BIOMASS ESTIMATES FOR TROPICAL FORESTS

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SUMMARY

The estimation of biomass of tropical forests has continually been refined over the past decade, as the methodologies and the technology available for such estimation improved. Consequently, the uncertainty associated with estimates of carbon flux to the atmosphere from changes in land use has declined. In this paper, we review the efforts, primarily within our group, to refine the process of estimating forest biomass across the tropics. Initial estimates of global biomass resulted from the synthesis of ecological studies on small experimental plots. These studies did not sample from the larger population of interest and were conducted in relatively undisturbed locations, so that extrapolations tended to yield overestimates. Later, forest inventories were used to estimate biomass which resulted in better estimates because large sampling units were used. A large effort ensued to maximize the information extraction and reliability from forest inventory data. However, geographic specificity of the estimate was usually limited to national or large subnational unit. This shortcoming led to the use of geographic information systems (GIS) to increase the spatial specificity and to extrapolate inventory information to areas that have not been assessed. We use GIS to assess biomass in Peninsular Malaysia, a country with very good inventories and maps, and in Continental South/Southeast Asia, a region with very sparse inventory information. In the later case, GIS is used to model forest biomass using a suite of map layers that most influence biomass.

INTRODUCTION

There is increasing in erest in tropical forests and the changes they are undergoing because of their r le in global biogeochemical cycles, atmospheric chemistry, and biodiversity issues. The global role of tropical forests heightened interest in quantifying the biomass they contain because this determines the atmospheric emissions that are produced from clearing and burning forests. Biomass estimates are also important for a variety of other scientific and management issues such as forest productivity, nutrient cycling, and inventories of fuelwood and pulp. Despite the needs for estimates of forest biomass, there are essentially no inventories that have measured biomass directly at the scale needed for addressing most of the above issues.

Research on the global carbon cycle illustrates one example of the problem associated with not knowing the biomass of tropical forests with a high degree of accuracy and precision. Two main sources of uncertainty, of equal weight, exist in models used for estimating carbon fluxes due to tropical land-use change: the rate of land-use change and the biomass (or carbon content) of the forests undergoing change. The main reasons for the component of uncertainty caused by biomass are that most models have generally relied on regional averages for only a few forest types (e.g., moist and seasonal forests [Houghton et al., 1987]), and the forest biomass data base being used for estimating these regional averages is poor. More recently, uncertainty associated with modeling carbon fluxes has been reduced by adding geographic specificity to the models, e.g., the country-specific biomass estimates of Hall and Uhlig (1991). However, adding the country-level of geographic detail is too coarse because within most tropical countries, particularly large ones, the distribution of forest biomass is still very variable (Brown and Lugo, 1992; Brown et al., 1991, 1992; Iverson et al., 1992).

Biomass of tropical forests varies considerably over the tropical landscape due to climatic, edaphic, and topographic differences as well as history of land use and human and natural disturbance. It is naive to think that this variation can be encapsulated into single regional or country-wide averages for use in carbon or other global biogeochemical models. The problem is compounded by the general lack of large-scale inventories at sufficient levels of detail for making biomass estimates.

The objectives of this paper are to (1) review past efforts, and their associated problems, of estimating tropical forest biomass from ecological studies; (2) present methods and results of estimating biomass based on forest inventory data; and (3) present current approaches of estimating biomass through the application of geographic information systems (GIS) technology. Our emphasis will be on estimating the total aboveground biomass density (biomass per unit area, or TAGBD) of trees 10 cm diameter or larger, including leaves, twigs, branches, bark, and bole. We do not include estimates of the biomass of other living aboveground components of a forest, such as saplings, shrubs, other understory plants, vines, epiphytes, etc., because they represent a small fraction of the total and the data bases available for them are totally unsuitable for extrapolating to a large scale. Belowground biomass is also not included. A more detailed discussion as to why these other forest components are not included is given in Brown and Lugo (1992).

