie, Tan and Chin, unpublished data, 2003.

Table 9(b). Main loadings on Principal Components 1 - 4

Variable groups	Individual variables	Communality	Principal Component 1	2	3	4
			Highest loading			
Whole solum	Texture class	0.50	0.56			
	Depth	0.37		0.44		
Organic matter	Humus thickness	0.32	0.42			
	Org C	0.79			0.83	
	C:N	0.73			0.62	
Topsoil labile nutrients	pH	0.60		0.71		
	Exch Ca	0.43		0.53		
	Exch Mg	0.78	0.78			
	Exch K	0.65	0.65			
	Exch Na	0.41				0.56
	Available P	0.75			0.81	
Topsoil reserve nutrients	P	0.83	0.83			
	K	0.80	0.84			
	Mg	0.86	0.92			
	Ca	0.56		0.45		
	Fe	0.70	0.78			
	Mn	0.80	0.66			
	Cu	0.50	0.49			
	Zn	0.78	0.86			
	B	0.69	0.77			
Subsoil labile nutrients	pH	0.60		0.77		
	Exch Ca	0.18	0.39			
	Exch Mg	0.82	0.77			
	Exch K	0.58				0.57
	Exch Na	0.28				0.44
	Available P	0.46	0.38			
Subsoil reserve nutrients	P	0.81	0.84			
	K	0.80	0.86			
	Mg	0.87	0.93			
	Ca	0.11		0.28		
	Fe	0.59	0.73			
	Mn	0.71	0.63			
	Cu	0.60	0.61			
	Zn	0.72	0.82			
	B	0.65	0.78			
Component interpretation and designation			Mica	Ca	Organic matter	Non-mica minerals

reserves than for labile forms of the same nutrients. Series means of reserves differ significantly for K, Mg, Fe, Zn and B at both depths. Series differences for reserve Mn are not statistically significant although the series means span an order of magnitude. Merit series has the highest means for 14 of the 18 reserve nutrient variables, and Peninjau series the lowest for ten. In the sandstone RYP's 12 of the reserve nutrient variables increase with clay content from Peninjau series through Nyalau to Bekenu. Significance levels of inter-series differences in reserve nutrients are similar for topsoils and subsoils.

As with more labile forms (exchangeable, extractable and available), the trends for reserve nutrients are clearer when individual sites are grouped by field texture. Clays have the highest means in 16 of the 18 reserve nutrient variables; differences for reserve Mn become statistically significant; and differences are more pronounced in subsoils than topsoils.

Principal component analysis (PCA)

Pedological and ecological interpretations of multivariate soil data are complicated by correlations between attributes. Apparently influential variables may not be important themselves but correlated with genuinely significant attributes. Alternatively, none of the correlated variables may themselves be causally important but may be indicators of underlying unmeasured trends. In order to identify the main trends in the Lambir soils, principal components (PC) were extracted from the 2003 data of 35 variables covering humus thickness, soil depth, textural class and nutrients for 60 sites (I. C. Baillie, S. Tan, and S.P Chin, unpublished). Total N and TEB were omitted from the initial data because of their linear dependence on other variables. A preliminary scree test indicated a break of slope at four components. Varimax rotation made little difference to an already interpretable structure, so the orthogonal PCA was retained.

The first four unrotated principal components incorporate almost two thirds of the total variance(Table 9a). Elision of the minor loadings highlights the main features of the component structures (Table 9b). The first three components are similar to those extracted for MDF soils on clastic sedimentary rocks in Central Sarawak (Baillie et al. 1987). The main component (PC1) incorporates 37 % of total variance and is heavily loaded with clay and reserve nutrients, especially Mg and K. It parallels the proportions of shale and sandstone in the soil parent materials, and is interpreted as reflecting the influence of micaceous minerals. Component PC2 (11%) is loaded by pH and Ca variables, although the Ca subsoil variables have low communalities, i.e. much error variance, with only a small fraction contributing to the PCA. The loading of Ca onto a separate component highlights the differences between it and the other cationic nutrients in these soils. The main loadings on component PC3 (8%) are for organic matter and topsoil available P. The loadings for subsoil exchangeable K and Na suggest that component PC 4 (7%) may reflect the effect of non-micaceous minerals in the parent material, such as feldspars and halites.

