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Biomass variation across selectively logged forest within a 225-km^2 region of Borneo and its prediction by Landsat TM

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ABSTRACT

Estimates of biomass integrated over forest management areas such as selective logging coupes, can be used to assess available timber stocks, variation in ecological status and allow extrapolation of local measurements of carbon stocks. This study uses fifty 0.1 ha plots to quantify mean tree biomass of eight logging coupes (each 450–2500 ha) and two similarly sized areas in un-logged forest. These data were then correlated with the spectral radiance of individual Landsat-5 TM bands over the 15 km × 15 km study area. Explanation of the differences in radiance between the ten forest sites was aided by measurements of the relative reflectance of selected leaves and canopies from ground and helicopter platforms.

The analysis showed a marked variation in the stand biomass from 172 t ha^{-1} in coupe C88 that was disturbed by high-lead logging to 506 t ha^{-1} in a similarly sized area of protection forest. A two-parameter linear model of Landsat TM radiance in the near-infrared (NIR) band was able to explain 76% of the variation in the biomass at this coupe-scale. The local-scale measurements indicated that the differences in the mean radiance of each coupe (in cloud-free areas) may relate to a change in the proportion of climax tree canopy relative to a cover of either pioneer trees or ginger/shrubs; the canopies of climax trees have the lowest NIR radiance of the vegetation characteristic of selectively logged forest. The coupe harvested following ‘Reduced Impact Logging’ guidelines had a residual biomass and NIR radiance more like that of undisturbed lowland dipterocarp forest than coupes disturbed by ‘conventional’ selection felling. The predictability of tree biomass (at the coupe-scale) by such a parsimonious model makes remote sensing a valuable tool in the management of tropical natural forests.

1. Introduction

Quantification of tree biomass across regions of natural forest within the humid tropics is essential for a wide range of contemporary research and management questions. Within forest management, these data are required to assess the volume of timber available within potential harvesting coupes (MacLean and Krabill, 1986; Jusoff and Souza, 1996; Trotter et al., 1997). Within tropical rain forests already disturbed by selective felling, forestry organizations need to quantify the rate of biomass recovery to judge the impact of previous operations and the timing of the next phase of selective logging (Pinard and Putz, 1996; Apan, 1997; Asner et al., 2002). Assessments of impacts of forest disturbance and rehabilitation on carbon sequestration (Chambers et al., 2007; Saatchi et al., 2007), would similarly benefit from regional biomass estimates.

Historically, assessments of tree biomass have been undertaken using forest enumeration plots. At the scale of the plot (typically <5 ha), biophysical data can be very accurate. There are, however, three key problems with this approach when regional biomass estimates are needed. First, the approach does not provide any information on the properties of forest in between the scattered plots, i.e., the majority of the forest. Secondly, because it is very time consuming to undertake biophysical measurements across a large number of plots, it is often considered impractical for frequent, repeat surveys of coupes following each cutting cycle (DeFries et al., 2007). Thirdly, for the assessment of extensive forest areas, occupying tens or hundreds of thousands of square kilometres in area (Chambers et al., 2007; Saatchi et al., 2007), it can be considered impractical to organize plot surveys. Because of these limitations, researchers in the last 20 years have attempted to correlate the spectral characteristics of the forest canopy (observed from satellite sensors) with plot-based, biophy-

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sical data (e.g., Lucas et al., 1993; Ekstrand, 1994; Imhoff, 1995; Foody et al., 1996, 2001, 2003; Salvador and Pons, 1998; Hyyppä et al., 2000; Steininger, 2000; Labreque et al., 2006; Meng et al., 2007). Within tropical rain forest regions, such of Borneo Island, much remote sensing of biomass has been undertaken using the Landsat 'Thematic Mapper' (TM) sensor (see e.g., Jusoff and Hassan, 1998; Foody et al., 2001, 2003; Foody, 2003; Foody and Cutler, 2003). Borneo is a key area for these analyses given the extent of felling (Curran and Trigg, 2006; Chambers et al., 2007) and the high rate of conversion of natural forests to oil palm plantations and other agro-forestry systems (McMorrow and Talip, 2001).

Despite much early promise, recent remote sensing analyses of Bornean forests have shown only weak correlations between data for one or two spectral bands and tree biomass, often with a coefficient of determination (r^2) <0.1 (Foody et al., 2001). Multiple regression involving combinations of many bands generally do a little better in the humid tropics (i.e., $r^2 < 0.3$: Foody et al., 2001; Foody, 2003), though good correlations have been observed where neural network models have been used (Foody et al., 2001, 2003; Foody and Cutler, 2003) rather than multiple regressions. These models are, however, high order (i.e., have many parameters), and therefore, may have large uncertainties associated with their predictions (Aires et al., 2004).

Given that comparisons of remotely sensed data (Landsat-5 TM resolution is 0.09 ha) with measurements from individual plots 0.1–5 ha in area will be sensitive to: (i) small errors in the geo-referencing, and (ii) difficulties in sampling the complex forest resulting from selective felling (Pinard and Putz, 1996; Pinard et al., 1996; Wan Mohd et al., 1997; Howlett and Davidson, 2003), weak correlations may be partly attributed to inadequacies in the handling of the 'ground truth' (i.e., the plot) data. Within this study, the detailed patterns of the forestry operations and resultant vegetative cover are known in more detail than those typically reported by other remote sensing studies. This has been possible given: (i) access to forestry company records (e.g., Moura-Costa and Karolus, 1992), (ii) published forestry studies undertaken within the local region (e.g., Pinard and Putz, 1996; Howlett and Davidson, 2003; Newbery et al., 1992), and (iii) because of a new programme of biophysical measurements undertaken as part of this study.

The ultimate aim of this study is to identify the simplest model of tree biomass (t ha^{-1}) over a managed tropical forest region that can be derived from Landsat TM data. If a simple or 'parsimonious' model (Tukey, 1961) can be identified, then uncertainty in biomass prediction may be constrained (Aires et al., 2004). The region selected for study is a 225-km^2 area of 'lowland dipterocarp forest' (Whitmore, 1990) that contains areas disturbed by commercial selective logging. These regions, eight in total, are annual timber harvesting coupes each 450–2500 ha in area. Two similarly sized areas of undisturbed forest were also available for comparison. The study region is located centrally within the 10,000 km^2 Yayasan Sabah Forestry Concession in Malaysian Borneo, close to the Danum Valley Field Centre (117°45′ to 118°00′ East and 4°50′ to 5°05′ North).

