4. Land-Use and Biomass Changes of Forests in Peninsular Malaysia from 1972 to 1982: A GIS Approach

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Abstract

Two maps depicting the forest resources of Peninsular Malaysia, one dated 1972 and the other 1982, were digitized into ARC/INFO for analysis of spatial and temporal trends. Estimates of 1972 and 1982 biomass density for each of 11 forest classes were also produced from inventory stand tables. These data allowed us to calculate changes in forest cover and biomass during the decade. Overall, forest area was reduced by 17%, and total biomass by 28%; however, this percentage varied among forest classes. For example, primary forest area declined by 23% while its biomass was reduced by 35%; disturbed forest area declined by 7% while its biomass was reduced by 19%. These data indicate that, in addition to loss of forest biomass because of changes in land use, biomass degradation was also occurring within the forests. Together, they represented a loss of 30 TgC/yr. Changes in perimeter area ratios were correlated with the degree of biomass degradation suggesting that the fragmentation of Malaysian forests, a process that increases their accessibility, was a cause of the degradation.

Introduction

The most recent comprehensive assessment of broadleaf forests (closed and open) in tropical Asia estimated their total area to be 323 million ha with an additional 71 million ha of forest fallows (Food and Agriculture Organization [FAO] 1981). According to this survey, most (90%) of the broadleaf forests were closed canopy, and as of 1980, their rate of deforestation was estimated to be 1.77 million ha/yr or 0.6%/yr. In addition, approximately 1.74 million ha of Asian undisturbed closed forest were logged each year for the production of veneer and saw logs. Open forests (mixed broadleaf forest-grassland formations with a continuous grass layer and tree canopies covering more than 10% of the ground) were cleared at about the same rate (0.6%/yr) as closed ones. No information on the rate of clearing of forest fallows to permanent agriculture is available.

The major cause of deforestation in tropical Asia is conversion of forest lands to a form of slash-and-burn agriculture or shifting cultivation, usually by people who had no legal title to the land (FAO 1981). However, this type of conversion is not a major cause in Peninsular Malaysia. Most of the Asian land converted to shifting cultivation originated from logged forests, about 59% of the deforested lands in this region. Logged-over areas are generally more accessible, require less effort to clear, and are on land that is topographically more suitable for agriculture (FAO 1981). The lands usually affected the least by deforestation are the unproductive forests because of their inaccessibility or unsuitability for agriculture (i.e., they have steep slopes and shallow soils).

In addition to deforestation, which brings about a major change in the landscape, degradation of forests is also occurring (FAO 1981). It brings about gradual changes that are often difficult to detect or quantify. Forest degradation has many causes. Logging activities degrade forests by felling large trees and, in the process, damaging residual stands and by constructing logging roads, skid trails, and loading areas. Logging tends to be more intensive in the dipterocarp forests of Asia than in other areas of the tropical world because so many of the dipterocarp species are useful. Thus the potential for degradation from logging is high in this region.

Forest degradation is also caused by local exploitation for fuelwood, charcoal, and structural materials. This form of degradation is more common in open forests, but it can occur in closed forests where population density is high. Over-grazing is another cause of degradation, one that is usually restricted to open or conifer forests. With the exception of planned logging activities, much of the forest degradation in tropical Asia is illicit but nevertheless appears to be fairly rampant (Brown et al. 1991). Moreover, degradation leads to an overall decrease in forest biomass density (biomass per unit area).

Deforestation and degradation of tropical forests can both contribute to the rise in atmospheric carbon dioxide. During clearing, forest biomass is cut and burned or left to decay onsite. In addition, conversion to agriculture decreases soil organic matter. In 1980, the flux of carbon to the atmosphere from deforestation in tropical Asia was estimated to be 0.62×10^{15} g/yr or about 37% of the global flux from tropical deforestation (Houghton et al. 1987). The absolute carbon flux for tropical Asia and for the entire tropics has been strongly debated because of uncertainty regarding:

- the rates of change of forest areas,
- the initial and final use of the changed forest land (i.e., from primary, logged, or forest fallow to some other forest or nonforest use), and
- the biomass density (or carbon content) of forests (Detwiler and Hall 1988; Houghton et al. 1987; Post et al. 1990).

The effects of forest degradation on the global carbon cycle have not been simulated because of the lack of data. To model the role of forest degradation in the carbon cycle, we must know by how much and at what rate biomass density is decreased.

To deal with the uncertainties in deforestation data and to quantify forest degradation, national forest inventories of all forest classes done at regular intervals are needed. These inventories must include (1) sufficient data to estimate biomass for all forests with some degree of reliability and (2) maps of forest areas produced from aerial photos or remote sensing and verified with ground information.

To our knowledge, such data exist in the tropical Asian region only for Peninsular Malaysia. National inventories were conducted in 1972 and in 1982 with identical methodologies and the same system of forest classification. Each inventory included a color map depicting 11 forest classes. Stand and stock tables (number of stems/ha and commercial volume/ha by diameter class, respectively) were given and used to estimate biomass density (with methods given in Brown et al. 1989). In this paper, we use information from these two national forest inventories to document and map changes in the forest area, forest biomass density, and total biomass of Peninsular Malaysia. In addition, we analyze spatial data for clues that will enable us to assess the degradation of biomass (loss in biomass per unit area of forest) over large landscapes.

Forests of Peninsular Malaysia

Peninsular Malaysia is located between latitudes 1°20' and 6°45' N and about longitudes 100° and 104°30' E. It encompasses an area of about 13.2 million ha. Practically all of the peninsula is in the tropical moist forest life zone (sensu Holdridge 1967) with annual rainfall in excess of 2000 mm fairly evenly distributed throughout the year.

A mountain range runs along most of the peninsula with peaks >2000 m. More than 60% of the area is undulating lowland <300 m above sea level, about 35% is hilly with elevations of 300 to 1300 m, and the remainder is very mountainous (FAO 1981).

The forests of Peninsular Malaysia are classified into undisturbed or disturbed groups and into 11 classes (Table 1). At one time, lowland dipterocarp forests (those dominated by species belonging to the Dipterocarpaceae family) were found at elevations lower than 300 m, but these lowland forests were extensively cleared for agriculture prior to 1966 (FAO 1981, Kumar 1986). The bulk of the remaining forests are undisturbed, primary hill dipterocarp forests (closed broadleaf) located at elevations

Table 1. Classification of Forest Classes and Their Acronyms for Peninsular Malaysia.

Undisturbed			
	Primary hill		
		Moderate hill	MHF
		Good hill	GHF
		Superior hill	SHF
	Restricted hill		
		Poor hill	PHF
		Upper hill	UHF
	Swamps		
		Freshwater	FS
Disturbed			
	Hill		
		Logged after 1966	LHF
		Logged before 1966	DHF
		Shifting cultivation	SC
	Swamp		
		Logged after 1966	LFS
		Logged before 1966	DFS

between 300 and 1300 m. Depending upon their stocking density (volumes per unit area), they are further categorized as superior, good, or moderate hill forests (SHF, GHF, and MHF, Table 1).

A second undisturbed forest is referred to as restricted hill forests (Table 1), either because of their soil conditions or their elevation. Certain edaphic associations of the hill forests are referred to as poor hill forests (PHF) and include the heath and limestone forests. These forests are characterized by low volumes and are generally considered unproductive. At elevations above 1300 m are the montane or upper hill forests (UHF), a mixture of a few species of dipterocarps, species of Fagaceae and Lauraceae families, and gymnosperm species of the genera *Agathis* and *Podocarpus*. The UHF are also considered quite unproductive.

Forested swamps occupy the lower areas of the coastal plain and include freshwater swamps and saltwater swamps or mangroves. Freshwater swamps (FS) include peat swamps, most of which have been selectively logged during the past several decades, and other swamp forests that are flooded less often and with more mineral-rich water than peat swamps. The saltwater swamps grow along the coastline, but we did not include them in the present analysis because of insufficient data for making biomass estimates.

The disturbed-forest group is composed of hill forests or freshwater swamp forests (Table 1). The inventories distinguished between forests that were selectively logged from about prior to 1966 (i.e., disturbed hill forest, DHF, or disturbed freshwater swamp, DFS) and forests that were selectively logged after 1966 (i.e., logged hill forest, LHF, or logged freshwater swamp, LFS). Shifting-cultivation forests are a mixture of cultivated areas, secondary forests, and patches of primary hill forest. The 1972 national mapping effort of forest lands relied on aerial photos taken in 1966, and these same photos also served as the basis for the 1982 inventory. Thus logged forests could be divided into two time periods (prior to and after 1966).

Since the fifties, deforestation from shifting cultivation has been of very limited importance in Peninsular Malaysia (FAO 1981), unlike the rest of Asia. Important causes of deforestation in Peninsular Malaysia are planned programs of rural development that convert disturbed forests to plantations of oil palm, rubber, and other tree crops (FAO 1973a, 1981; Kumar 1986; Flint and Richards, this volume). The magnitude of this conversion from 1970 to the present is demonstrated by the large increases in tree-crop area and production of palm oil, rubber, and cocoa since 1970 (Kumar 1986; Yusof 1988). For example, the area of land under plantations of oil palm trees in 1972 was about 380,000 ha; by 1976 this had almost doubled (Kumar 1986). Cocoa production rose rapidly from 1970 to the late 1980s, and rubber production remained high throughout the period (Yusof 1988).

In addition to deforestation, Peninsular Malaysian forests were also logged. Timber production increased from 1972 to 1982, mostly for domestic use (Kumar 1986).

Malaysian forests are very important for global biodiversity. The remaining forests of the peninsula have been placed on Conservation International's list of "hot spots" for megadiversity, one of ten areas in the world where significant plant and animal extinctions will occur in the near future unless major preservation efforts are taken. These ten areas cover only 0.2% of the earth's land surface, yet they contain 12 to 20% of all plant species and a high proportion of the animal species (Conservation International 1990).

Data Sources and Analyses

The two national forest inventories for 1972 (FAO 1973a) and 1982 (Government of Malaysia 1987) contained (1) stand and stock tables for all species of trees to a minimum diameter of 15 cm for all forests described in Table 1 and (2) forest maps at a scale of 1:750,000 based on aerial photographs and ground measurements. Stand and stock tables for only the undisturbed primary and logged hill forests of the 1972 inventory were also reported by six planning units (regional areas divided along eco-geographic divisions).