DISCUSSION

International soil correlations

The use of the Sarawak system for the classification of the soils of the plot parallels applications of local soil taxonomies to edaphic characterisation of other forest ecological research sites (Baillie et al. 2007a; Clark et al. 1999; Johnston, 1987; Sollins *et. al.,* 1994; Yamashita et al. 2003). However, local taxa are meaningful only in their home territories and it is necessary to correlate them with international systems such as WRB and/or ST for wider communication and comparisons.

Most of the mature RYP soils on the plot correlate with Acrisols in WRB, with the required increases in clay with depth, low base saturations, and low activity clays (< CEC 24 $cmol_c\ kg^{-1}$ clay) (Table 10). Most of them are sufficiently base-depleted to be Hyperdystric, with the remainder mainly Haplic. There are a few soils in Bekenu and Merit series with more active clays, on which Al is the dominant labile cation, and these qualify as Alisols.

Like the Sarawak system, WRB separates very coarse textured soils at high level, and those soils in Peninjau series with loamy sand textures to below 1 m correlate as WRB Arenosols. The weak clayskins, high friability and porosity in some subsoils in Peninjau and Nyalau series are ferralic attributes, and these soils qualify as Ferralsols or Ferralic Arenosols.

In ST all of the Lambir RYP's are Udults. They are subdivided on the depth profiles of their clay contents. Most of the Lambir RYP's show no systematic decrease below the clay-increase argillic horizon, and the textural profiles are 'stepped' rather than 'bulging'. Many therefore appear to be Paleudults. However, as its name indicates, this group is intended for old, well developed soils and is defined as having the paralithic contact at least 1.5 m deep. At Lambir most soils in Peninjau and Nyalau series and some in Bekenu are sufficiently deep, but most of the clays in Merit series are too shallow. They

Table 10. International correlations of soils of Lambir LTER plot

Sarawak soil taxon	**World Reference Base** (FAO, 2006)	**Soil Taxonomy** (Soil Survey Staff, 1999 and 2006)	
		Subgroup	Particle size and mineralogy families
Peninjau series	Hyperdystric, Haplic or Ferralic Arenosol; or Arenic Acrisol; or Areni-Acric Ferralsol	Psammic, Hapludoxic or Typic Paleudult or Kandiudult; Psammic Hapludox	Sandy and coarse-loamy; kaolinitic and mixed
Nyalau series	Hyperdystric or Haplic Acrisol; or Acric Ferralsol	Hapludoxic and Typic Paleudult and Kandiudult	Coarse-loamy; kaolinitic and mixed
Bekenu series	Haplic or Hyperdystric Acrisol or Alisol	Typic Hapludult, Paleudult, Kanhapludult and Kandiudult	Fine-loamy; mixed
Merit series	Haplic Acrisol or Alisol	Typic Hapludult or Kanhapludult	Clayey; mixed
Kapit series	Skeleti-Dystric Cambisol	Lithic Dystrudept	Loamy- skeletal; mixed
Meluan series	Dystric Leptosol or Skeleti-Dystric Cambisol	Lithic Dystrudept	Loamy- skeletal; mixed
Tutoh series	Skeleti-Dystric Regosol	Typic Udorthent	
Semadoh family	Lepti-Dystric Gleysol	Lithic and Typic Endoaquent	

Based on Tie (1982); Teng, (1996); I C Baillie, J. D. Mamit and S. Tan, unpublished data, 1971-2003

therefore correlate as Hapludults (Typic or Inceptic). Transitional oxic subsoils mean that some profiles of Peninjau and Nyalau series qualify for the Hapludox group or the Hapludoxic subgroups of the Paleudults. A few soils in Peninjau series are coarse textured enough to be Psammic, but most of the non-oxic Paleudults have loam or finer textures, and so qualify for Typic subgroup.