ESTIMATING THE BIOMASS FROM ECOLOGICAL STUDIES

The first estimates of biomass for use in global carbon models (e.g., Houghton et al., 1983) were based on a synthesis of ecological studies (e.g., Ajtay et al., 1979; Brown and Lugo, 1982; Olson et al., 1978; Whittaker and Likens, 1973) in which biomass was estimated by direct measurement on small experimental plots. All the data were collected for undisturbed or mature forests and represented a tallied area of less than 30 ha. The weighted average total biomass (above and below ground) for all closed forests was 328 Mg/ha (range of 160-538 Mg/ha) and for open forests was 80 Mg/ha (range of 40-140 Mg/ha) (Brown and Lugo, 1982). Over 50% of the variation in the data could be explained by differences in life zones (sensu Holdridge, 1967) in which the forests grew (Brown and Lugo, 1982).

Several problems exist in using these ecological data for global analyses. Ecological studies are used to characterize local forest structure, and the study sites are usually not truly randomly located and do not represent the larger forest population. These type of studies are suitable for studying local forests, but not to be used for making inferences about larger populations (Brown and Lugo, 1992). In addition, Brown and Lugo (1992) and Brown et al. (1989) have shown that biomass determinations of a few small plots usually yield high biomass estimates because the plots tend to be non-randomly located within the higher biomass portions of the forest.

A further problem of using data from small, non-randomly selected plots is the inherent bias to large diameter trees. Brown and Lugo (1992) suggested that there is a tendency for ecologists to adjust the placement of study plots in tropical forests based on their notion of what a mature forest should look like, i.e., one with many large diameter trees. The effect of adjusting plot placement to include large diameter trees is to overestimate forest biomass because biomass per tree increases geometrically with increasing diameter. Bias in plot placement is also considered to be a serious sampling problem in studies of old-growth forests in the midwestern USA (McCune and Menges, 1986).

ESTIMATING BIOMASS FROM FOREST INVENTORIES

To overcome the problems of using ecological studies, reliable methods have been developed for converting stand table data (number of trees by diameter classes) or volume of stemwood per ha, as typically reported in forest inventories, into TAGBD estimates (Brown et al., 1989; Brown and Lugo, 1992; Gillespie et al., 1992). Data from forest inventories are generally more abundant and are collected from large sample areas (subnational to national level) using a planned sampling method designed to represent the population of interest. Although most tropical countries have had at least one inventory performed on their forest lands, many of the results are of limited value for estimating biomass. Typical problems include:

1. Minimum diameter of trees included in the inventory is often greater than 30 cm, and sometimes as large as 50 cm; this excludes smaller trees that can account for more than 30% of the biomass (Gillespie et al., 1992).
2. The maximum diameter class in stand tables is generally open ended, with trees greater than 80 to 90 cm in diameter lumped into one class. The actual diameter distribution of these large trees can significantly affect total tree biomass (Brown and Lugo, 1992).
3. Not all species of trees are always included.
4. Reports resulting from the inventories often leave out critical data, and the detailed field measurements are not archived and are lost.
5. Many of the inventories are old (1960s-1970s or earlier), and the forests probably no longer exist or at least are not the same now as they were then.
6. Very little descriptive information is given as to the actual condition of the forests; they are often described as primary but diameter distributions and volumes suggest otherwise (see e.g., Brown et al., 1991).

Conversion of Forest Inventory Data to Biomass Estimates

Some of the above problems can be overcome and many inventories have been successfully used for estimating TAGBD of tropical forests. Depending on the data reported in the inventory (stand table or volume per unit area), a choice of two methods is available to estimate TAGBD (Brown et al., 1989). One method is to start with a stand table that includes all tree species measured to some minimum diameter (preferably to 10 cm, but stand tables to larger minimum diameters can be used after first accounting for the smaller diameter trees using the methods of Gillespie et al., 1992) and estimate the TAGBD directly from use of the appropriate regression equation (Table 1). Confidence intervals based on the error due to the regression can also be calculated by this approach. The regression equations are based on trees that

Table 1. Regression equations for estimating total aboveground biomass (TAGBD) of tropical forests by life zone (revised equations of Brown et al. 1989 based on additional data[a])

Y = biomass in kg/tree, D = dbh in cm, and H = height in m

Life zone	Equation	N	R^2
DRY			
	$Y = 34.47 - 8.068(D) + 0.659(D^2)$	32	0.67
MOIST			
Single	$Y = 38.49 - 11.788(D) + 1.193(D^2)$	168	0.83
Double[b]	$Y = 1.276 + 0.034(D^2H)$	168	0.83
	$H = 6.972 + 0.468(D) - 0.0015(D^2)$	3824	0.61
WET			
	$Y = 21.297 - 6.953(D) + 0.740(D^2)$	169	0.92
	$\ln Y = -3.375 + 0.948 \ln(D^2H)$	169	0.97

[a] New data were for 100 trees from the wet forest life zone of Costa Rica (A. Joyce, NASA, 1989, pers. comm.).