Biomass Estimates

In this chapter, we distinguish between biomass density and total biomass. We define forest biomass density as the total aboveground biomass (TAGB) of trees to a minimum diameter of 10 cm per unit area. Total biomass is the area of a given forest multiplied by that forest's biomass density.

Estimates of biomass density do not include understory biomass (shrubs, herbs, saplings, etc.), which has been estimated to account for 3 to 4% of the TAGB of closed forests (Brown and Lugo 1984). Nor do we include fine litter, because it is assumed to remain constant over time and its dynamics are likely to be in steady state. Furthermore, we do not include coarse woody debris because the magnitude of its pool and dynamics in tropical forests are poorly known; however its pool in some forests may vary from

10 to 40% of TAGB (Greenland and Kowal 1960; Saldarriaga et al. 1986; Uhl et al. 1988; Uhl and Kauffman 1990). Belowground biomass is also not included because there are so few studies of this component that accurate and precise estimates are very difficult to make. Belowground biomass can vary between 10 and 40% (with an average of about 20%) of the aboveground biomass in lowland tropical humid forests (Brown and Lugo 1982).

Biomass density estimates of forests (mean and 99% confidence interval) were calculated from stand tables and the methods outlined in Brown et al. (1989) after first estimating the number of trees in the 10- to 15-cm interval with the methods of Gillespie et al. (1992). Biomass per tree was then estimated by substituting the midpoints of the diameter classes into a biomass regression equation (the equation for moist forests based on diameter only and given in Brown et al. 1989). This value was multiplied by the number of trees in each class. The summed biomass of all classes produced a point biomass density estimate (in Mg/ha) for the forest represented by the stand table. The estimate of the 99% confidence interval around the point was calculated from the covariance matrices of the coefficients of the biomass regression equations. Estimates of uncertainty in the biomass densities reported here are based solely on the regression equation. The error associated with the stand tables was not reported in the original sources; thus the uncertainty in biomass-density estimates caused by this component could not be calculated.

Biomass density was estimated for the 11 forest classes for 1972 and for 1982. For the 1972 inventory only, stand tables (and thus biomass-density estimates) for all undisturbed primary and logged hill forests (five classes; see Table 1) were reported by six planning units encompassing the whole country, thereby adding another level of resolution. In other words, six biomass-density estimates representing the six planning units were made for each forest class.

Mapping

We digitized the two forest maps (Fig. 1 as an example for 1982) into a geographic information system using ARC/INFO (by ESRI Inc., Redlands, California). All 11 forest classes were digitized for the 1982 map; however, because of the large number of polygons (>2000) on the maps and the amount of time needed to digitize them, we reduced the digitizing effort for the 1972 map by using the 1982 map to add detail. We reconstructed the distribution of the three classes of primary hill forests by overlaying the 1982 map of primary hill forests on that for 1972, assuming that their classification was the same at both times. In this way, only polygons that had changed to a different major forest class, e.g., undisturbed primary hill to disturbed hill forests between 1972 and 1982 needed to be digitized for the 1972 map. A similar approach was used to separate the classes of the restricted hill forest, undisturbed and disturbed swamp forest, and disturbed hill forest for the 1972 map. The boundaries of the planning units were also digitized onto the forest maps. Following digitization, the maps were georeferenced to the Albers Equal Area Cones projection.

Stand tables were not reported by the six planning units for the 1982 inventory. To estimate and add this level of resolution to the 1982 biomass map, we analyzed changes in forest area during the 10 yr interval to determine if unusual patterns of change had caused significant reduction in biomass density. We found that biomass-density estimates in 1972 for all forest classes reported by planning unit (all primary hill forests, DHF, and LHF) differed by a factor of 1.2 to 2.4 between the lowest and highest estimates. We then addressed whether changes in land use for these forest classes varied by planning unit. That is, did logging of superior hill forests or conversion of disturbed forests to nonforest occur more frequently in planning units with the highest biomass?. If so, the average biomass density values in 1982 for all planning units combined would reflect these variations. Instead, we found that percent changes in major land uses for these forests were generally similar across all planning units. Therefore, the ratio of the area-weighted biomass density for a given forest class in 1982 to the area-weighted biomass density of the same class in 1972 was applied to the individual 1972 biomass-density estimates by planning unit to obtain estimates for 1982 by planning unit.

Biomass-density estimates by forest class were incorporated with the digitized forest-area maps, resulting in forest biomass density maps for the two inventory periods. These spatial data bases were then used to perform overlay analysis to depict changes in area and total biomass during the intervening 10 years.

We also used the digital maps to calculate perimeter-to-area ratios (P/A) for the forest polygons. These ratios are useful for describing forest fragmentation. The larger the ratio, the more edge per unit area and thus the more fragmented the forest. Brown et al. (1991) suggested that the decreasing trend in biomass density for Malaysian forests represented forest degradation from increased human impact, albeit often illicit. We hypothesize that remaining forests that become more fragmented because of clearing or logging will be subject to a greater degree of human impact and that biomass density will decrease. We used the changes in P/A between 1972 and 1982 to evaluate this hypothesis.

The level of detail available on changes in area and biomass density for the forests of Peninsular Malaysia is generally not available for forests in other parts of the world. Moreover, its level of resolution is too fine to be practical for global models. To begin to understand the dynamics of scale and to produce data more usable for global models, the highly detailed polygonal data were also aggregated into 66 0.5^{o} x 0.5^{o} cells. Changes in forest-to-nonforest area and total-biomass estimates were calculated at this level of resolution for each cell. First, the total biomass for each cell of the 1972 and 1982 maps was estimated as the product of area and biomass density for each forest class occurring in that cell. Then, the 1972 map of total biomass was subtracted from the 1982 map cell by cell. The results were expressed as absolute values and as percent changes for all 66 cells.

Results and Discussion

Change in Area

Forest Loss

In 1972, 64% of the total land area of Peninsular Malaysia was forested. Most of these forests were undisturbed, primary hill forests (43%) and disturbed hill forests (42%)

with the remainder occupied by the restricted hill and undisturbed and disturbed swamp forests (Table 2). By 1982, 53% of the total land area was forested, and the remaining forests were dominated by disturbed forests (47% of the total area, Table 2 and Fig. 1) because of the large absolute loss in primary hill forests. Small percentage changes occurred in the other major forest classes during the decade.

Overall, 17% of the forest land was lost between 1972 and 1982 (Table 2). Of the total net loss, 82% was from forests that were considered undisturbed in 1972 (primary hill, swamp, and restricted hill forests). The greatest percentage loss was for freshwater swamps (39%), but in absolute terms, primary hill forests lost the most area (almost 60% of the total forest loss). Restricted forests lost 24% of their area, almost entirely from poor hill forests (PHF). Upper hill forests (UHF) in the central mountains experienced essentially no loss because of their inaccessibility.

Table 2. Changes in forest area in Peninsular Malaysia between 1972 and 1982 as determined from the overlay of two digital maps with a GIS.

Forest class	Area (10^3 ha)		
	1972	1982	% Change[a]
Undisturbed			
Primary hill	3577	2742	-23
Moderate hill	1572	1143	-27
Good hill	1160	916	-21
Superior hill	845	683	-19
Restricted hill	708	542	-24
Poor hill	424	261	-38
Upper hill	284	281	-1
Swamps	612	401	-34
Freshwater	458	280	-39
Saltwater	155	121	-22
Disturbed			
Hill	3491	3258	-7
Logged after 1966	1231	2246	+82
Logged before 1966	1615	481	-70
Shifting cultivation	317	216	-32
Swamp			
Logged after 1966	177	276	+56
Logged before 1966	152	39	-74
All forest classes	8388	6943	-17
Nonforest	4725	6170	+31
Total	13113	13113	

[a]Based on 1972 areas.

The area of disturbed forests changed little overall (-7%, Table 2). The area of logged forests (LHF and LFS) increased markedly (82 and 56%, respectively), whereas DHF and DFS decreased by more than 70%. Area under shifting cultivation (SC) represented only 4% of the total forest area in 1972, and this percentage was reduced even further by 1982.

Areas of each forest class were included in the original reports of the inventories (FAO 1973a, Government of Malaysia 1987). These areas were estimated by counting the number of dots falling on a particular forest class. Our estimates of total forest area for 1972 and 1982 were 2.5 to 3.5% higher than the original sources, with estimates for individual classes differing by no more than a 3% underestimate to an 8% overestimate. We believe that these estimates are well within acceptable limits, with the possibility of our numbers being more accurate because each polygon was digitized.

Forest Classes

By overlaying the two digital maps, we were able to estimate the types of land-use change that had occurred during the 10 years (Table 3). Changes on the order of a few percent are most likely caused by errors in interpretation of the original aerial photos (e.g., difficulty in distinguishing in between various forms of primary forests and restricted forests) and errors in digitizing and overlaying the maps with the GIS.

Most of the change in primary hill forest area was caused by conversion to logged forests (20 to 22%), with less than 9% overall converted to nonforest (NF) (Table 3 and Fig. 2). The highest-volume SHFs were the most stable over the decade, with 77% of their area unchanged and only 2% converted to NF. On the other hand, the low-volume MHF changed to LHF and NF at the highest rates.

About 40% of the PHF present in 1972 were converted to either nonforest use or were logged (Table 3 and Fig. 3), even though these forests had lower yields and grew on poorer soils than primary hill forests. In contrast, the more inaccessible UHF exhibited practically no change in area during the decade.

Overall, disturbed forest area in 1972 decreased by 42% during the subsequent decade, with conversion to NF accounting for 80% of that loss (Table 3 and Fig. 4). But, because undisturbed-forest classes were concurrently converted to the disturbed categories, the net loss of disturbed forests during the 10 years was only 7% (Table 2). Logged hill forests had a net increase in area between 1972 and 1982 of 82% (Table 2). This rapid increase in logged area is even more dramatic when one considers that more than 30% of the LHF present in 1972 were converted to NF during the decade (Table 3). The large increase in LHF area was mostly derived from the conversion of primary hill forests, PHF, DHF, and SC (Table 3).