Interpretation of the spatial variation of spectral properties between logging coupes was addressed with a parallel programme of spectral observations of different forest features from a helicopter platform and from ground-based observations of 49 individual leaves (or small groups of leaves). The sampling of canopies and leaves was structured to incorporate vegetation features indicative of both undisturbed lowland dipterocarp forest and that disturbed by commercial selective forestry. Canopy-scale features indicative of forests affected by commercial selective felling in the area include: (a) patches dominated by pioneer trees (e.g., *Macaranga* spp.: Howlett and Davidson, 2003), (b) areas around former 'high-lead masts' (Conway, 1982) now dominated by ginger (*Zingiber* spp.), shrubs and vines, (c) areas of undisturbed climax forest (e.g., 'riparian protection forest': Chappell and Thang, 2007), and (d) areas still dominated by climax trees, but with a high level of anthropogenic disturbance. While the focus of the research was on tree biomass estimation, other key biophysical characteristics, namely tree (stem) volume, tree density, and basal area were quantified within the enumeration plots. Tree species were identified (Tangki, 2008), but are not reported here.

2. Study region

The 225 km^2 study region is located within the Ulu Segama Forest Reserve and is managed by the state organization called 'Yayasan Sabah' for research, education and commercial timber production. The area is covered by lowland diperocarp forest, which has an upper and emergent canopy dominated by the family Dipterocarpaceae (Whitmore, 1990). It is the most extensive forest type in Borneo (Newbery et al., 1992). The annual harvesting coupes were logged by selection felling in years: 1981 (Coupe 1981, or 'C81'), 1982 (Coupe 1982, or 'C82'), 1983 (Coupe 1983, or 'C83'), 1988 (Coupe 1988, or 'C88'), 1989 (Coupe 1989, or 'C89'), 1992 (Coupe 1992, or 'C92'), and 1993 by conventional selective felling ('C93c') and Reduced Impact Logging methods ('C93RIL'). The region also includes undisturbed forest of the water catchment area of the Danum Valley Field Centre (DVFC), and a small corner of the 438 km^2 Danum Valley Conservation Area (DVCA or CONS). The C81, C82, C83, C88 and C89 coupes were logged using a combination of tractor and high-lead harvesting techniques. With 'high-lead yarding' (see Conway, 1982) a series of cables radiate from a central spar-pole. Each felled tree is then attached to one of these cables and winched to the central collecting point; this leaves an area of approximately 20 ha around the spar-pole with few or no trees. This contrasts with the C92, C93c and C93RIL coupes, which were logged using tractor logging alone. Further, the C93RIL coupe was harvested using local Reduced Impact Logging (RIL) guidelines (Pinard et al., 1995; Putz and Pinard, 1993; Sabah Forestry Department, 1998). These rules aim to minimize collateral damage to the forest during selection felling to help maintain sustainable timber yields (Pinard and Putz, 1996) and reduce environmental impacts (Chappell and Thang, 2007). Selection felling within all logging coupes was restricted to only commercial trees with a diameter breast height (dbh) greater than 60 cm. Moura-Costa and Karolus (1992) and Rakyat Bejaya Sdn. Bhd (1992) collated the timber volumes extracted from each coupe during the logging operations, and these are presented in Table 1. Coupes C82, C83, and some of C88 were subject to forest rehabilitation, which involved the planting of indigenous trees from 1992 onwards. This 'enrichment planting' involved field maintenance (e.g., slashing weeds around the line planting) during the first to the three years after tree planting at 3–6 month intervals.

The physiography of the 225 km^2 study region is one of rugged terrain at moderate elevation. The terrain consists of a series of steep ridges, with approximately 75% of the area occurring on slopes exceeding 20° that are generally more than 200–300 m long (Pinard, 1995). Annual rainfall recorded at the Danum Valley Field Centre (DVFC) within the centre of the study area is 2799 mm (1986–2005).

3. Methods

The methodology involved the establishment and measurement of fifty 0.1 ha forest plots, sub-sampling of corrected Landsat TM data and subsequent averaging of spectral properties within cloud-free areas of each logging coupe, and the observation of the spectral properties of selected canopies and leaves using a Milton Multiband Radiometer.

3.1. Plot measurement of tree biophysical data

Tree identification and measurement was undertaken by establishing 50 plots, each 0.1 ha in area (Figs. 1 and 2; Table 1). Each of the 10 regions studied contained 5 plots based on a concentric circular design. With this plot design, the smallest/inner circle (radius 2 m) was for the measurement of 'regeneration seedlings' (below 2 cm dbh at 1.3 m height). In the next circle (radius 12.61 m) all saplings and poles with 2 to 20 cm dbh were measured. In the large outer circle (radius 17.84 m or 0.1 ha) all trees larger than 20 cm dbh were measured. Sanden (1997) reported that using a concentric sample plot design in his study allowed compensation for a decreasing numerical density with an increasing diameter and height of trees. Each plot was located randomly within each coupe. Within each plot, tree species were identified and measurements of the diameter at breast height (dbh), stem height (for trees with a dbh $\geq$ 20 cm), and tree location within the plot recorded (Tangki, 2008). The dbh was undertaken

Table 1
Details of the logging coupes and protected forest areas within the 225 km^2 study region, Malaysian Borneo

Coupes	Code	Approximated total area (ha)	Sampling plots		Logging information			
			Plot	Terrain slope	Year of started logging	Block	Logging technique	Approximated mean volume extracted (m^3 ha^{-1})
Danum Valley Conservation Area	CONS	48 000	1	−20	–	–	–	
			2	−10	–	–	–	
			3	−10	–	–	–	–
			4	−12	–	–	–	
			5	−30	–	–	–	
Water Catchment Area	CATCH	1 000	1	0	–	–	–	
			2	−5	–	–	–	
			3	−31	–	–	–	–
			4	−30	–	–	–	
			5	−12	–	–	–	
Reduced Impact Logging Project	C93RIL	450	1	−3	1993	35	Tractor	87–175*
			2	−26		37		
			3	−30		34		
			4	−26		29		
			5	−20		29		
Conventional Area YL2/93	C93c	1 945	1	−30	1993	24	Tractor	68**
			2	−40		23		
			3	−20		24		
			4	−23		25		
			5	−20		24		
Coupe 1992	C92	2 500	1	−30	1992	96	Tractor	115**
			2	−19		83		
			3	−21		114		
			4	−28		86		
			5	−34		71		
Coupe 1989	C89	2 280	1	−13	1989	56	High-lead	100
			2	−28		52		
			3	−2		9		
			4	−18		58		
			5	−28		67		
Coupe 1988	C88	2 262	1	−12	1988	5	Tractor	96
			2	−10		10	Tractor	
			3	−35		43	High-lead	
			4	−10		60	Tractor	
			5	−26		23	Tractor	
Coupe 1983	C83	996	1	−20	1983	9	Tractor	122
			2	−10		25		
			3	−17		15		
			4	−12		13		
			5	−5		29		
Coupe 1982	C82	2 073	1	−18	1982	1	Tractor	126
			2	−20		41	Tractor	
			3	−20		46	High-lead	
			4	−30		56	High-lead	
			5	−35		2	High-lead	
Coupe 1981	C81	1 637	1	−15	1981	46	Tractor	81
			2	−25		30	High-lead	
			3	−17		21	Tractor	
			4	−19		80	Tractor	
			5	−23		4	Tractor	

Data source was Moura-Costa and Karolus (1992), except for * which refers to Pinard (1995) and ** Rakyat Bejaya Sdn. Bhd (1992).