Like WRB, ST differentiates on clay activity but, unfortunately, it does not use the same criterion. Many Lambir RYP subsoils have CEC values below the ST limit for low activity clays (16 $cmol_c.kg^{-1}$ clay), and qualify as kandic horizons. The deep sandstone soils are therefore mostly kandic equivalents of the Paleudults and qualify as Hapludoxic or Typic Kandiudults. Similarly, some of the clays of Merit series are Typic Kanhapudults.

The shallow scarp soils of Kapit and Meluan series are Leptic and Haplic Cambisols in WRB and Dystrudepts in ST. The deeper debris soils of Tutoh series are Colluvic Regosols in WRB and Typic Udorthents in ST.

Humus mats and the absence of Humults

Despite its limitations (Baillie, 1996, and 2001), ST has been used in previous ecological studies at Lambir and elsewhere in Bornean MDF. Non-humic soils at Lambir were correctly classified as Udults, but those with humic mats were designated as Humults (Ashton, and Hall, 1992; Cranbrook and Edwards, 1995; Davies, et al. 1998; Nagamasu and Momose, 1997; Palmiotto et al. 2004; Potts et al. 2004; Yamada et al. 1997). This was based on the reasonable assumption that a feature as ecologically significant as a humus mat would warrant pedotaxonomic recognition. However, most soil classification systems have agricultural, rather than ecological, orientations and differentiate soils on features that survive changes in land use and persist in agricultural soils. As thin surface humus disappears when forest is cleared and soil surfaces are exposed to direct rainfall, fire, cultivation, sunlight, high temperatures and desiccation, humus layers less than 10 cm thick are considered ephemeral and are ignored as pedotaxonomic criteria in the tropics.

Furthermore, the ST Humult suborder is defined as having organic matter extending well into the subsoil, with organic carbon contents >0.9% down to at least 15 cm into the argillic horizon, and is intended for soils with active mixing of organic and mineral matter. Humults mostly develop on volcanic parent materials, as in Jaguar and Matabuey series at La Selva (Sollins et al. 1994). As humus at Lambir occurs as discrete, unmixed surface layers, none of the RYP's qualifies as Humults.

Although understandable, this discounting of thin surface humus layers is ecologically regrettable, as it means that the conventional soil classifications ignore an important attribute in soils that remain under forest. If the Lambir RYP's are separated at phase (i.e. sub-series) level on the presence/absence of humus mats > 5 cm thick, there are clear differences between the soil series. 88% of the 2003 augerings in Peninjau series would qualify for the epihumic phase, 59% in Nyalau and 56% in Bekenu, but only 12% in Merit and 13% in Kapit (I.C. Baillie and S. Tan, unpublished data).

Edaphecological habitat characterisation

This review was undertaken in order to provide the fullest possible data for the consideration of edaphic effects in the ecology of MDF at Lambir. Early studies of site-forest association at Lambir were limited by the lack of systematic data on soil nutrients, and the differentiations of edaphic habitats were mainly based on altitude and slope gradients, and humic and non-humic surfaces (Davies, et al. 1998; Nagamasu and Momose, 1997; Palmiotto et al. 2004; Potts et al. 2004; Yamada et al. 1997 and 2000). The application of Mantel analysis to the 2001 topsoil labile nutrient data was a considerable advance (Potts et al. 2004), and enabled convincing confirmation of the existence of strong soil-forest associations (Davies, et al. 2005; Russo et al. 2005). Figure 4 compares our soil series, which are mainly defined on field-observable morphological attributes, with the nutrient-defined Mantel habitats. The correspondence is striking, and our morphologically-based soil map delineates edaphecologically distinct areas (Fig. 4b and Table 11). The distributions of edaphic specialist tree species (Davies et al. 2005) correspond well with the soil map, as do differences in forest dynamics (Russo et al. 2005).