Although we could not separate DHF from SC on the 1972 map accurately, we did observe that most of the loss in area of SC (Table 2) showed up as increases in area of LHF and DHF categories; very little of it entered the NF category (<1%; see Table 3). Whether the more than 30% conversion of DHF and SC to the LHF category during the 10 years was caused by a misclassification during the 1972 inventory or whether it showed evidence of actual logging is unclear.

Freshwater swamps occupied only about 9% of the total forest area in 1972, but they exhibited some of the largest relative changes in area. Only 50% of the undisturbed

Table 3. Changes in area of forest classes[a] (percentage of 1972 area) between 1972 and 1982. Key to forest classes are given in Table 1. NF = nonforest and tr = trace.

From 1972 to 1982	Undisturbed	Primary	SHF	GHF	MHF	Restricted	PHF	UHF	FS	Disturbed	LHF	DHF	SC	DFS	LFS	NF
Undisturbed	67.9										21.8					10.3
Primary		68.6				0.4			tr	22.3						8.6
SHF			76.8	tr	tr		0.2	tr	0.0		20.2	0.4	0.0	0.0	0.0	2.3
GHF			0.1	69.3	tr		0.3	tr	tr		21.2	0.9	tr	0.0	tr	8.1
MHF			tr	tr	63.7		0.5	tr	tr		22.1	0.7	tr	0.0	0.3	12.4
Restricted		3.1				69.4			tr	16.7						10.9
PHF			1.2	1.6	2.2		53.2	tr	tr		23.7	1.1	tr	0.0	tr	16.8
UHF			0.1	0.3	0.4		tr	92.6	0.0		3.8	0.1	0.5	0.0	0.0	2.2
FS		0.6	tr	0.1	0.4	tr	tr	tr	50.2	26.9	2.5	0.8	0.2	0.7	22.8	22.2
Disturbed	9.3	6.9				0.4			1.1	57.8						33.7
LHF			1.8	6.5	6.7		0.2	0.2	0.2		51.9	0.8	0.1	tr	0.2	31.4
DHF[b]			0.7	1.0	1.3		0.3	0.2	0.0		31.3	19.7	10.2	0.0	1.2	33.4
SC[b]											0.0			0.0		0.6
DFS			0.0	0.0	0.0		0.0	0.0	11.0		0.0	0.0	0.0	20.0	23.0	46.0
LFS			0.0	0.0	0.0		0.0	0.0	9.8		3.9	0.8	0.0	0.4	47.9	32.7
NF	1.1	0.4	0.1	0.1	0.2	0.1	0.1	tr	0.2	4.5	3.1	0.9	0.0	0.0	0.4	94.9

[a] Totals for rows only will equal 100%.

[b] Most land-use changes for these two categories are lumped into one (and reported in the DHF row) because we could not separate them on the 1972 map accurately based on our mapping procedure (see text).

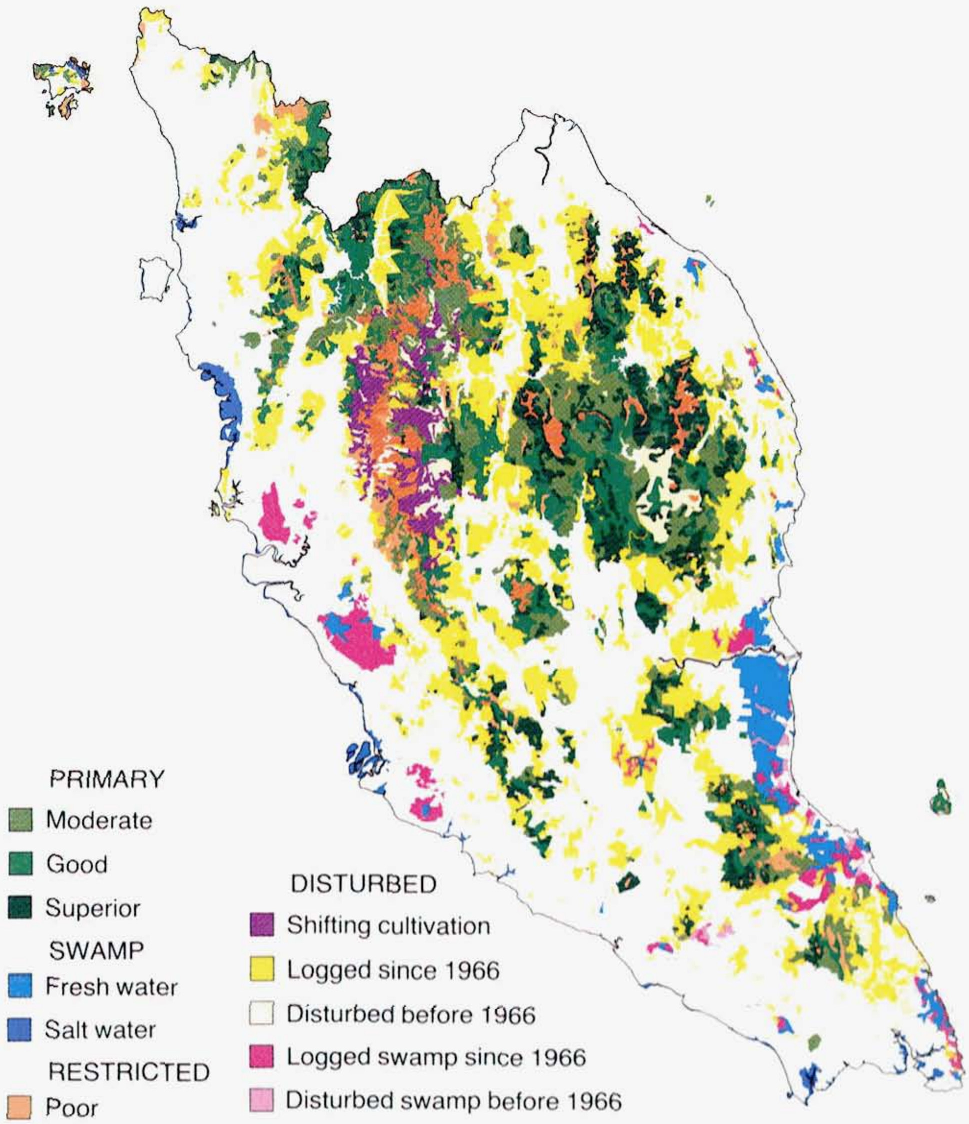

Figure 1. The forest of Peninsular Malaysia, 1982. A map from the forest inventory report (Government of Malaysia 1987) was digitized into ARC-INFO to create this image.

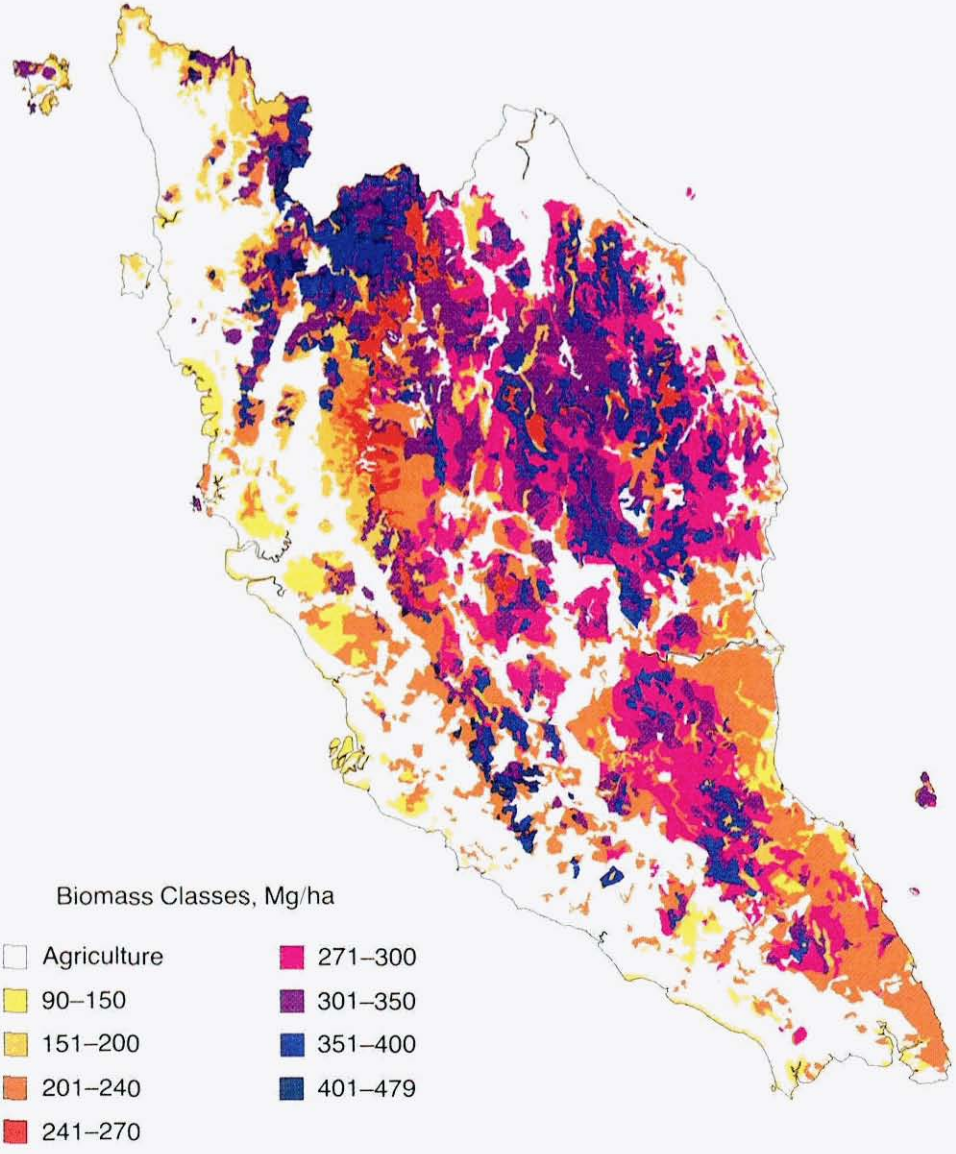

Figure 6. Forest biomass density (Mg/ha) distribution for 1972. Biomass density classes are not uniform because of constraints of the data.