Fig. 1. The map of the 15 km × 15 km study area showing the forestry coupe boundaries, haulage roads, the location of the biophysical sampling plots and the Danum Valley Field Centre (DVFC).

at a 1.3 m height above the ground or 30-cm above the buttress for large trees. Stem height (i.e., the distance between the buttress top and first main tree branch) was estimated using a clinometer. The dbh measurements were then used to estimate the tree basal area pooled from 5 replicate plots ($m^2\ ha^{-1}$) and the biomass of trees. Biomass was calculated using an equation derived from inventory data collected in the moist tropics, including dipterocarps in Borneo (Brown, 1997), namely:

$$B_t = e^{(-2.134+2.530\ln(\text{dbh}))}$$

where B_t is the tree biomass (kg) and dbh is the diameter breast height (m). The average biomass for each coupe ($t\ ha^{-1}$) was then derived by summing the biomass for each diameter class (from the 5 replicate plots) and normalizing by the respective sampling areas. Stem volume again pooled over 5 replicate plots ($m^3\ ha^{-1}$) was estimated from the dbh and stem height data using equations specific to 15 local species groups derived by Forestal International Limited (1973).

3.2. Satellite radiometry

The remotely sensed image available to this project was recorded by the Landsat-5 TM platform in March 1997 and covers the 15 km × 15 km study area. These data were recorded approximately 4 months prior to the biophysical survey. The data from the six non-thermal bands were pre-processed and corrected as part of the INDFORSUS research project (Foody et al., 2001). The observed digital numbers (DNs) had been first radiometrically corrected to spectral radiance using post-launch calibration coefficients. Atmospheric correction was then achieved using the Chavez (1996) modified dark object subtracts technique. Geometric correction was achieved with the aid of a set of eleven ground control points at road and river junctions in the locality. Lastly, the data were co-registered to a digital elevation model of the study region using the topographic correction method of Ekstrand (1996).

The aim of the analysis in this study was to derive mean radiances for each of the 10 regions for correlation with the areal averages of biomass density derived from the enumeration plots. As the Landsat-5 TM image available contained a relatively high proportion of cloud, each coupe area needed to be sub-sampled only in cloud-free areas. The classified image of Tangki (2008) was used to identify cloud-free areas for subsequent radiance sampling in 62 polygon areas (Fig. 2) comprising a total of 1000 pixels. The average spectral radiance of all selected pixels within each of the 10 forest sites was then calculated.

3.3. Canopy and leaf radiometry

In order to understand how spectral properties averaged over the 450–2500 ha regions differ, a programme of local-scale measurements with a Milton Multiband Radiometer or MMR

(Milton, 1980, 1987) was undertaken. Measurements of canopy elements of the lowland dipterocarp forest disturbed by selective logging were undertaken from a helicopter platform; for example, measurements of 10 m × 10 m areas of only *Macaranga* spp. pioneer trees. Potential sampling sites had been recorded in an extensive ground survey prior to the helicopter work and then marked on a detailed map taken into the helicopter. The MMR was used from the open door of a Bell 206 helicopter at a height of 50–100 m above each canopy target at a 70–80° angle during cloud-free light conditions. Directly after each canopy reading, a grey card reading was taken and the relative reflectance calculated. A photograph of each canopy target was also taken for reference (Tangki, 2008). The sites associated with the resultant dataset are shown in Fig. 3.

The same MMR approach was used to measure the relative reflectance of different leaf surfaces. Here the objective was to see if individual leaf surfaces of climax trees (that predominate in undisturbed areas) had different spectral signatures to those of pioneer trees, ginger and shrubs that become more prevalent in the highly disturbed coupes. The MMR was placed at a height of 1 m above the 49 sampled leaves for the measurements.

Comparison of the satellite radiometry data with the ground and aerial observations was undertaken using *T*-tests, Pearson correlation and linear regression analyses (Freund and Wilson, 2002).

4. Results

4.1. Tree measurements and interpretation

The primary aim of the biophysical measurements within the 50 plots was to estimate the mean biomass (t ha^{-1}) for each of the eight logging coupes and two similarly sized blocks of protection forest. To help to explain the cause of biomass variations between the coupes, other associated biophysical data of tree volume, density and basal area were collected and interpreted.