Comparison with other tropical forest soils

RYP and associated shallow soils are the most extensive soils in Sarawak (Andriesse, 1972; Teng, 1996), and are the main lowland soils on clastic sedimentary parent materials in Borneo and aseasonal Southeast Asia (Dudal and Moormann, 1964; Soepraptohardtjo and Ismangun, 1980). Morphologically similar Acrisols are extensive on clastic sedimentary parent materials elsewhere in the humid tropics (Driessen and Dudal, 1991; Duivenvoorden and Lips, 1995; Johnston, 1987; Wright et al. 1959)

They form a distinct subgroup within the soils of tropical forests. Their physical distinction results from the substantial contents of 2:1 and 2:1:1 clay minerals, which give their subsoils moderate bulk density, porosity and firm consistence. This makes the subsoils less

Table 11. Correspondence between Mantel edaphic habitats and Sarawak soil taxa, Lambir LTER plot

Mantel habitat (after Potts et al. 2004)	Predominant lithology	Topographic position	Main Sarawak soil taxa	Ranking of edaphic constraints
1	Sandstone	Main dipslope	Peninjau, Nyalau and Bekenu series	Low nutrients > moisture stress > site instability
2	Shale	Lesser dipslope	Meritseries	Occasional anoxia and moderately low nutrients > site instability
3	Sandstone + some shale	Steep convex upper scarp	Kapit and Tutoh series	Site instability > moisture stress > low nutrients
4	Shale + some sandstone	Steep concave lower scarp	Semadoh and Meluan families	Site instability >> patchy moisture stress and occasional anoxia and moderately low nutrients