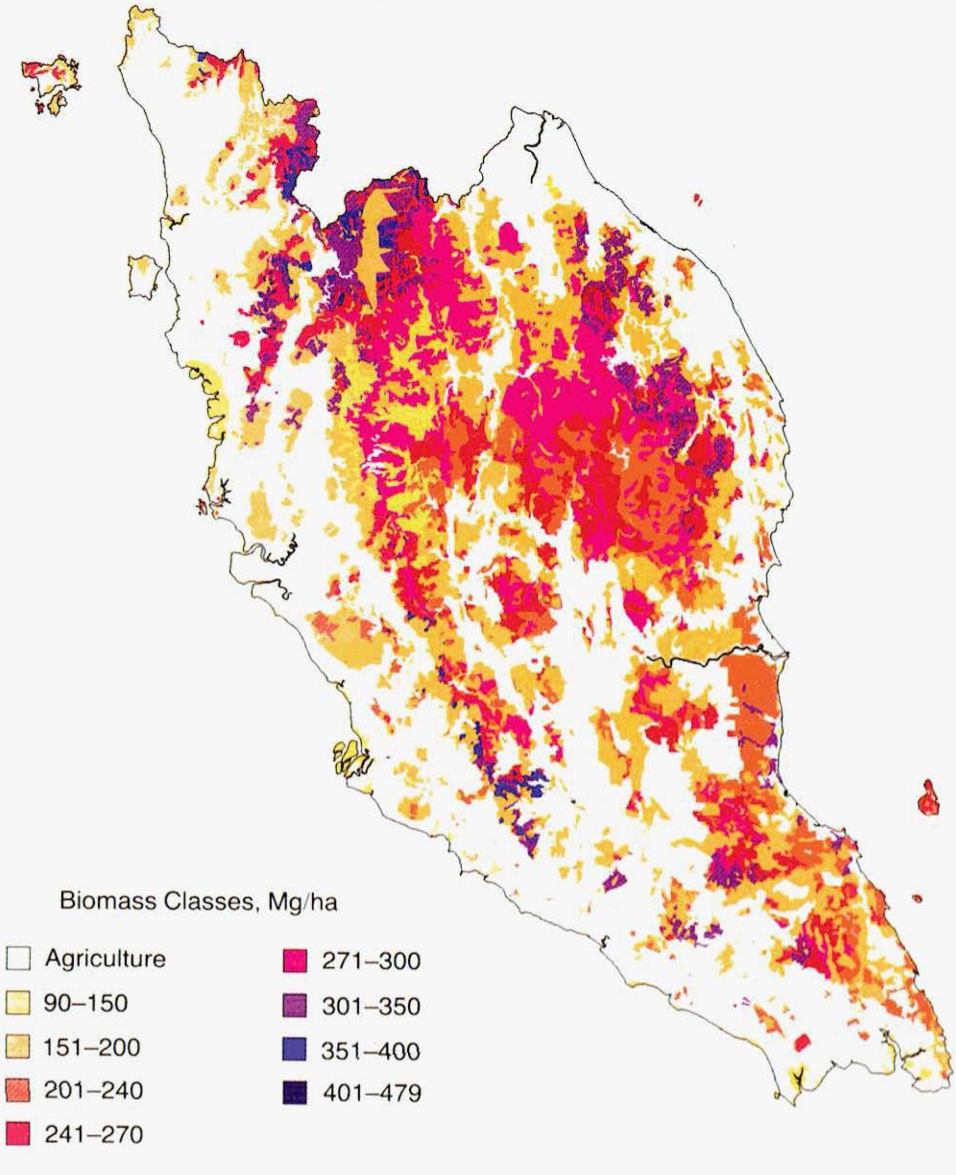

Figure 7. Forest biomass density (Mg/ha) distribution for 1982. Biomass density classes are not uniform because of constraints of the data.

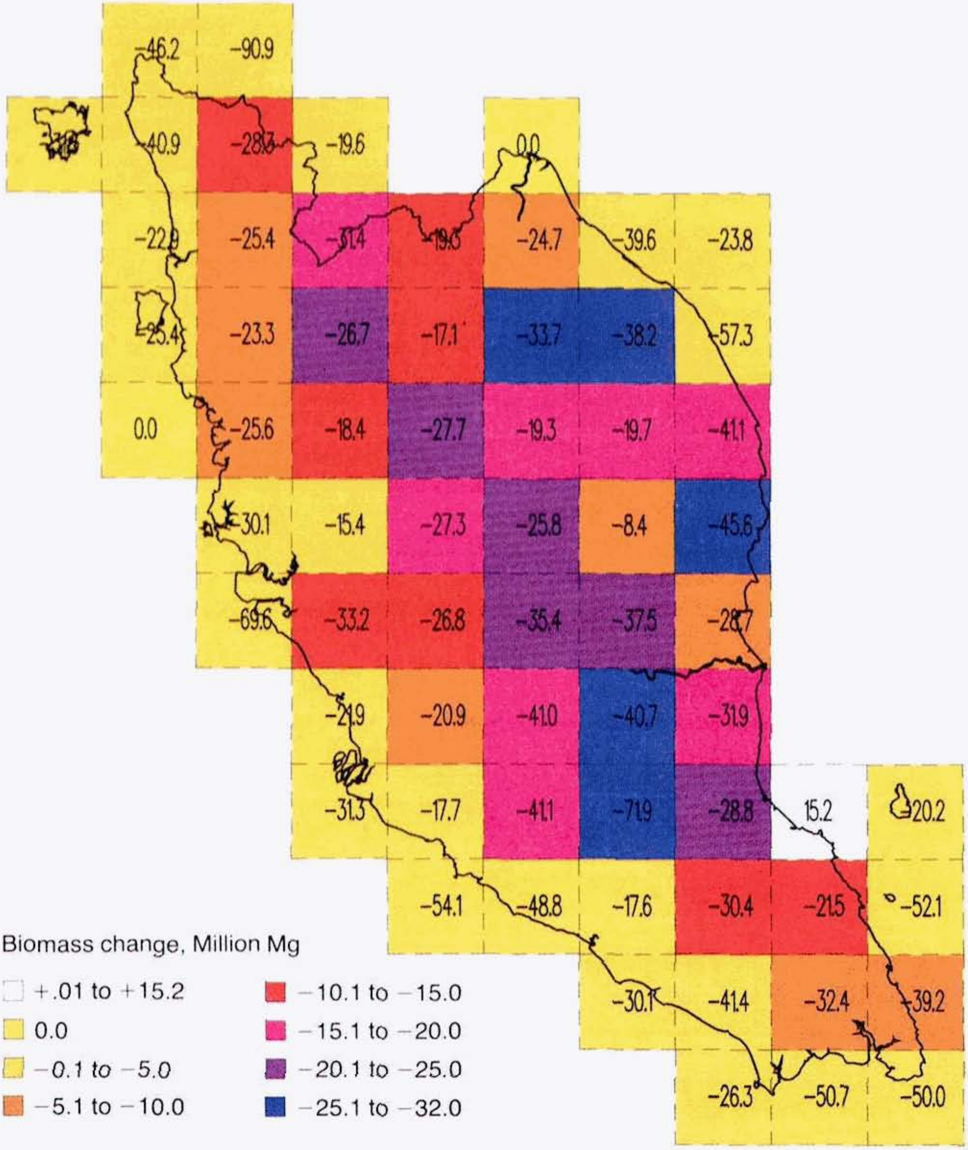

Figure 12. *Spatial representation of net changes in total biomass in* (10^6 Mg for the 10 years) because of changes in forest areas and biomass density, aggregated into 0.5^0 x 0.5^0 cells. Labels in the cells give percent change from 1972, and the color scale gives the actual changes.

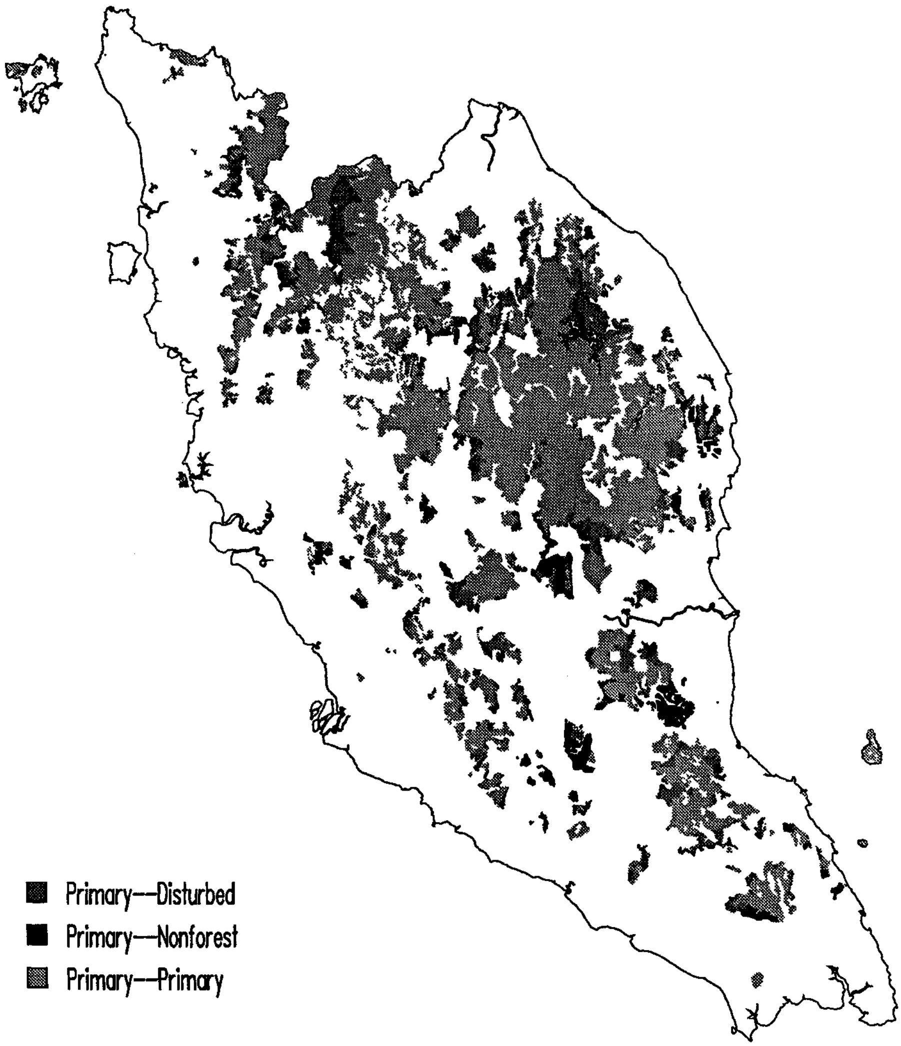

Figure 2. Location and changes in area of primary hill forests (superior, good, and moderate hill forests shown in green in Fig. 1) to nonforest and disturbed forests between 1972 and 1982.