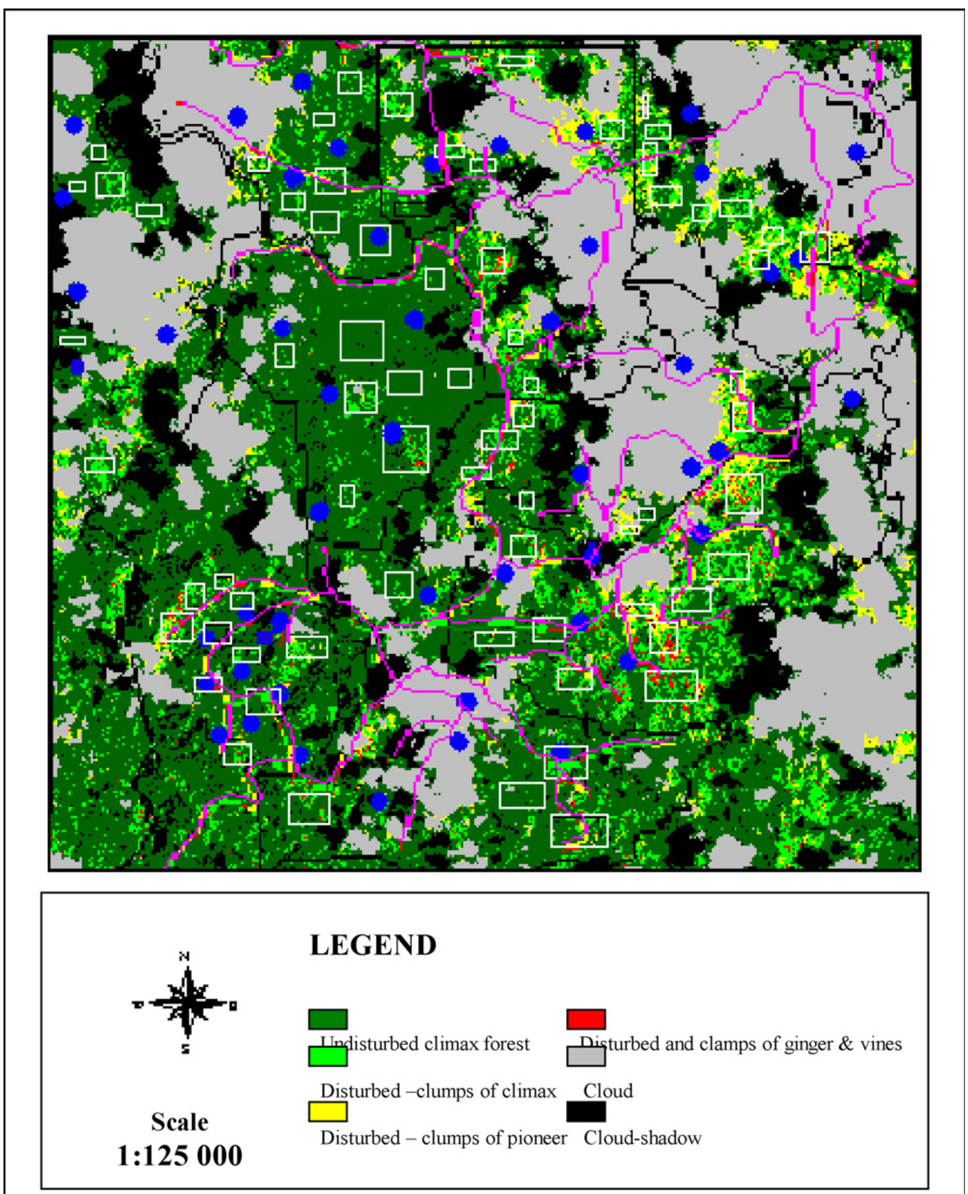

Fig. 2. The Landsat-5 TM image (following supervised classification by Tangki, 2008) overlain with the biomass sampling units (circles), and the polygons sampled for mean radiance value per coupe (boxes). The black lines are the coupe boundaries and grey lines are the haulage roads.

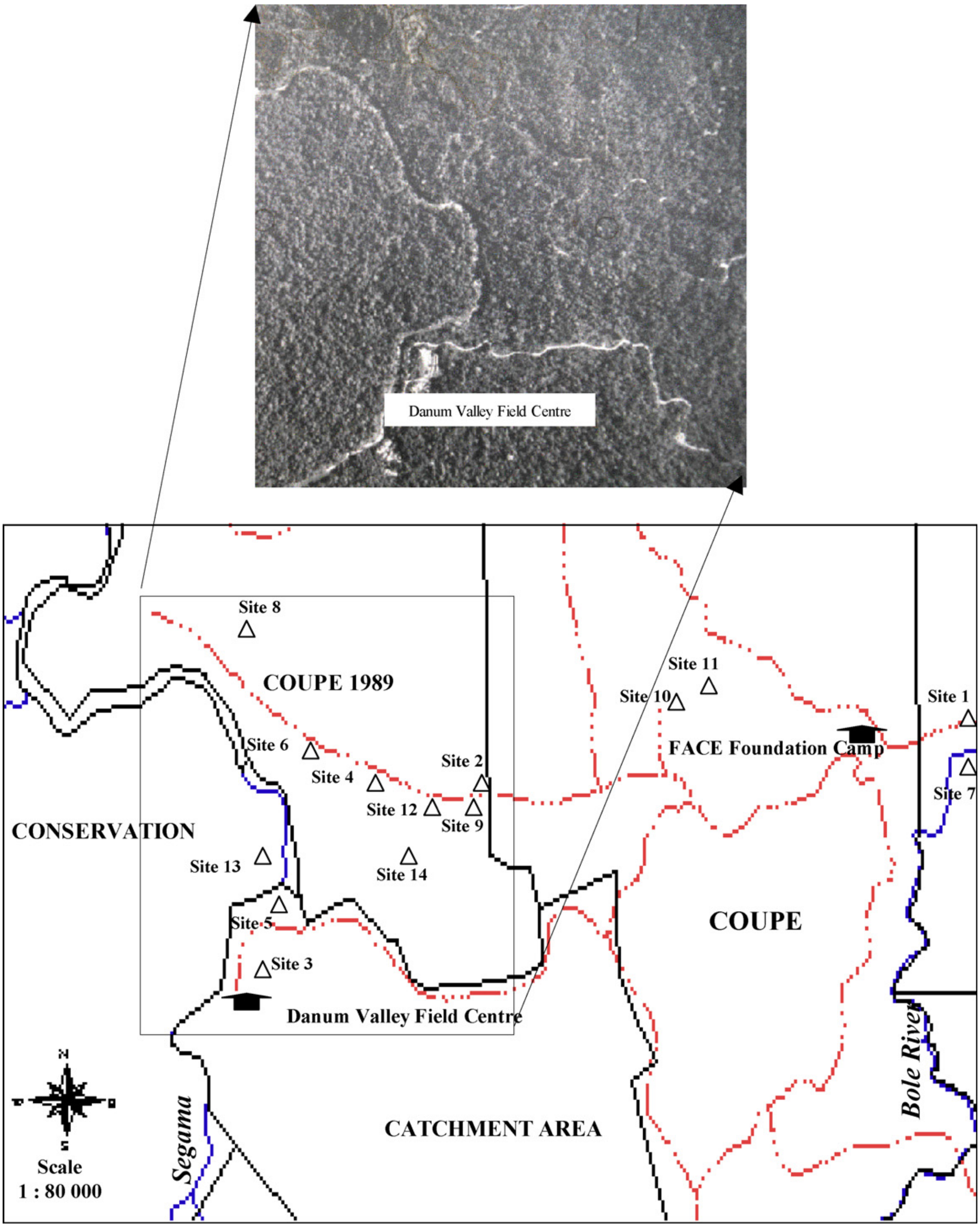

Fig. 3. The map shows the location of the aerial MMR sampling. Solid lines indicate the coupe boundaries, while the broken lines are haulage roads. The small insert at the top shows an aerial photograph taken on 10 October 1995 from 3962 m above sea level.