> More important than >> Much more important than

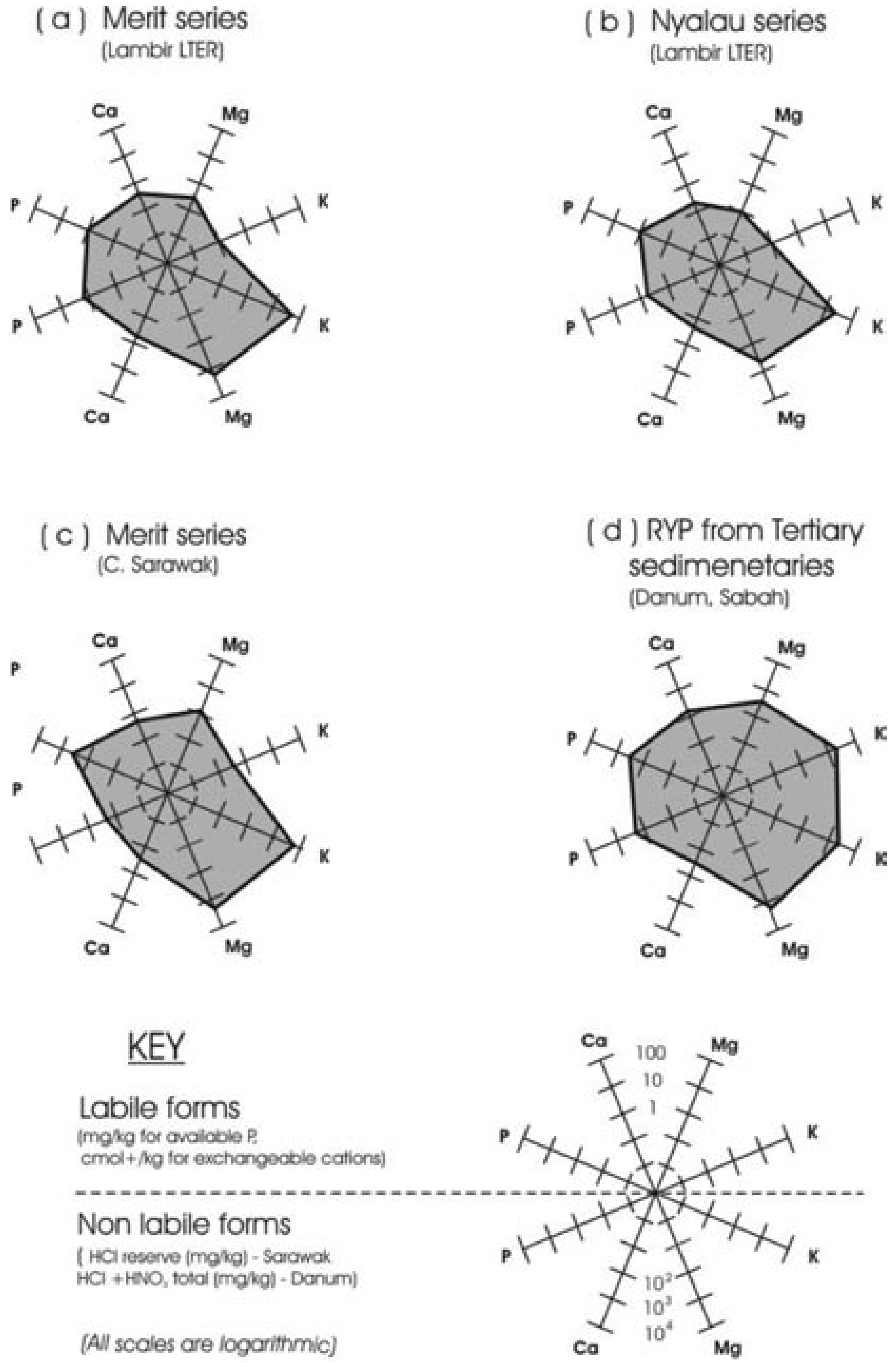

Fig. 5. Stoichiometric roses of topsoil mineral nutrients of Lambir LTER Plot and other Borneo RYP on Tertiary sedimentary parent materials

Lambir roses based on Baillie, Mamit and Tan unpublished data, 1971 - 2003; Central Sarawak data from Baillie (1978) ; Danum data from Burghouts et al. (1998)