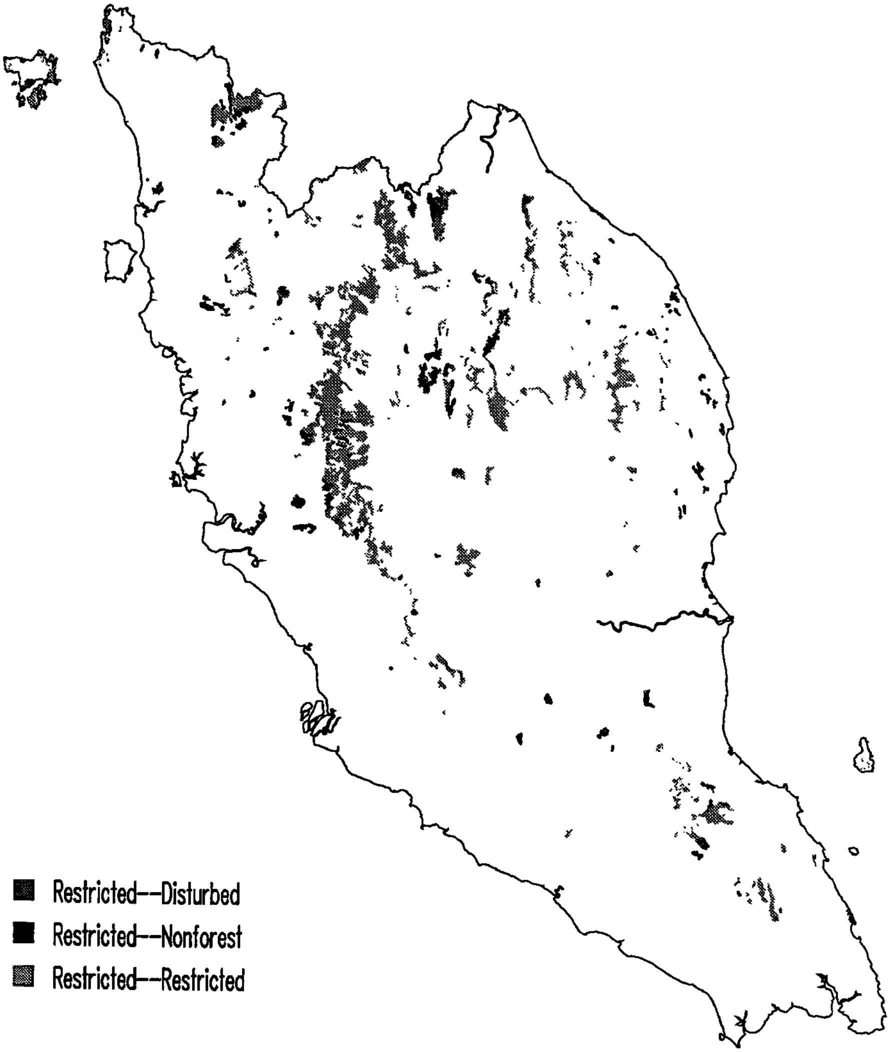

Figure 3. Location and changes in area of restricted hill forests (poor hill and upper hill forests shown in orange in Fig. 1) to nonforest and disturbed forests between 1972 and 1982.

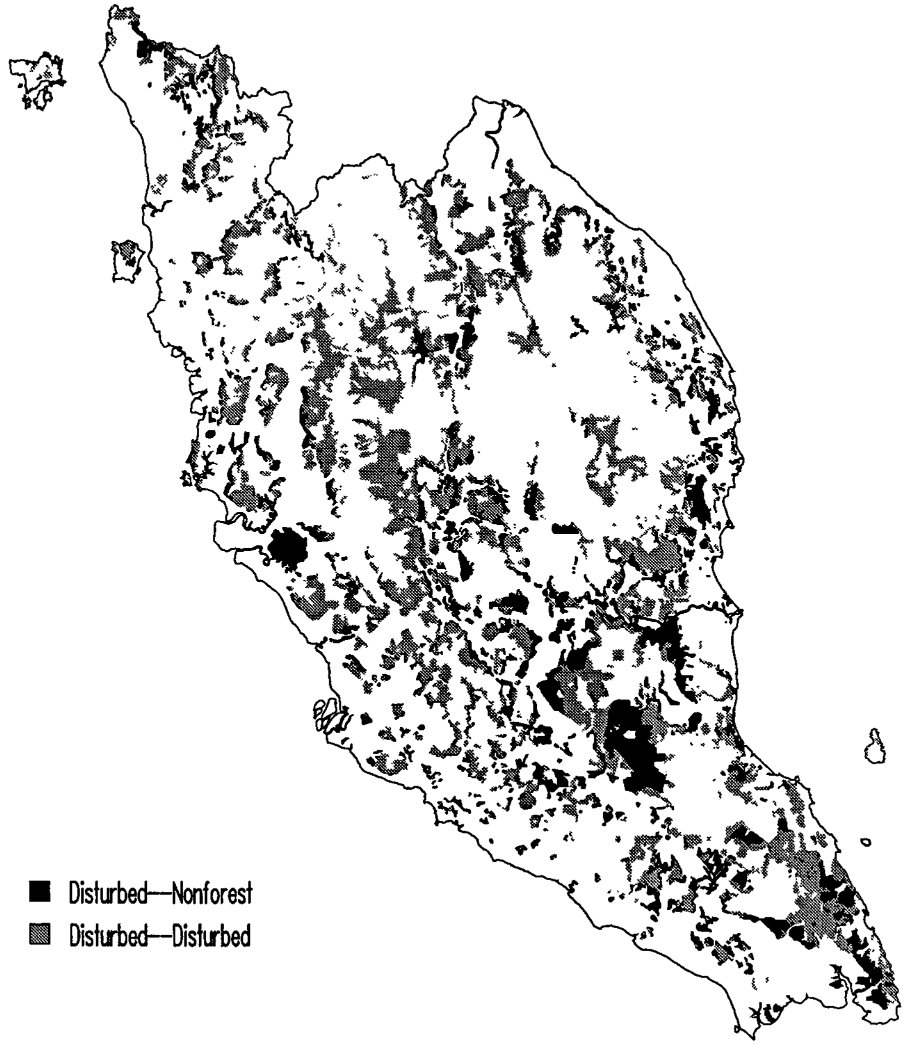

Figure 4. Location and changes in area of disturbed hill forests (logged and shifting cultivation, shown in yellow and purple in Fig. 1) to nonforest between 1972 and 1982.

swamps in 1972 remained in 1982, with some gain from LFS and DFS as they recovered from past disturbance to resemble the undisturbed state (Table 3 and Fig. 5). Most of the change in undisturbed swamp forest area was produced by conversion to LFS and NF.

Forest Biomass

Changes in Biomass Density

Mean biomass density of forests of Peninsular Malaysia in 1972 ranged from 379 Mg/ha for SHF (range of 359 to 478 Mg/ha for the various planning units) to 120 Mg/ha for DFS (Table 4). By 1982, biomass density was generally lower for many of the forests, and significantly lower for LHF and SC (based on the 99% confidence interval produced by the variance of the biomass regression equation). For those forestclasses that decreased in biomass density, the loss ranged from 15 to 36%; for all forest classes, the overall decrease in biomass density was 13% (Table 4).

For about half of the forest classes, biomass density increased (Table 4). For example, the biomass density of remaining stands of restricted hill forests, disturbed hill forests, and undisturbed and disturbed freshwater swamps was higher in 1982 than in 1972, and the latter two classes were significantly so.

We combined biomass density with maps of forest areas to produce maps of forest biomass density for the two inventory periods (Figs. 6 and 7). Forests with the highest biomass density in 1972 were mostly the primary hill forests in the north-central region of the peninsula (Fig. 6). A few areas of high-biomass-density forests were also located in smaller tracts along the south-westerly fringe of the primary hill forests. Most of the low-biomass-density forests (<200 Mg/ha; shades of yellow) were located at the edge of the forested areas.

By 1982, major changes in forest biomass density had occurred (Fig. 7). From a 1972 map that was mostly shades of magenta, purple, and blue (biomass >270 Mg/ha; Fig. 6), we move to one in which reds to yellows in smaller fragments dominate, the biomass-density values represented are less than 270 Mg/ha (Fig. 7). Most of the higher-biomass-density forests had disappeared, and forests generally had biomass-density values below 300 Mg/ha.

Forest classes that had an increase in biomass density are also shown in these two maps (compare Figs 6 and 7 with Fig. 1). Much of the disturbed-forest areas with the lowest biomass (<150 Mg/ha; yellow in Fig. 6) had either disappeared or moved up to a higher biomass class. A similar trend was found for the remaining restricted hill forests, which were shaded red in 1972 and magenta in 1982.