Table 2 shows coupe-specific tree biomass estimates, and as expected shows that the highest tree biomass was observed in the two undisturbed forest areas (namely 349 and 506 t ha^{-1}); these datasets were not statistically different from each other (*T*-test 2α 0.05, t_{crit} 2.306, t_{calc} −2.282: Freund and Wilson, 2002). Similarly, for trees with a dbh > 10 cm the highest tree density and basal area was observed in the undisturbed forest with 499 t ha^{-1} (σ 108) and 33.2 m^2 ha^{-1} (σ 3.60), respectively (Tables 3 and 4). These values of tree density and basal area are at the centre of the range observed in undisturbed, natural forests in the Borneo region (Table 5). Using the 15 equations derived by Forestal International Limited (1973), the tree stem volume within the two undisturbed forest areas was 328 and 423 m^3 ha^{-1} (Table 6) and thereby smaller than the figure of 464 m^3 ha^{-1} recorded in Bako Forest in Sarawak (Ashton and Hall, 1992).

Within the disturbed forest, logging coupes C88 and C89 had the smallest remaining biomass of 172 and 174 t ha^{-1}, which was only 49 and 50% of the total tree biomass and was significantly different (*T*-test 2α 0.05, t_{crit} 2.306, t_{calc} −3.692 and −3.676, respectively) from that of the undisturbed forest in the adjacent water catchment area (CATCH: Table 2). This relates primarily to the lack of trees and reduced biomass from trees in the

Table 2
Tree biomass (t ha^{-1}) of the study area including statistics of mean ($\bar{X}$), number of sampling plots (n), standard deviation (S.D.) and percentage contributed in each site by diameter breast height (dbh) classes and total tree density per hectare based on 5 sampling units in each forest class

Forest class	Sites	n	dbh 10–20 cm			dbh 20–40 cm			dbh 40–60 cm			dbh > 60 cm			Total (t ha^{-1})
			$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	
Disturbed forest	C81	5	25.94	11.49	13.51	68.6	46.85	35.72	34.09	12.36	17.75	63.41	63.81	33.02	192.03
	C82	5	50.72	18.33	23.39	94.47	22.23	43.57	71.65	35.67	33.04	0	0	0	216.84
	C83	5	31.85	5.69	13.46	66.4	21.06	28.05	78.09	26.19	32.99	60.36	40.45	25.5	236.7
	C88	5	36.91	17.26	21.49	78.71	19.71	45.83	19.92	30.23	11.6	36.19	52.08	21.08	171.73
	C89	5	31.17	15.90	17.93	52.3	19.75	30.09	28.13	11.42	16.18	62.22	62.00	35.8	173.83
	C92	5	28	13.15	11.34	100.5	63.82	40.68	103.31	40.04	41.82	15.25	34.09	6.17	247.05
	C93c	5	32.52	11.28	11.22	68.52	42.48	23.63	89.84	25.35	30.98	99.11	72.50	34.18	289.99
	C93RIL	5	18.7	11.24	5.54	56.41	32.67	16.71	41.77	25.66	12.37	220.69	223.83	65.37	337.58
Undisturbed forest	CATCH	5	38.33	16.33	10.99	66.68	29.45	19.13	65.91	43.01	18.91	177.7	105.61	50.97	348.62
	CONS	5	24.02	6.23	4.74	58.2	11.37	11.49	65.7	36.09	12.97	358.45	160.97	70.79	506.37

Table 3
Tree density (t ha^{-1}) in the study area, including statistics of the number of plots (n), mean per size class ($\bar{X}$), standard deviation (S.D.) and percentage contributed in each site by diameter breast height (dbh) classes and total tree density per hectare based on 5 sampling units in each forest class

Forest class	Sites	n	dbh 2–10 cm			dbh 10–20 cm			dbh 20–40 cm			dbh 40–60 cm			dbh > 60 cm			Total (t ha^{-1})
			$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	
Disturbed forest	C81	5	1920	1083.5	82.5	260	115.8	11.2	120	54.8	5.2	18	4.5	0.8	8	8.4	0.3	2326
	C82	5	2324	835.8	76.4	492	140.4	16.2	188	47.1	6.2	36	15.2	1.2	0	0	0	3040
	C83	5	2044	426.2	80.7	328	68.7	12.9	114	31.3	4.5	38	11.0	1.5	10	7.1	0.4	2534
	C88	5	1428	960.7	74.5	316	133.7	16.5	156	26.1	8.1	12	16.4	0.6	4	5.5	0.2	1916
	C89	5	2288	765.1	83.9	312	136.1	11.4	102	32.7	3.7	14	5.5	0.5	10	7.1	0.4	2726
	C92	5	2424	514.7	82.7	288	141.8	9.8	164	104.8	5.6	50	17.3	1.7	4	8.9	0.1	2930
	C93c	5	2284	629.8	80.6	356	111.7	12.6	130	71.8	4.6	46	8.9	1.6	16	11.4	0.6	2832
	C93RIL	5	1932	786.7	84.7	196	120.3	8.6	102	52.6	4.5	26	5.5	1.1	24	32.9	1.1	2280
Undisturbed forest	CATCH	5	2348	637.3	80.1	408	160.4	13.9	116	30.5	4.0	34	23.0	1.2	24	13.4	0.8	2930
	CONS	5	2708	367.3	86.7	256	60.7	8.2	104	15.2	3.3	30	15.8	1.0	26	16.7	0.8	3124

Table 4
Tree basal area (m^2 ha^{-1}) in the study area, including statistics of the number of plots (n), mean per size class ($\bar{X}$), standard deviation (S.D.) and percentage contributed in each site by diameter breast height (dbh) classes and total tree density per hectare based on 5 sampling units in each forest class

Forest class	Sites	n	dbh 10–20 cm			dbh 20–40 cm			dbh 40–60 cm			dbh >60 cm			Total (m^2 ha^{-1})
			$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	
Disturbed forest	C81	5	4.10	1.77	21.94	7.53	4.77	40.32	2.96	0.98	15.84	4.09	4.14	21.9	18.68
	C82	5	7.98	2.68	32.2	10.64	2.48	42.94	6.16	2.94	24.86	0	0	0	24.78
	C83	5	5.08	0.90	22.03	7.25	2.18	31.45	6.65	2.13	28.83	4.08	2.62	17.69	23.07
	C88	5	5.66	2.58	30.52	8.91	2.03	48.05	1.71	2.66	9.21	2.27	3.20	12.22	18.54
	C89	5	4.93	2.40	28.3	5.91	2.15	33.93	2.42	0.97	13.88	4.16	3.81	23.89	17.41
	C92	5	4.46	2.12	17.64	10.9	6.89	43.1	8.78	3.21	34.7	1.15	2.57	4.55	25.29
	C93c	5	5.28	1.78	19.35	7.63	4.57	27.98	7.73	1.98	28.35	6.63	4.66	24.32	27.28
	C93RIL	5	2.98	1.81	10.88	6.20	3.54	22.62	3.61	2.18	13.18	14.62	14.23	53.32	27.42
Undisturbed forest	CATCH	5	6.16	2.56	20.1	7.31	2.91	23.86	5.70	3.73	18.6	11.47	6.65	37.43	30.63
	CONS	5	3.85	0.97	10.78	6.44	1.15	18.04	5.53	2.99	15.49	19.89	8.66	55.7	35.72