[b] Most inventories do not include height data, but equations considering H as well as D should yield better estimates of TAGBD. To improve the precision and accuracy of TAGBD estimates, a double sampling estimate can be computed using the relationship between H and D to first estimate H, and then substituting this estimated H and D into the double sampling equation (see Brown et al. 1989).

have been harvested in forests from all over the tropics (see Brown et al., 1989 for sources plus additional data for Costa Rica from A. Joyce, 1989, pers. comm.). This method is very similar to that used by ecologists, but the major difference is that the stand table for a given forest type is based on data gathered from many statistically selected plots over a large area.

The second method is based on data on commercial volume of stemwood per unit area for all species of trees to some minimum diameter (once again 10 cm is preferred, but factors are available for adjusting volumes when the minimum diameter is larger than this [Brown, 1990]). The basic approach is as follows:

$$\text{TAGBD (Mg/ha)} = V \times WD \times BEF$$

where:

V = commercial volume of stemwood in m^3/ha

WD	=	average wood density, Mg/m^3
BEF	=	biomass expansion factor [= TAGBD/ commercial biomass]

Biomass expansion factors have been calculated from inventory sources for many forest types throughout the tropics and vary between 1.75 to greater than 7.5. Significant relationships, with high R-squares, between BEF and mean diameter of the forest stand (Brown et al., 1989) or the stemwood biomass (Brown and Lugo, 1992) have been obtained. These relationships are used to estimate a suitable BEF.

Biomass Estimates from Forest Inventory Data

Application of the methods described above to (a) tropical Asia (data for ten countries from Brown et al., 1991), (b) tropical America (excluding Brazil, data from forest inventories for Bolivia, Guyana, Ecuador, Guatemala, Nicaragua, Panama, Peru, Suriname and Venezuela; from S. Brown, unpublished data), and (c) Brazilian Amazonia forests (from Brown and Lugo 1992) clearly shows that the TAGBD of tropical forests in these areas varies widely (Fig. 1). Note that the vertical scale for (a) and (b) is twice that of (c). The inventories for tropical Asia and America span the periods from the 1960s to the 1980s. The absolute range of TAGBD for moist forests (rainfall between 2000 to 4000 mm/yr) in tropical America was < 20 to about 410 Mg/ha and in tropical Asia it was <20 to about 550 Mg/ha. The simple means, however, were similar for each continent. The wide range in TAGBD reflects a high degree of human disturbance and a corresponding biomass reduction (Brown et al., 1991). Total aboveground biomass in wet forests (rainfall >4000 mm/yr) of tropical America ranged from <20 to >560 Mg/ha, but with a lower mean than moist forests.

Although there were similarities between the range and mean TAGBD between moist forests of tropical America and Asia, the distribution of their biomass classes were different (compare Fig. 1a to 1b). About half (46%) of the forests in tropical Asia had TAGBD between 100 and 220 Mg/ha. In tropical America, however, half of the forests had higher TAGBD estimates of between 180 and 260 Mg/ha. These differences most likely are the result of greater human use over a longer time period in tropical Asia than in America (Iverson et al., 1992).

Most wet forests in tropical America (65%) contained <160 Mg/ha of TAGBD (Fig. 1b). Most of these forests were in Panama and were described as low density forests, secondary forests, or forests mixed with agriculture and pasture (Food and Agriculture Organization, 1972). All these forest classes are expected to have low biomass and once again reflect human-caused degradation. Even forests described as having high tree density, and presumedly less human disturbance, generally contained between 180 to 260 Mg/ha of TAGBD, or less biomass than similar forest classes in the moist life zone. Forests growing under wetter regimes than moist forests generally show reductions in TAGBD (Brown and Lugo, 1982).