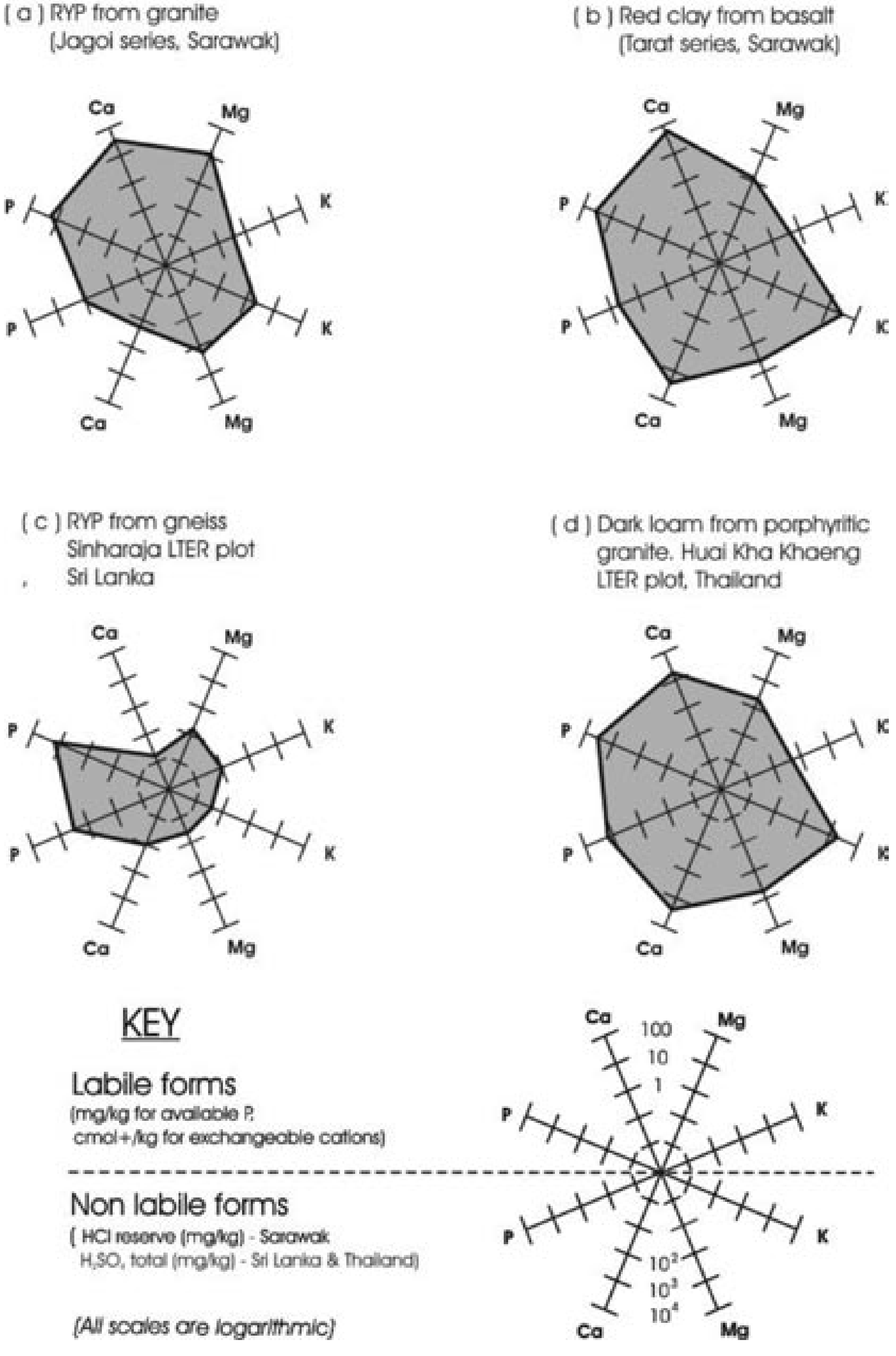

Fig. 6. Stoichiometric roses of topsoil mineral nutrients of tropical forest soils on crystalline parent materials
Sarawak profiles (a and b) based on data of Andriesse (1972); Sinharaja profile (c) after Baillie et al. (2007b); Huai Kha Khaeng profile (d) based on S. Bunyavejchewin, unpublished data, 2007

permeable than the topsoils, so that much soil water movement occurs as shallow lateral throughflow (Wenzel et al. 1998). The discrete wet layers seen in some Lambir sandstone dipslope subsoils in 2003 are attributed to concentrated throughflow. The throughflow in this instance is apparently too infrequent and short lived to affect drainage, aeration and colours. However, the lack of gleying and mottles may be also partly due to a deficiency of carbonaceous energy sources for the endothermic microbial reduction of iron (Stemmler and Berthelin, 2003). The prevalence of throughflow differentiates the RYP's hydrologically from more permeable modal kaolisols (Ferralsols/Oxisols), in which drainage is predominantly vertical (Baillie, 1996).

The RYP/Acrisols on clastic sedimentary rocks are also chemically distinct. The low pH and low contents of available nutrients are common to many tropical forest soils. However, their combination with moderate reserves/totals of K and Mg and low reserves of P and Ca results in distinctive stoichiometric profiles for these soils. These can be depicted as stoichiometric roses (Fig. 5), as devised for Amazonian soils by Alvim (1978) and also used for the nutrient characterisation of tropical forest soils in Sri Lanka and Panama (Baillie et al. 2007a and b). The larger rose for Merit series (Fig 5a) indicates that its contents of all nutrients are higher than those of the sandstone soils (Fig. 5b). The congruent shapes mean that the nutrient ratios are similar, so that the Lambir RYP's can be arrayed along a single mineral nutrient fertility axis. The roses of other RYP's on Tertiary clastic sedimentary rocks in Sarawak and Borneo are also more or less congruent with those on the plot (Figs. 5c and 5d), reflecting similarly micaceous source rocks. However, the roses of Sarawak RYP's on felsic crystalline rocks and of ferralic/oxic clays and loams on mafic rocks (Fig.6) are incongruent, indicating substantially different nutrient ratios.