Table 5
Comparison of mean tree density and tree basal area for trees with a dbh greater than 10 cm within undisturbed forest sites in Borneo

Sites	Trees above 10 cm dbh		References
	Tree density (t ha^{-1})	Basal area (m^2 ha^{-1})	
Mulu, Sarawak	739	57.0	Proctor et al. (1983)
Andalau, Brunei	628	35.2	Ashton (1964)
Sepilok, Sabah	608	37.8	Nicholson (1965)
Silam, Sabah	573	42.2	Proctor et al. (1988)
Kalimantan	541	29.7	Kartawinata et al. (1981)
Danum Valley, Sabah	499	33.2	This study
Danum Valley, Sabah	470	26.58	Newbery et al. (1992)
Danum Valley, Sabah	431	42.8	Kamaruddin (1986)
Danum Valley, Sabah	–	27.5	Pinard and Putz (1996)
Segaliud, Sabah	283	28.4	Fox (1967)

Table 6
Tree volume estimation (m^3 ha^{-1}) of the study area including statistics of mean ($\bar{X}$), number of sampling plots (n), standard deviation (S.D.) and percentage contributed in each site by diameter breast height (dbh) classes and total tree density per hectare based on 5 sampling units in each forest class

Forest class	Sites	n	dbh 10–20 cm			dbh 20–40cm			dbh 40–60 cm			dbh > 60 cm			Total (m^3 ha^{-1})
			$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	$\bar{X}$	S.D.	%	
Disturbed forest	C81	5	19.69	9.37	13.21	51.51	38.35	34.57	25.22	20.25	16.93	52.58	53.90	35.29	149
	C82	5	42.32	12.07	18.99	104.38	38.60	46.85	76.11	45.23	34.16	0	0	0	222.81
	C83	5	28.41	2.78	12.23	75.37	29.75	32.44	80.15	28.59	34.5	48.39	31.12	20.83	232.32
	C88	5	28.64	14.87	20.28	64.86	13.16	45.92	13.92	21.06	9.85	33.83	49.75	23.95	141.24
	C89	5	31.19	17.37	19.44	44.43	9.60	27.7	31.25	16.91	19.48	53.53	50.58	33.37	160.4
	C92	5	23.58	11.06	8.84	119.59	79.74	44.85	105.47	47.33	39.55	18.03	40.32	6.76	266.68
	C93c	5	27.77	14.77	10.12	74.55	60.80	27.16	80.71	39.82	29.4	91.49	62.42	33.33	274.52
	C93RIL	5	13.98	10.14	4.92	38.25	29.61	13.45	40.36	23.25	14.19	191.73	189.51	67.43	284.32
Undisturbed forest	CATCH	5	34.03	18.30	10.39	69.5	31.19	21.22	61.92	39.19	18.9	162.14	96.26	49.5	327.59
	CONS	5	19.84	9.23	4.69	51.32	9.58	12.13	58.81	40.50	13.9	293.1	133.91	69.28	423.07

Table 7
The average biomass contribution observed in each forest site together with the average Landsat TM band radiance (mW m^{-2} μm^{-1}) and standard deviation (S.D.)

Site	Biomass		No. of pixels	Band 1		Band 2		Band 3	
	(t ha^{-1})	S.D.		$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.
C81	192.03	214.66	120	3.420	1.110	3.178	1.202	1.592	0.880
C82	216.84	194.4	140	3.153	0.919	3.003	0.877	1.447	0.436
C83	236.7	293.4	48	3.175	0.958	3.053	0.959	1.549	0.508
C88	171.73	151.61	64	3.354	0.988	3.189	0.957	1.648	0.522
C89	173.83	151.1	96	3.187	0.940	3.011	0.893	1.421	0.430
C92	247.05	109.07	162	3.064	0.882	3.154	0.893	1.460	0.405
C93c	289.99	119.28	106	3.153	0.880	2.995	0.878	1.439	0.456
C93RIL	337.58	93.39	52	2.915	0.837	2.770	0.827	1.320	0.413
CATCH	348.62	76.23	152	2.958	0.861	2.863	0.812	1.349	0.383
CONS	506.37	134.51	60	3.010	0.927	2.840	0.880	1.357	0.436

Site	Biomass		No. of pixels	Band 4		Band 5		Band 7		NDVI	
	(t ha^{-1})	S.D.		$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	Index	S.D.
C81	192.03	214.66	120	7.504	2.786	0.625	0.259	0.095	0.048	0.650	0.088
C82	216.84	194.4	140	7.235	2.159	0.656	0.208	0.100	0.034	0.667	0.026
C83	236.7	293.4	48	7.509	2.296	0.704	0.232	0.106	0.034	0.658	0.032
C88	171.73	151.61	64	7.480	2.333	0.712	0.199	0.112	0.035	0.639	0.048
C89	173.83	151.1	96	6.674	1.926	0.664	0.179	0.100	0.029	0.649	0.029
C92	247.05	109.07	162	6.460	2.172	0.703	0.217	0.119	0.032	0.631	0.035
C93c	289.99	119.28	106	6.400	2.168	0.616	0.195	0.102	0.030	0.633	0.053
C93RIL	337.58	93.39	52	6.100	2.079	0.541	0.201	0.087	0.027	0.644	0.037
CATCH	348.62	76.23	152	6.151	1.866	0.564	0.168	0.087	0.025	0.640	0.078
CONS	506.37	134.51	60	5.364	1.942	0.482	0.189	0.077	0.030	0.596	0.042

Band 1 is blue, 2 is green, 3 is red, 4 is NIR, 5 is MIR(I), 6 is thermal IR (not used) and 7 is MIR(II).

dbh > 40 cm classes, post-harvesting (Tables 2 and 3). Similarly, C88 and C89 have a small basal area (18.5 and 17.4 m^2 ha^{-1}) and tree stem volume (160 and 141 m^3 ha^{-1}; Tables 3 and 6). In all logged coupes except C93RIL, stem volume was particularly poorly represented in the >60 cm dbh class compared to that in the undisturbed DVCA (CONS: Table 6). Indeed, all logged coupes except C93RIL, had a significantly different volume of stems >60 cm diameter (T-test 2α 0.05, t_{crit} 2.306, t_{calc} 3.726 C81, 4.894

Table 8
Linear model of biomass (t ha^{-1}) from radiance (mW m^{-2} μm^{-1}) or NDVI index values, together with the coefficient of determination from Pearson correlation