The TAGBD estimates for dense forests of the Brazilian Amazon were derived from two distinct data sets. The 1950s inventories were done during the period 1954 to 1960 in forests south of the Amazon River and were located mostly in the moist life zone with a small section of one inventory in a drier, transitional zone (Brown and Lugo, 1992). Estimates of TAGBD for these forests ranged from 175 to almost 400 Mg/ha. Most of the estimates (78%) were in the range of 240 to 340 Mg/ha (Fig. 1c). The 1970s estimates were derived from data for an almost complete Legal Amazon-wide inventory of dense forests. Total aboveground biomass

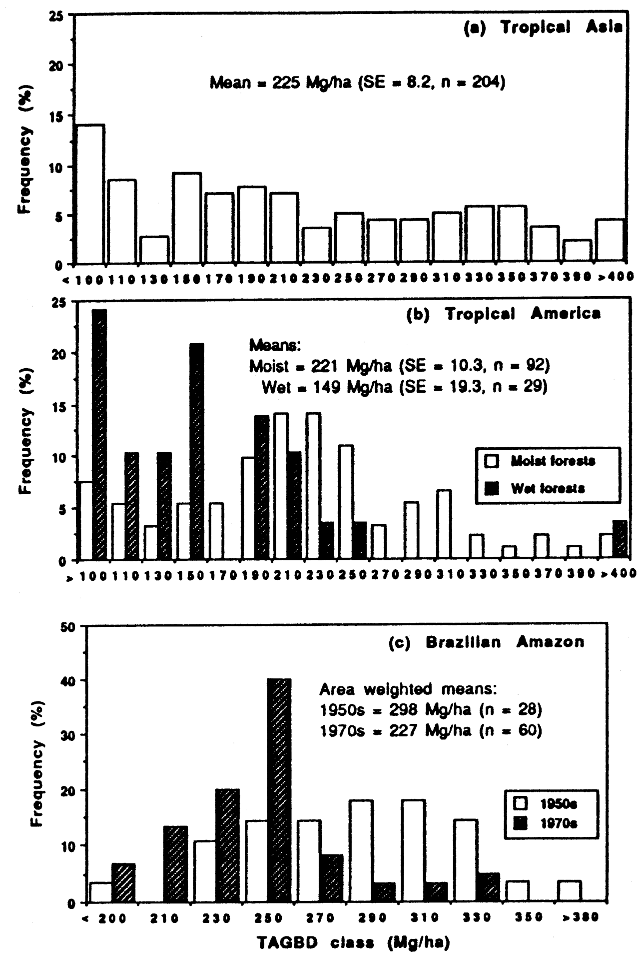

Figure 1 Frequency distribution (percent of total number of data points in a given biomass class) of total aboveground biomass density classes plotted at the mid-point of 20 Mg/ha classes.

estimates based on this inventory ranged between 166 to 332 Mg/ha. About 75% of these estimates ranged between 200 to 260 Mg/ha, representing an apparent shift to lower values compared to the 1950s estimates (Fig. 1c).

Because the areas of the two inventories do not overlap completely, one cannot conclude that the difference in TAGBD between the two periods is proof for biomass degradation. There is always the possibility that the differences were statistically non-significant. This could not be tested as the data for the 1950s inventory of volume-based data did not allow confidence intervals to be computed. Nonetheless, for overlapping areas the biomass was reduced on the order of 1% of the 1950s biomass per year (Brown and Lugo, 1992). This reduction could easily be accomplished, but yet not readily noticed by the casual observer, by the removal of one large diameter tree/ha every 2-3 yr (Brown and Lugo, 1992). For non-overlapping areas, it is difficult at this time to conclude that biomass change is caused by continued human degradation; it could instead reflect differences in environmental factors that influence biomass (e.g., edaphic or hydrologic factors).