Edaphic effects of mineral weathering

The distinctive hydrology and stoichiometery of the RYP/Acrisols are attributed to the lithology of the clastic sedimentary materials and their weathering products, especially the primary micas and secondary 2:1 and 2:1:1 clay minerals. The persistence of some moderately active clay minerals, combined with moderate solum depths and fragments of saprolite, indicate that weathering is not terminal in these soils, despite the high leaching potential of the climate (Islam et al. 2002; Selvaraj and Chen, 2005). On the plot, these slightly immature features are more pronounced in the Merit clays than in the sandstone soils. The less intense weathering in the clays is partly due to their high proportion of throughflow. This limits deep vertical leaching and the amount of water available for weathering lower subsoils and saprolites. More moisture leaches vertically in the sandstone soils and their subsoils weather more rapidly. The creation of shear planes in anisotropically wetted layers is another mechanism by which throughflow contributes to the persistence of moderately shallow soils. Failures along such planes can cause soil profile truncation (Furian et al. 1999; Jackson, 1966), and facilitate the uprooting of trees (Blancaneaux, 1973), thus exhuming fresh minerals and resetting weathering.

The reserves of Mg and K and the distinct stoichiometric profile of these soils also derive from the micaceous, 2:1 and 2:1:1 minerals. Although not rapidly labile, these nutrient reserves appear to be partially accessible to, and to figure in the budgets of, long-lived organisms such as mature trees. Reserve nutrients are ecologically important in Bornean MDF and are more closely associated than more labile forms with the dynamics of litter decomposition at Lambir (Baillie et al. 2006), and the distribution of tree species in MDF in Central Sarawak (Baillie et al. 1987).

Their effect is attributed to significant replenishments of forest nutrient cycles by micaceous weathering. Such replenishments may be slight but they allow for partially open cycling of mica-sourced Mg and K in shale-derived Merit soils. The lower mica and illite contents and replenishment capacities of the sandstone soils constrain their forests towards more closed nutrient cycles, shown by the greater sequestration of nutrients in recalcitrant humus mats (Baillie et al. 2006), and by the slow growth and low mortality rates of sandstone specialist tree species (Russo et al. 2005).

Such replenishment of mineral nutrients requires that weathering occur within rooting depth. This is more likely in landscapes where tectonic activity and topographic dissection tend to keep sola shallow (Taylor and Howard, 1999; Vitousek et al. 2003). It is also favoured by deep rooting (Schenk and Jackson, 2002), as in MDF in Central Sarawak, where roots penetrate several metres down into saprolite and along cracks in slightly weathered shale (Baillie and Mamit, 1983). In some tropical forests, however, deep roots appear to tap the saprolite moisture reserves, but not nutrients (Poszwa et al. 2002).

Ecologically significant replenishment also requires that the weathering minerals contain the essential nutrients in significant quantities. At Lambir, mineral reserves of Ca are low, and weathering replenishment appears to be an unimportant. Ca may be mainly topped up by atmospheric inputs, similar to the aeolian contributions to the K nutrition of Hawaiian forests on old geomorphic surfaces with deeply weathered K-deficient mafic regoliths (Chadwick et al. 1999; Juang and Uehara, 1968; Vitousek, 2004).

CONCLUSION

The collation of multiple soil data sets shows that pedological taxa and soil maps differentiate edaphecological habitats on the Lambir 52 ha LTER plot. The combination of soil series with physiographic factors enables edaphic characterisation to extend beyond labile nutrients and to encompass the other important facets of tropical forest soil fertility, i.e. moisture, root aeration, site stability and non-labile mineral nutrients (Table 11).

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