Biomass model, based on Landsat-5 TM bands	r^2
Biomass = 1711.1 − 458.46 × Band 1	0.51
Biomass = 1897.6 − 540.82 × Band 2	0.58
Biomass = 1244.1 − 666.61 × Band 3	0.49
Biomass = 1098.8 − 123.62 × Band 4	0.76
Biomass = 1006.3 − 1171.5 × Band 5	0.76
Biomass = 877.3 − 6144.4 × Band 7	0.55
Biomass = 2914.4 − 4124.1 × NDVI	0.58

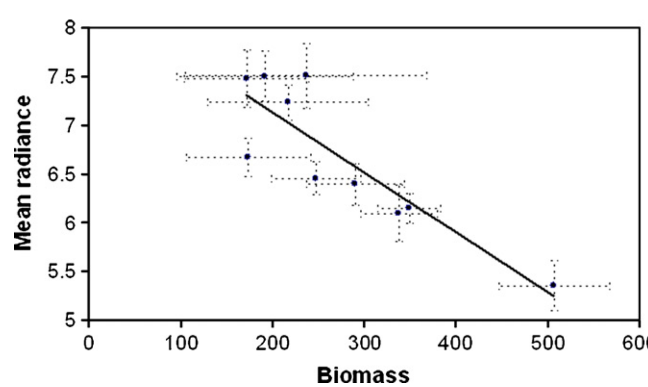

Fig. 4. The linear regression model of Landsat-5 TM band 4 (near-infrared) radiance (mW m^{-2} μm^{-1}) against biomass (t ha^{-1}) for 10 forest areas in the Ulu Segama Forest Reserve, Malaysian Borneo. The broken lines show the standard error of the two variables for each forest site.

Table 9
The MMR relative reflectance and NDVI for different targets at the 'canopy-scale'

Sites	General feature	Relative reflectance				
		Blue (Band 1)	Green (Band 2)	Red (Band 3)	NIR (Band 4)	NDVI
1	Haulage road	0.93	1.03	1.05	1.27	0.10
2	Quarry (road stone)	0.54	0.70	0.78	1.38	0.28
3	Bare soil	0.61	0.83	0.84	1.09	0.13
4	Log landing/skid trail	0.32	0.58	0.54	2.12	0.60
5	Ginger and shrubs	0.32	1.08	0.61	1.48	0.42
6	Ginger and shrubs	0.36	0.89	0.56	2.07	0.58
7	Ginger and shrubs	0.44	0.64	0.54	2.04	0.58
8	Ginger and vines	0.21	0.44	0.53	1.81	0.55
9	Landslide with shrubs	0.82	0.99	0.61	1.31	0.36
10	Pioneer trees + ginger	0.81	1.09	0.87	2.14	0.42
11	Pioneer trees	0.47	0.69	0.73	1.91	0.44
12	Pioneer trees	0.34	0.54	0.73	2.12	0.49
13	Natural forest gap	0.80	0.87	0.79	1.14	0.18
14	Undisturbed forest	0.82	1.01	0.84	0.98	0.07

See Fig. 3 for the location of the sampling sites.

C82, 3.980 C83, 4.058 C88, 3.741 C89, 4.398 C92, 3.051 C93c). In the C93RIL and other logging coupes, cutting had been limited to commercial trees with a stem diameter >60 cm. The smaller impact of logging on large stems in C93RIL may be attributed to a smaller degree of collateral damage to large, non-commercial trees compared to that in the conventionally logged areas.

The majority of trees (i.e., 75–87%) within either undisturbed or disturbed areas were saplings (i.e., 2–10 cm dbh class; Table 3). The numbers of saplings in logged forest were mostly similar (i.e., 1920–2424 saplings ha^{-1}) to in those in the two undisturbed forest areas (namely 2348 and 2708 saplings ha^{-1}). The exceptions being the lower numbers of saplings in C83, C88 and C93RIL, which were significantly different to the numbers in the undisturbed DVCA (*T*-test 2α 0.05, t_{crit} 2.306, t_{calc} 2.639, 2.783, 4.317, respectively), though these were not significantly different from sapling numbers in the undisturbed water catchment area. Others (e.g., Kuusipalo et al., 1996) have noticed that seedling and sapling growth can be high even in highly disturbed forest.

The five logging coupes that utilized high-lead harvesting techniques, namely, C81, C82, C83, C88 and C89 (Table 1) had the smallest remaining tree biomass (Table 2). These low levels may result from a higher level of collateral damage during high-lead harvesting, given that extracted timber volumes were not larger than those of areas logged using only tractor skidders (Table 1). However, no significant difference between biomass in coupes with tractor-only harvesting and tractor plus high-lead harvesting was observed. From 1996 onwards, the practice of high-lead timber harvesting was banned across the whole of the 10,000 km^2 Yayasan Sabah Forestry Concession (YSFC).

4.2. Landsat TM estimation of tree biomass at coupe-scales

Table 7 shows the mean radiance values for the 10 selected forest regions around the Danum Valley Field Centre. For example, mean radiance in Landsat-5 TM band 4 (near-infrared, NIR) varied from 7.480 mW m^{-2} μm^{-1} (σ 2.333) in C88 to 5.364 mW m^{-2} μm^{-1} (σ 1.942) in the sampled area of the DVCA. Coupes C81, C82, C83, and C88 had the highest NIR radiance values, and each were significantly different from the Reduced Impact Logging (C93RIL) area (*T*-test 2α 0.05, t_{crit} 1.960, t_{calc} 3.652, 3.327, 3.208 and 3.365, respectively). Additionally, all coupes, with the exception of C93RIL, had a mean NIR radiance value significantly different to that in the un-logged DVCA (*T*-test 2α 0.05, t_{crit} 1.980, t_{calc} 5.992, 6.034, 5.162, 5.502, 4.112, 3.614, 3.164 and 2.687, respectively); the NIR radiance for the un-logged DVCA was lower than all other areas (Table 7). While the undisturbed water catchment area (CATCH: Table 7) had a similar NIR reflectance to the areas logged only by tractors, those areas experiencing high-lead harvesting (C81, C82, C83, C88 and C89) had a significantly different mean NIR reflectance compared to the same undisturbed area (*T*-test 2α 0.05, t_{crit} 1.960–1.980, t_{calc} 4.572, 4.572, 3.727, 4.045 and 2.108, respectively).