Role of Large Diameter Trees in Biomass Estimation

For purposes of this discussion on the role of large diameter trees, we define a large tree as one with a diameter > 70 cm and an aboveground biomass of > 5 Mg (Brown and Lugo, 1992). Typically, trees of this size can be ≤ 4% of the total number of trees or ≤ 20 trees/ha. The presence or absence of large diameter trees influences the computation of TAGBD from forest inventories using the methods described above. The regression equations used with stand table data for estimating TAGBD are based on a data set that contains an insufficient number of large diameter trees. For example, there were three trees only >70 cm diameter in the data set for the regression for moist forests (Brown et al., 1989;) and 22 trees >70 cm for the regression for the wet forest. To partly overcome this problem, models were chosen that were expected to behave reasonably upon extrapolation up to 300 cm diameter (Brown et al., 1989). However, this lack of sufficient numbers of large trees in the regression is cause for concern and highlights the need for studies that measure the biomass of tropical trees to focus on this deficiency.

Another potential problem of estimating TAGBD from stand tables is that the largest diameter class is usually open-ended, so that information about the actual distribution of large diameter trees is poor. Often times, auxiliary information is provided (e.g., basal area or volume of the class) so that estimates of the likely average diameter in this class can be made. However, future inventories should ensure that the actual diameters or mean diameter of the largest class should be included to better estimate their biomass. Clearly, the diameters of these large trees must have been measured and their lack of reporting just illustrates some of the problems of using inventories outlined above.

Despite these potential problems in computing TAGBD due to large trees, they did not pose a real problem for the estimates presented in this paper because of our judicious selection of the inventories. In general, the larger the proportion of the TAGBD in large trees, the larger the TAGBD (Fig. 2). Effects of logging forests and other human disturbances can clearly be seen in the data for the Philippines and Peninsular Malaysia (Fig. 2a and b). Mature dipterocarp forests of the Philippines generally had >30% of their biomass in large trees and contained >400 Mg/ha of TAGBD, whereas logged forests had <20% of biomass in large trees and TAGBD of <400 Mg/ha.

Gradual decline in both the TAGBD and its proportion in large trees for Peninsular Malaysian forests (Fig. 2b) was caused by logging and other human activities (Brown et al., 1992a). The three forest classes in Peninsular Malaysia with the highest TAGBD were classified as primary hill forests, as were all the forests in Sarawak (Fig. 2b). Compared to the high density (HD) Sarawak forests, the primary forests of Peninsular Malaysia and low density (LD) forests of Sarawak generally had a smaller proportion of large trees with concomitant lower TAGBD. We have argued that the lower TAGBD and lower proportion of large trees in these forests was caused by illicit removal of commercially valuable trees ("log poaching") and that these forests were indeed not primary (Brown et al., 1992a). Furthermore, if forests in this region should contain >40% of their TAGBD in large trees in a truly primary state as is indicated by the data for high density forests of Sarawak, then the TAGBD for the Peninsular Malaysian and low density Sarawak forests may have been >450 Mg/ha instead of <350 Mg/ha (Brown et al., 1992a).

A similar trend between TAGBD and proportion of biomass in large trees was observed for forests in Sri Lanka and Bangladesh (less so), but the patterns differed (Fig. 2c). Forests in Sri Lanka generally showed a rapid increase in TAGBD once trees >70 cm occurred. When forests contained >20% of their TAGBD in large trees, TAGBD could reach 500 Mg/ha or more. Extrapolation of this trend to >40% in large trees, assuming that >40% is representative of truly primary forests in this region, resulted in TAGBD estimates of about 650 Mg/ha. This is a reasonable value for primary forests in this area based on environmental factors (Iverson et al., 1992 and below). No clear trend was exhibited for forests in Bangladesh where forests have been so heavily impacted by humans for decades to centuries (Flint and Richards, 1992a). These forests bear little resemblance to any natural formation. This pattern between TAGBD and proportion of TAGBD in large trees was also exhibited for forests in the Brazilian Amazon. All forests had a TAGBD of <400 Mg/ha with a percentage in large trees of <40% (Brown and Lugo, 1992). The generally low percentage in large trees was attributed to a history of human degradation.

We believe that the relationship between TAGBD and the percentage in large trees has potential for determining the condition of a forests, i.e., mature or disturbed. What is needed to develop this approach is accurate enumeration of large trees along with auxiliary information that describes, in as much detail as possible, the history of the area. We suspect that different patterns in the relationship may exist depending upon differences in environmental factors that determine forest biomass such as soils, climate, topography, and elevation.