Causes for Changes in Biomass Density

The Role of Large Trees

To investigate the causes of the differences in biomass density of the Peninsular Malaysian forests, we compared diameter distributions for the two dates (examples in Fig. 8). Forest classes that exhibited a decrease in biomass density (e.g., SHF, LHF, and

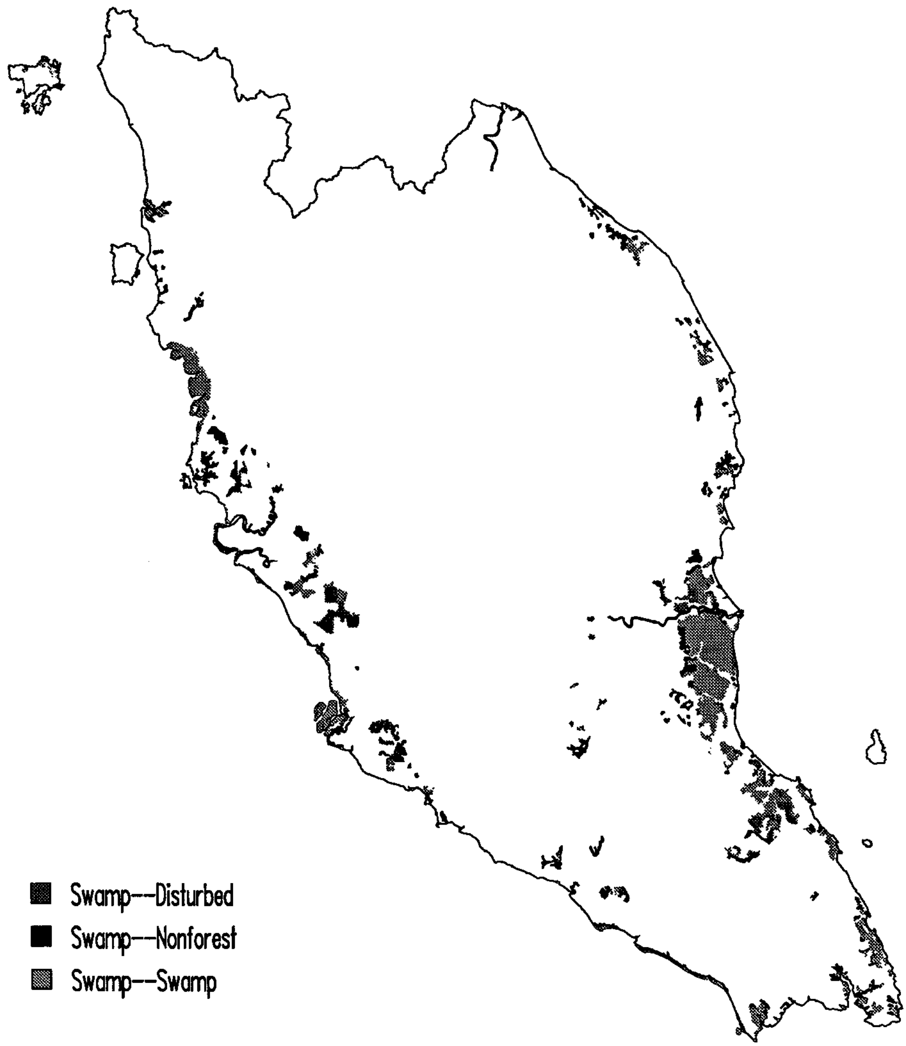

Figure 5. Location and changes in area of undisturbed freshwater swamp forests (shown in blue in Fig. 1) to nonforest and disturbed swamp forests between 1972 and 1982.

Table 4. Changes in forest biomass density in Peninsular Malaysia between 1972 and 1982.

Forest class	Biomass, Mg/ha (99% CI[a])		
	1972	1982	% Change[b]
Undisturbed			
Primary hill	330	279	-15.5
Moderate hill	298(30)	250(25)	-16.1
Good hill	340(34)	288(29)	-15.3
Superior hill	379(39)	315(31)	-16.9
Restricted hill	212	242	+14.2
Poor hill	179(17)	191(18)	+6.7
Upper hill	262(25)	287(28)	+9.5
Swamps			
Freshwater	204(19)	233(22)	+14.2
Disturbed			
Hill	221	192	-13.1
Logged after 1966	275(27)	191(18)	-30.6
Logged before 1966	196(19)	209(20)	+6.6
Shifting cultivation	227(22)	145(14)	-36.1
Swamp			
Logged after 1966	138(13)	196(18)	+42.0
Logged before 1966	120(12)	302(28)	+151.7
All forest classes	267	233	-12.7

[a] CI = confidence interval.
[b] Based on 1972 values.

SC) showed a noticeable decrease in the number of larger trees and only a slight increase in the number of small trees (Fig. 8a-c; MHF and GHF, not shown, exhibited the same tendency). This finding is not surprising when we consider that a few large trees can account for proportionally more of the biomass than many small trees (Gillespie et al. 1992). This decrease in biomass was most likely caused by illicit cutting of trees for fuel or roundwood in the "undisturbed" forests, increased timber extraction from the logged forests, and a shortening of the rotation time combined with degradation of remaining forests in the shifting cultivation/hill forest mosaic (Brown et al. 1991).

The diameter distributions for forests that exhibited small gains to no change in biomass during the decade had similar patterns for 1972 and 1982 (e.g., DHF, Fig. 8d). Forests that showed significant increases in biomass had much larger numbers of smaller trees (LFS and DFS, Fig. 8e-f). In these two examples, the remaining stands were exhibiting regeneration and accumulating biomass at about 6 to 11 Mg $ha^{-1}yr^{-1}$ (LFS and DFS, respectively). Logged swamps (LFS) appeared to accumulate less biomass than the DFS because of the age of regrowth. Logged swamps (LFS) contained newly logged (between 1972 and 1982) as well as older logged (between 1966 and 1972) stands, whereas DFS had been undergoing regrowth since before 1966. Moreover, the increase in biomass density of LFS since 1972 must also suggest that logging was less intensive between 1972 and 1982 than prior to 1972.

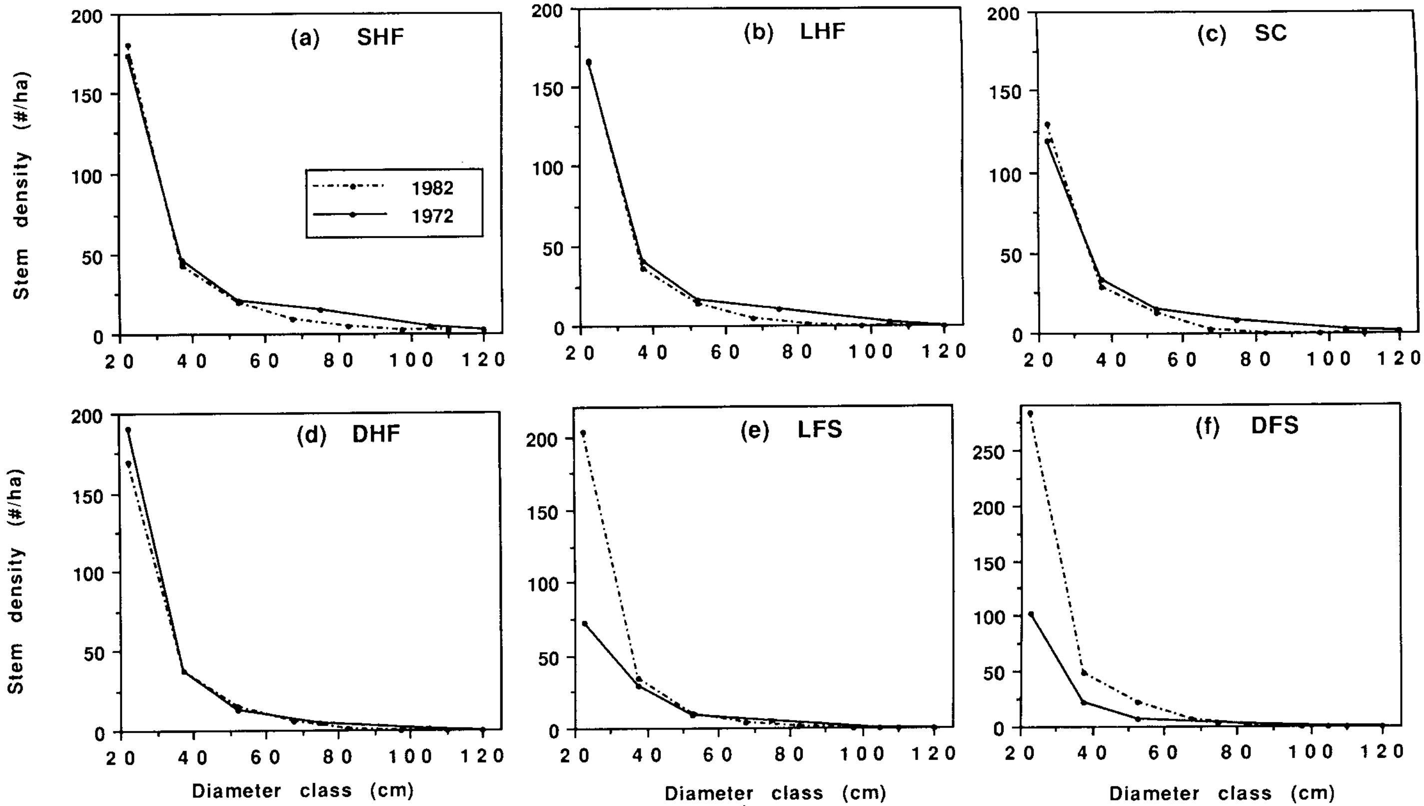

Figure 8. Diameter distributions for various forest classes that showed decreases in biomass between 1972 and 1982: (a) superior hill forests (SHF), (b) logged hill forests after 1966 (LHF), and (c) shifting cultivation (SC); no change: (d) logged hill forests before 1966 (DHF); and increases: (e) freshwater swamp forest logged after 1966 (LFS) and (f) freshwater swamp forest logged before 1966 (DFS).

Table 5. Changes in perimeter-to-area ratios (P/A) in Peninsular Malaysia between 1972 and 1982.

Forest class	P/A 1972	P/A 1982	% Change[a]
Undisturbed			
Primary hill	1.55	1.92	+24
Moderate hill		1.95	
Good hill		1.85	
Superior hill		1.95	
Restricted hill	2.39	2.42	+1
Poor hill	3.85	2.51	-35
Upper hill	2.10	2.10	0
Swamps			
Freshwater	2.03	1.59	-22
Disturbed			
Hill	1.99	2.12	+4
Logged after 1966	1.77	2.06	+16
Logged before 1966	3.03	2.33	-23
Shifting cultivation	1.87	1.70	-9
Swamp			
Logged after 1966	2.20	1.70	-23
Logged before 1966	2.03	0.67	-67

[a]Based on 1972 values

The Role of Forest Fragmentation

The least-fragmented forest group in 1972 was the primary hill forests; they had the smallest perimeter:area ratio (P/A). The most-fragmented was the restricted PHF (Table5). By 1982, this picture had changed, with the primary hill forests experiencing the greatest increase in fragmentation (largest increase in P/A). This change in P/A was correlated with change in forest biomass density during the 10 years (Fig. 9).