The results of linear correlation and regression of the coupe-average biomass with mean radiance values in each of the six non-thermal Landsat TM bands, are shown in Table 8. The distribution of the residuals gave no indication that models other than two-parameter linear models should be fitted. The strongest coefficient of determination (from the Pearson correlation coefficient) observed, came from the near-infrared (r^2 = 0.76) and middle infrared bands (r^2 = 0.76: Table 8). Correlation of the same bands

Table 10
The MMR relative reflectance and NDVI for different targets at the 'leaf scale'

Target categories	Sample target	No. of sampled leaves	Relative reflectance									
			Blue (Band 1)		Green (Band 2)		Red (Band 3)		NIR (Band 4)		NDVI	
			$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.	$\bar{X}$	S.D.
Disturbed forest	Ginger leaves	10	0.41	0.15	0.87	0.21	0.55	0.12	2.27	0.48	0.61	0.02
	Shrub leaves	10	0.46	0.37	0.68	0.09	0.55	0.00	2.08	0.14	0.58	0.01
	Pioneer leaf	11	0.63	0.06	0.84	0.22	0.60	0.07	1.96	0.14	0.53	0.02
Undisturbed forest	Climax tree leaf	18	0.53	0.48	0.76	0.45	0.62	0.32	1.93	0.25	0.51	0.07

Category 'ginger' includes leaves of *Zingiber* spp.; category 'shrub' includes leaves of shrubs and vines *Tetracera akasa*, *Merremia borneensis*, *Mikania cordata*, *Dissochaeta annulata*, *Maesa ramentacea*, *Caesalpinia latisiliqua*, *Uncaria ferrea*, *Rubus lucens*, *Jacquemontia tomentella*, *Mucuna mikilii*; 'pioneer' includes leaves of *Eugenea* spp., *Octomeles sumatrana*, *Macaranga* spp.; 'climax tree' includes leaves of *Shorea* spp., *Parashorea melaanonan*, *Shorea johorensis*, *Dryobalanops* spp., *Durio* spp., *Dillenia* spp. and *Koilodepas longifolium*.

with the coupe-average, stem volume gave an equally high coefficient of determination for the near-infrared band ($r^2 = 0.75$), but a much weaker strength of association in the middle infrared band (i.e., $r^2 = 0.44$). Explanation of $\geq$75% of biomass and stem volume variations between areas the size of logging coupes (i.e., 450–2500 ha) with the NIR spectral signature alone, was much greater than that produced by single spectral bands previously examined for the area (see e.g., Foody et al., 2001). The small number of samples (10 sites) means that the statistical significance of the regression model cannot be calculated. The standard error of each variable, therefore, is shown in Fig. 4 as a visual estimate of the uncertainty. Others have sought to improve the strength of the radiance-biomass correlation by combining different spectral bands, but this can have the negative effect of increasing the uncertainty in the model further (Aires et al., 2004). Indeed, combining the NIR values with band 3 (red) values in the Normalized Difference Vegetation Index (NDVI) produced a much lower strength of correlation within this study (Table 8).

The preliminary NIR-based biomass model, we call the *nir*B model, is expressed as:

$$B_a = 1098.8 - 123.64\,(\text{NIR}); \quad r^2 = 0.76$$

where B_a is the mean biomass of a 450–2500 ha area of lowland dipterocarp forest (t ha^{-1}) and NIR is the Landsat TM near-infrared radiance for vegetation canopies unaffected by cloud (mW m^{-2} μm^{-1}). The preliminary model indicates that the coupe cut by RIL methods (C93RIL) had a greater residual biomass compared to the other logging coupes (Table 7; Fig. 4), particularly those incorporating high-lead logging, despite having a similarly high extraction volume (Table 1). Indeed, the mean biomass and NIR radiance of the RIL area looks more like undisturbed forest than conventionally logged forest (Fig. 4).

4.3. Interpretation of the radiance-biomass association using sub-coupe radiometry

The helicopter-based radiometry of selected 0.01 ha canopy areas (Table 9) indicated that the highest relative reflectance in the NIR band was observed for areas dominated by either ginger/shrubs (1.31–2.07) or pioneer tree canopies (1.91–2.14). In contrast, the canopy of undisturbed climax trees had the lowest relative reflectance in the NIR band (0.98) for vegetated areas (Table 9).

Examination of the spectral signature of individual leaves (or small groups of leaves) in the NIR band gave similar results. The highest relative reflectance in the NIR band was observed for ginger and shrub leaves (2.08–2.27) or pioneer tree leaves (1.96). The lowest NIR reflectance was for the leaves of climax trees (1.93: Table 10), and this was significantly different from that of ginger leaves (*T*-test 2α 0.05, t_{crit} 2.056, t_{calc} −2.088), but not for the shrub or pioneer tree leaves. While the relative importance of ginger/shrubs or pioneer trees to NIR reflectance seems to depend on scale (Tables 9 and 10), it is clear that leaves and canopies of climax trees have low NIR reflectance. This finding is consistent with the coupe-scale estimates, where undisturbed climax forest has the lowest average NIR radiance (i.e., corrected reflectance: Table 7).

5. Extending the work and forest management applications

There are several ways that this research could be extended and applied to the management of lowland dipterocarp forests. The satellite-based technique for biomass estimation in lowland dipterocarp forest presented here should be extended by validating the *nir*B model across a much larger distribution of annual logging coupes of similar forest that have intensively sampled and high quality forest enumeration data. Such areas may be present elsewhere within the 10,000 km^2 Yayasan Sabah Forestry Concession, or elsewhere within Borneo Island.

Even before wider testing is undertaken, the *nir*B model for lowland dipterocarp forest should be evaluated as part of tropical forest management. Application of the *nir*B model to all of the annual coupes within the 10,000 km^2 Yayasan Sabah Forestry Concession could be helpful in the assessment of timber stocks, and in the assessment of the ecological status of this large forested region (Sinun et al., 2007). Further, application of the *nir*B model to more recent Landsat TM data, for example, data collected in 2007 following a further 10 years of forest recovery could be beneficial. By differencing the coupe-scale biomass estimates between the two periods (e.g., 1997 and 2007) the current rate of forest recovery can be assessed, including the effects of enrichment planting within some of the coupe areas (Moura-Costa et al., 1996). This assessment would be most valuable if the measurements on the fifty (geo-referenced and tagged) enumeration plots were also repeated. Lastly, application of the *nir*B model to the whole 438 km^2 Danum Valley Conservation Area would allow a preliminary assessment of the spatial variations in tree biomass across the DVCA that would help in the planning of future management options for this protected area (Marsh, 1995).

Following validation of the model and a demonstration of the technique's value to forest management across a large tract of forest, the *nir*B model could be evaluated in other lowland dipterocarp forests elsewhere in Borneo or Southeast Asia.

6. Conclusions

This study has demonstrated the considerable potential for estimating tree biomass at the scale of annual logging coupes within an area of lowland dipterocarp forest. Considerable opportunities for extending and applying this research within the Ulu Segama Forest Reserve or whole Yayasan Sabah Forestry Concession exist, and following validation of the model, to other areas of lowland dipterocarp forests in Borneo or Southeast Asia.

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