APPLICATION OF GIS TO BIOMASS ESTIMATION

For many of the global issues related to tropical forest biomass, the primary information needed is the biomass of the forests undergoing disturbance or outright clearing and burning.

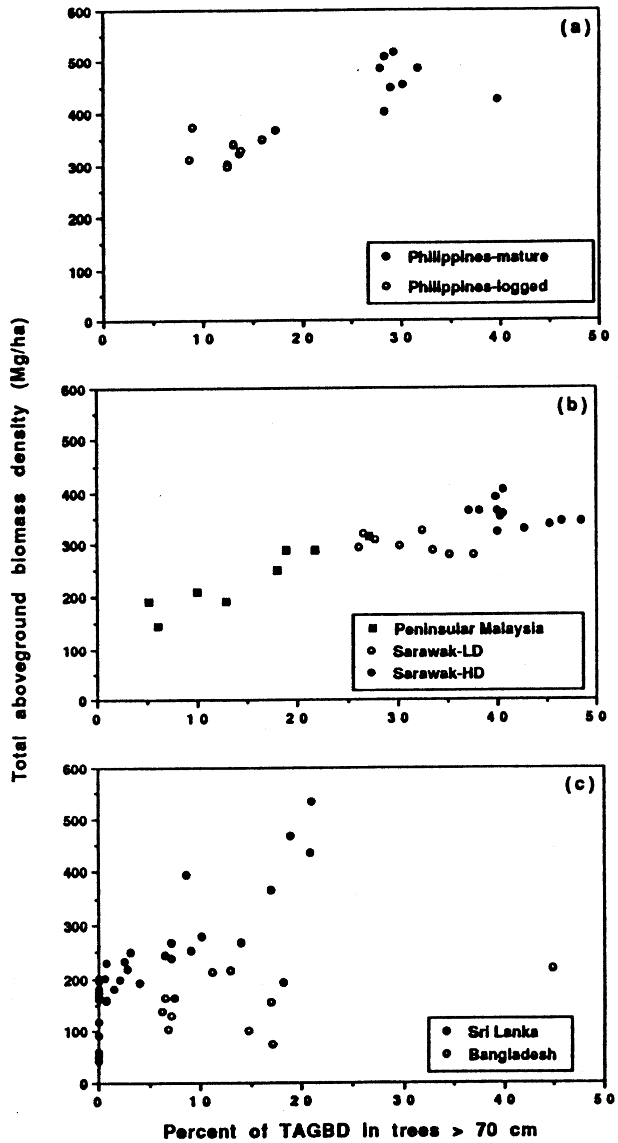

Figure 2 Relationship between TAGBD and percent of TAGBD in trees with diameters >70 cm.

Table 2. Estimates of total aboveground biomass (TAGBD, with 99% confidence intervals in parentheses) and area of forests in Peninsular Malaysia in 1982 (data from Brown et al. 1992).

Forest class	TAGBD (Mg/ha)	Area (10^3 ha)
UNDISTURBED FORESTS	**270**	**3564**
PRIMARY HILL	**279**	**2742**
Moderate hill	250(25)	1143
Good hill	288(29)	916
Superior hill	315(31)	683
RESTRICTED HILL	**242**	**542**
Poor hill	191(18)	261
Upper hill	287(28)	281
SWAMPS		
Freshwater	233(22)	280
DISTURBED FORESTS	**192**	**3258**
HILL	**191**	**2943**
Logged after 1966	191(18)	2246
Logged before 1966	209(20)	481
Shifting cultivation	145(14)	216
SWAMP	**209**	**315**
Logged after 1966	196(18)	276
Logged before 1966	302(28)	39
ALL FOREST CLASSES	**233**	**6943**

Remote sensing technology can determine where forests are being cleared and maps of forest/non-forest areas can be produced which depict change over time. Unfortunately, current technology in remote sensing cannot reliably determine the biomass of complex tropical forests (Nelson et al., 1988; Sader, 1988). This means that other methods for producing forest biomass maps must be developed. Clearly, the use of forest inventories has potential, however, the areal coverage is generally insufficient to make generalizations across highly heterogeneous regions.