Forests that exhibited a decrease in edge (i.e., a negative change in P/A) became less accessible; consequently, biomass was able to recover, and gains in biomass density resulted. Forests that experienced a loss in biomass density during this interval had an increase in P/A. In other words, the edge of these forests increased proportionally more than the decrease in area. We suggest that increased edge permitted increased accessibility into the forest and a consequent loss in biomass density. An example of this "nibbling" (and sometimes "gobbling") of the edge of the forests is shown in Fig. 10. Much of the conversion to NF occurred at the edges of forests (e.g., the northern and western sections) or from forest blocks surrounded by NF (e.g., the southeast quarter of the peninsula).

The significant relationship between change in forest biomass density and change

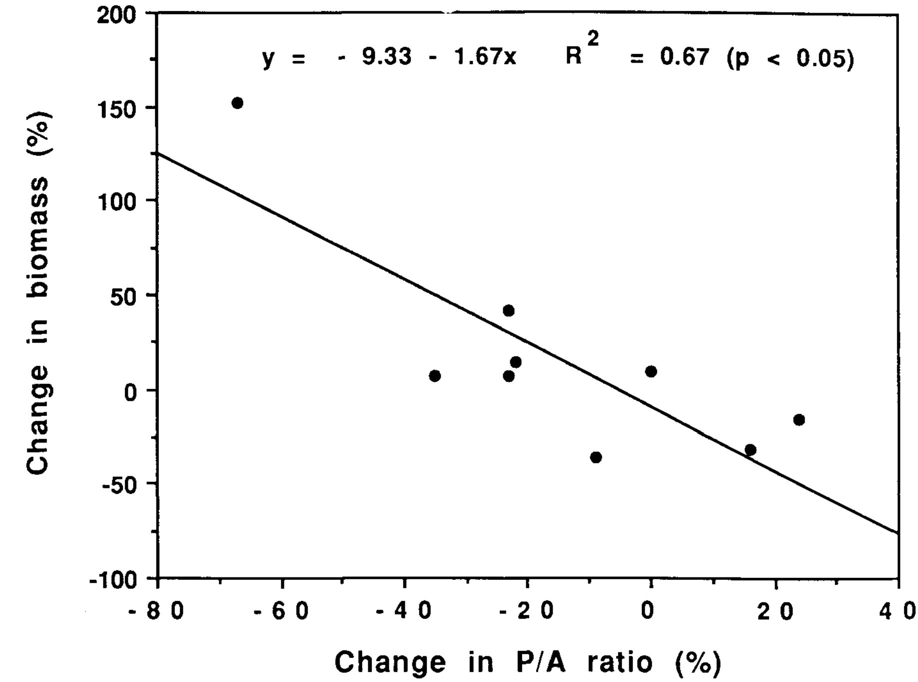

Figure 9. Relation between percent change in perimeter-to-area ratio and percent change in biomass density between 1972 and 1982.

in P/A suggests a useful approach to detecting and monitoring biomass degradation at the landscape level. Remote-sensing data can be used to calculate the P/A of a forested landscape, and with regular measurements, changes in this ratio at regional, subnational, or national levels potentially could be detected. Positive changes in P/A would probably indicate forest degradation.

The relationship between forest degradation and increased edge has useful implications for forest managers. It suggests that every effort should be made either to create no change or to reduce the P/A to minimize fragmentation and degradation of the resource. This principle would, in turn, govern decisions regarding access, logging, or clearing.

Estimating Biomass Density of Truly Primary Forests

If decreases in forest biomass density occurred between 1972 and 1982 in the "undisturbed" primary hill forests of Peninsular Malaysia, then it is likely that their biomass in 1972 had already been reduced from a truly "undisturbed" state. Humans certainly inhabited and affected these forests prior to 1972. We have suggested above

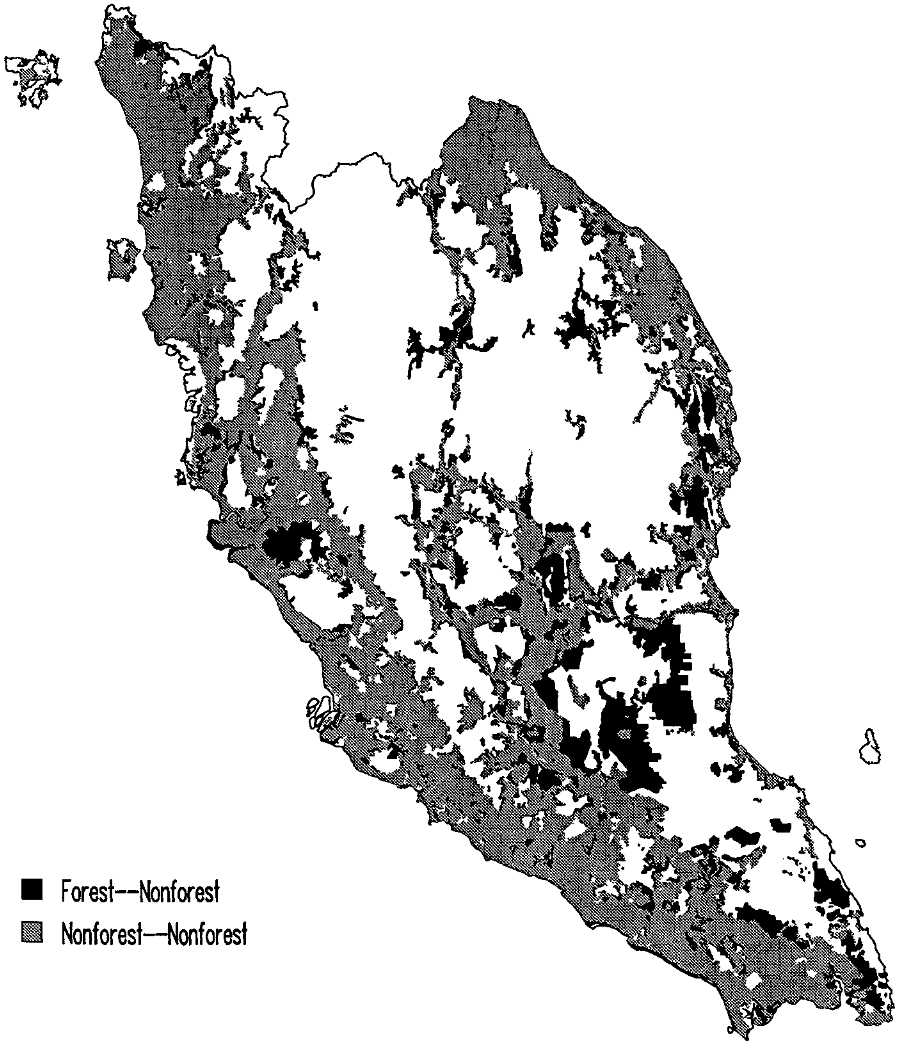

Figure 10. Increase in nonforest area caused by conversion of forests between 1972 and 1982.

that biomass-density reductions occurred because large trees were removed. To discover the cumulative impact that humans may have had on the biomass density of these forests, we must determine a plausible estimate of the biomass density of these hill forests in a truly undisturbed state

To discover the impact of large trees on forest biomass, we estimated the proportion of a stand's biomass that is represented by large trees (here defined as those with biomass of >5 Mg/tree or a diameter of $\geq$70 cm) for all forest classes in the 1982 inventory. (We could not use the 1972 data because diameter classes were such that the number of trees with diameters >70 cm could not be extracted.). We then compared these values with those for forests of Sarawak, eastern Malaysia, which, based on their descriptions and remoteness from human population centers, appear to be undisturbed. This comparison was based on an application of the biomass-estimation techniques to an inventory of Sarawak (FAO 1973b).

We found that the majority of forests in Sarawak of high stocking density on flat-to-rolling or mountainous terrain had biomass-density estimates that ranged from about 350 to more than 400 Mg/ha and 38 to 48% of their biomass in large trees (Fig. 11). Medium-stocking-density forests in Sarawak had lower biomass-density estimates and about 25 to 35% of the biomass in large trees. Malaysian hill forests in 1982 generally had lower biomass densities and only 5 to 27% of their biomass in large trees.

Based on the analysis of the Sarawak and Malaysian data, we suggest that in an undisturbed state, the Malaysian hill forests would have resembled the high-density forests of Sarawak and would have had more than 40% of their biomass in large trees. By fitting a linear regression to all the Malaysian hill forest data and extrapolating the regression to about 45% (Fig. 11), we find that the Malaysian hill forests' biomass density may have been 450 Mg/ha or more. Even the good and moderate hill forests may have had biomass densities this high, and their present classification (based on stocking density) may well reflect intensive past and ongoing human impact. In 1972, the biomass density of the superior hill forests for some planning units approximately equaled this undisturbed estimate (Fig. 6), suggesting they were relatively undisturbed at that time.

Changes in Total Biomass

Overall, total biomass declined 28% (ranging from 12 to 41%; see Table 6) while forest area declined 17% (Table 2) between 1972 and 1982. Primary hill forests underwent the greatest loss in total biomass because of loss in forest area and in biomass density. Only three forest classes showed a gain in biomass (UHF, LHF, and LFS). The increase in biomass density of the UHF overcompensated for the slight decrease in area. The gain for LHF was caused solely by its large increase in area; its biomass density decreased. The gain in biomass for LFS was caused by a combination of an increase in area and an increase in biomass density.