In this section, we will demonstrate how GIS technology can be applied to forest biomass mapping. We present a case study for Peninsular Malaysia, a country that has excellent national forest inventories and forest maps, as an example of what could be done if all the tropical forests had been properly inventoried. We then present a method for regions lacking proper inventories which combines, in a GIS, a multitude of data bases suitable for estimating TAGBD.

Forest Biomass Map for Peninsular Malaysia

To produce country maps of forest biomass requires forest inventories at the national level that include (1) sufficient data to estimate biomass for all forests with some degree of reliability and (2) maps of the forest areas produced from aerial photos or remote sensing and verified with ground information. To our knowledge, Peninsular Malaysia is the only tropical country that has inventories that meet these criteria. They have done complete forest inventories for 1972, 1982, and are in the process of doing one for the early 1990s. We have developed biomass maps for the 1972 and 1982 inventories and used these to document forest area and TAGBD and their change between 1972 and 1982, and to search for clues that enable forest degradation to be assessed. (The results of this analysis are reported in Brown et al., 1992a.) Here we present results on part of this work only, namely the biomass map for 1982.

The inventories divided the forest area into 11 classes, including six undisturbed and five disturbed classes (Table 2). The undisturbed group includes (1) primary hill forests of three different levels of stocking density (volume/ha) and at elevations of 300 to 1300 m, (2) restricted hill forests caused by soil condition (poor hill forest) or elevation (upper hill forest), and (3) freshwater swamp forests. The disturbed group is comprised of (1) logged hill and swamp forests (before or after 1966 when the first aerial photos were taken) and (2) shifting cultivation forests, a mixture of cultivated areas, secondary forests, and patches of primary forest.

Stand tables for each forest class to a minimum diameter of 15 cm were included. The stand tables were first "completed" to include estimates of the number of trees in the 10-15 cm class using the methods outlined in Gillespie et al. (1992), and then were converted to estimates of TAGBD using the appropriate regression equations (see above for methods). The forest map, depicting the 11 forest classes and non-forest, was digitized into a GIS using ARC/INFO (ESRI Inc., Redlands, CA). An additional level of resolution was added to the map caused by the division of the country into six planning units; biomass estimates were also computed for the five most important of the 11 forest classes by these six planning units (see Brown et al., 1992a for further details).

Estimates of TAGBD by forest class (Table 2) and planning unit were computed and were incorporated into the 1982 forest-area map, resulting in a forest biomass map. Undisturbed forests comprised the largest percent of the total forest area (53%), with primary hill forests accounting for the most (74% of the undisturbed forests; Table 2). The mean TAGBD of these forests ranged from 250 to 315 Mg/ha. The disturbed hill forests had the lowest overall mean TAGBD of 191 Mg/ha, with the shifting cultivation mosaic having the lowest of all (145 Mg/ha).

When the biomass density and total biomass data were aggregated for 0.5 x 0.5 degree grids across the peninsula, one can begin to evaluate the amount of forest biomass available and its variation at a resolution appropriate for current global models. Total aboveground biomass density (Fig. 3a) and total biomass (Fig. 3b) were generally highest in a few cells in the northeast portion of the country (257-270 Mg/ha and 73.4-78.6 million Mg