A spatial representation of the net biomass changes, aggregated into the 0.5^{o} x 0.5^{o} cells and at a scale suitable for modeling, is shown in Fig. 12. Absolute changes are indicated by the color scale, and percent changes by labels in the cells. All cells showed a loss in biomass, with losses ranging up to 32 x 10^{6} Mg during the 10 years. The highest biomass loss was for a cell where large blocks of primary and disturbed forest

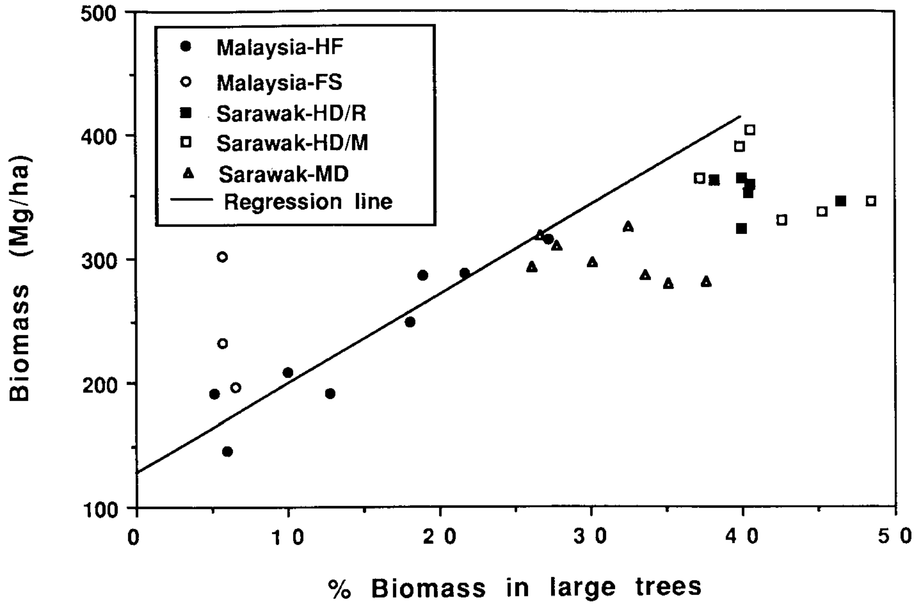

Figure 11. Relation between percent biomass density in trees of diameter >70 cm and biomass density for forests in Peninsular Malaysia and Sarawak. HD/R = high-stocking-density forests on flat to rolling terrain, HD/M = high-stocking-density forests on mountainous to steep mountainous terrain, MD = medium-stocking-density forests on all terrain types, HF = all undisturbed and disturbed hill forests (see Table 1), and FS = undisturbed and disturbed freshwater swamp forests. The line is a linear regression equation for Peninsular Malaysian hill forests only, where $Y = 127.53 + 7.15 X$ and $R^2 = 0.88$ ($n = 8$, $p < 0.01$).

land had been converted to NF (see Fig. 10). For other cells showing high biomass loss (>20 x 10^6Mg), a combination of conversion to lower-biomass-density forests and to NF was generally the cause (see Figs. 2 to 5). These data, aggregated to 0.5^o cells, provide a tractable means of quantifying carbon loss to the atmosphere via global carbon models.

Implications of Changes in Area and Biomass on Carbon Fluxes

The changes in forest area and biomass that we have presented here for Peninsular Malaysia demonstrate the complexity of these processes in tropical countries. Attempts to capture the numerous human impacts on tropical forests have been oversimplified in global carbon models to date (e.g., Houghton et al. 1987; Detwiler and Hall 1988). For instance, these models have generally assumed that most deforestation for agriculture takes place in undisturbed forests and that these forests remain undisturbed until they are cleared.

We have demonstrated for Peninsular Malaysia that most of the forest clearing for agriculture occurs in previously disturbed forests of lower biomass density and that only a relatively small percent of the higher-biomass-density primary hill forests are converted to nonforest use (Table 3). Furthermore, the so-called undisturbed forests undergo biomass degradation over time, usually because of the removal of large trees. Other research suggests that this process of biomass degradation is common in tropical forests of south and southeast Asia (Brown et al. 1991; Flint and Richards 1991) and Brazil (Brown and Lugo 1992).

Table 6. Changes in total biomass in Peninsular Malaysia between 1972 and 1982.

Forest class	Total Biomass, 10^6 Mg (99% CI[a]) 1972	1982	% Change[b]
Undisturbed			
Primary hill	1182	765	-35
Moderate hill	468(47)	286(29)	-39
Good hill	394(39)	264(27)	-33
Superior hill	320(33)	215(21)	-33
Restricted hill	150	131	-13
Poor hill	76(7)	50(5)	-34
Upper hill	74(7)	81(8)	+9
Swamps			
Freshwater	93(9)	65(6)	-30
Disturbed			
Hill	770	627	-19
Logged after 1966	339(33)	429(40)	+27
Logged before 1966	317(31)	101(10)	-68
Shifting cultivation	72(7)	31(3)	-57
Swamp			
Logged after 1966	24(2)	54(5)	+125
Logged before 1966	18(2)	12(1)	-33
All forest classes	2195(217)	1588(155)	-28
Range[c]			-12 to -41

[a]CI = confidence interval.
[b]Based on 1972 values.
[c]Range is based on error associated with estimating biomass density from the regression equation only. Upper range = [(maximum biomass for 1972 - minimum biomass for 1982)/maximum for 1972](100), and lower range = [(minimum biomass for 1972 - maximum biomass for 1982)/minimum for 1972](100).

For 1972 to 1982, the net loss in biomass calculated from data on clearing, change in forest land use, biomass degradation, and regrowth in residual stands was 607 x 10^6 Mg (Table 6), about 61 x 10^6 Mg/yr. Calculated only with consideration of land-use change and without biomass degradation and regrowth (i.e., no change in biomass density), the average loss in biomass would have been 379 x 10^6 Mg, 62% of the total. This latter figure, when converted from biomass to carbon estimates by multiplying by 0.5, represents an average carbon flux of 19 x 10^6 Mg/yr. This carbon flux compares favorably with an earlier estimate of 24 x 10^6 Mg/yr for Peninsular Malaysia that excluded biomass degradation but included the carbon flux from soils (Houghton et al. 1987). However, converting the 10-year net loss in biomass to annual carbon flux results in an estimate of 30 x 10^6 Mg/yr, excluding soils. In other words, a consideration of all processes that change forest biomass density results in a carbon flux that is about 160% higher than that based on land-use change alone.

We have shown that a gain in biomass density occurs over large geographic areas in forests recovering from human use and in forests that experience low human pressure because of site limitations (Table 4). We estimate that the increase in biomass density in these forests during the 10 years was about 37 x 10^6 Mg for the region. This value was derived by multiplying the areas of forests in 1982 exhibiting biomass-density increases (see Table 2 and 3) by the differences between 1982 and 1972 biomass densities (Table 4). This result underscores the need to address the role of forest regrowth in all forest classes, even those considered undisturbed (e.g., PHF, UHF, and FS; see Table 2), in the carbon balance equation.

A truer estimate of total biomass loss from degradation during the interval was 265 x 10^6 Mg. This value was calculated by taking the total biomass loss (607 Mg), subtracting the biomass loss from land-use change (379 Mg), and adding the biomass increase from regrowth of previously disturbed forests and growth in remaining undisturbed forests (37 Mg).

With respect to the carbon cycle, however, the key question is: What happens to the biomass that is removed from the forests either by intensive logging or illicitly? If, as we imply, large trees account for most of the loss in biomass density, then we would argue that much of the biomass removed is converted into long-term storage (buildings, etc.) and does not enter the atmosphere very quickly. Clearly, these issues need to be addressed in the next generation of global models if we are to determine the role of tropical forests in the global carbon cycle with greater accuracy.

Conclusions

This study used GIS analysis to document changes in forest area, biomass density, and total biomass of Peninsular Malaysia from 1972 to 1982. Forestland was converted to nonforest uses at an average annual rate of 1.7%. Most of the conversion to NF, however, came from previously disturbed forests. The pattern of deforestation was logging followed by further clearing and conversion rather than the outright conversion of undisturbed forests. Contrary to several other Asian countries, shifting cultivators played only a minor role in the deforestation cycle.

The biomass density of forests decreased 12.7% overall, indicating a general degradation of the resource. Several classes (SHF, GHF, MHF, LHF, and SC) showed more than 15% biomass degradation, an indication of illegal felling or intensive logging. On the other hand, several classes (FS, PHF, UHF, LFS, and DFS) exhibited increases in biomass density, primarily a result of natural forest growth in the absence of illegal felling or because of reduced logging intensity.

By evaluating the role of large trees on biomass density of undisturbed forests in neighboring Sarawak, we concluded that large trees with diameters >70 cm contributed about 45% of total biomass density in a truly undisturbed state. For Peninsular Malaysia, where essentially all forestlands have now been disturbed to some degree, extrapolation produced an estimated biomass density of about 450 Mg/ha, a value approached in the 1972 inventory of SHF for some planning units.

A significant relationship was found between the change in biomass density over the decade and the change in forests' perimeter-to-area. Forests that exhibited a decrease in biomass density had an increase in forest edge, indicating that increased edge may allow increased accessibility to forest interiors, thereby encouraging the harvest and removal of biomass, especially of large trees.

Multiplying area changes by biomass-density changes yielded the change in total biomass during the 10 years: an overall loss of 28% for all forest classes. Forests that lost both area and biomass density (primary hill forests and SC) had very large decreases in total biomass as did forests logged prior to 1966 (DHF and DFS). The latter group lost at least 70% of its area (mostly as a result of conversion to NF). Only the two classes logged since 1966 (LHF and LFS) gained in total biomass, primarily because of large increases in area during the decade at the expense of previously "undisturbed" forestlands.

The dynamics of the carbon cycle were seen to be more complex than researchers have generally assumed in the formulation of models. This study shows that carbon modeling needs to consider more than just land-use change in calculating carbon fluxes from the tropical landscape. Specifically, it needs to consider biomass degradation in so-called undisturbed forests and biomass accumulation in previously disturbed forests or forest considered to be of little commercial value.

For Peninsular Malaysia, estimated carbon flux ranged from 19×10^6 Mg/yr when only land-use change was considered to 30×10^6 Mg/yr when biomass degradation was included in the calculation. However, the situation is further complicated by not knowing the fate of the biomass removed. If much of it goes into long-term storage, carbon flux would be reduced. Much more effort is needed to sort out these questions to improve the next generation of global carbon models.

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