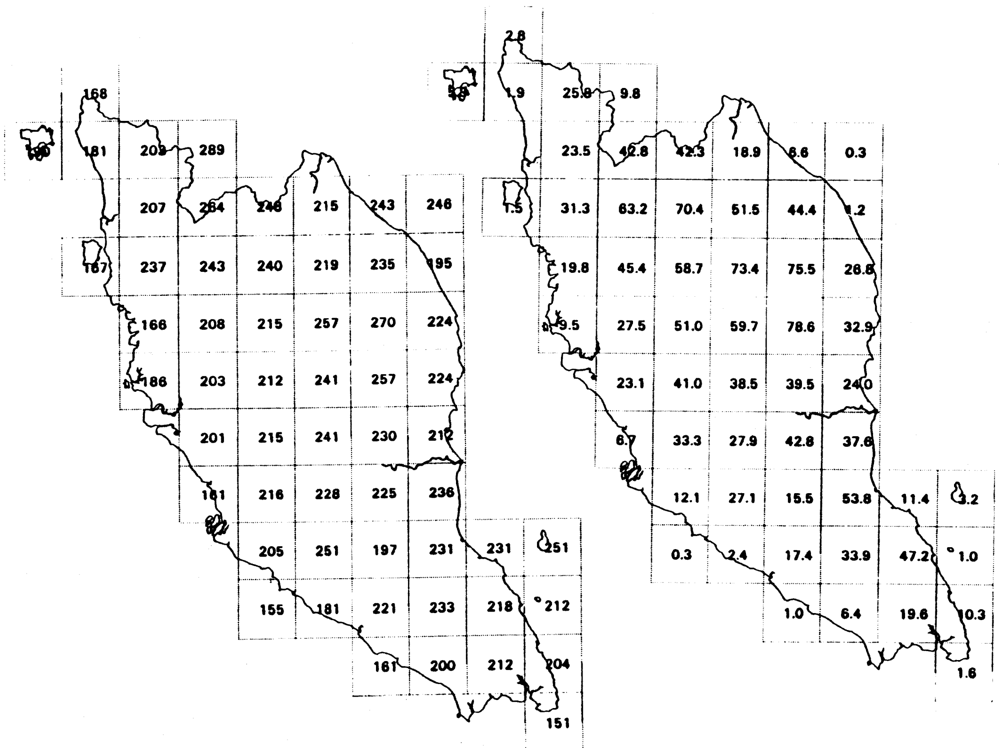

Figure 3 Total aboveground biomass density (TAGBD, Mg/ha, left) and total aboveground biomass (million Mg, right) of forests of Peninsular Malaysia in 1982, aggregated into 0.5 x 0.5 degree cells (data from Brown et al., 1992a).

biomass, respectively). This area of high biomass overlaps the largest national park in the country, which is expected to have been disturbed the least. Only one interior cell had an average TAGBD equal to the average for all of Peninsular Malaysia's undisturbed forests (270 Mg/ha, see Table 2). For all other cells, the presence of disturbed forests lowers the TAGBD significantly.

Forest Biomass Map for Continental South/Southeast Asia

Because of the general lack of sufficient forest inventory data for South/Southeast Asia, we used GIS along with modeling, to develop a forest biomass map (Iverson et al., 1992). The current distribution of forest biomass was assumed to be based on the potential amount that a landscape can support under the prevailing climatic, edaphic, and topographic conditions, and the cumulative impact from human activities such as clearing, logging, shifting cultivation, fuelwood collection, degradation, etc. The approach, therefore, was to first generate a potential biomass map from a model of the bio-physical parameters that most influence biomass. Then, using available forest inventories (these measure the state of the forest at some relatively recent time), recent vegetation maps, population density data, and historical accounts of land use (e.g., Brown et al., 1992a; Flint and Richards, 1992a, b) the potential biomass map was "deforested" and "degraded", resulting in an actual forest biomass map.

To generate a potential biomass map, GIS data layers of the environmental factors that most influence biomass were first produced. These included elevation, soil texture classes, slope classes, precipitation, and an integrated climate index (Iverson et al., 1992). Relationships between how each of these environmental factors (GIS data layers) alone influence biomass were developed. The model to generate an index of potential biomass was a simple additive one that performed an overlay of the data layers of environmental factors according to the specified relationships (Iverson et al., 1992). The product of this model was calibrated to TAGBD units using a variety of sources, including a few data from inventories which were identified as being in relatively undisturbed forests, ecological studies, relationships between TAGBD and proportion of biomass in large trees, and the advice of other experts in the region.

The potential forest biomass map was then masked with a map of forest locations for 1980 (Food and Agriculture Organization, 1989). This overlay yielded a map of the potential biomass occurring on locations still in forest in 1980. The final step was to add the influence of human activity to account for the degradation or biomass reduction of forests. This step was accomplished by developing regression equations of degradation ratios (actual TAGBD from inventories to potential TAGBD from potential TAGBD map

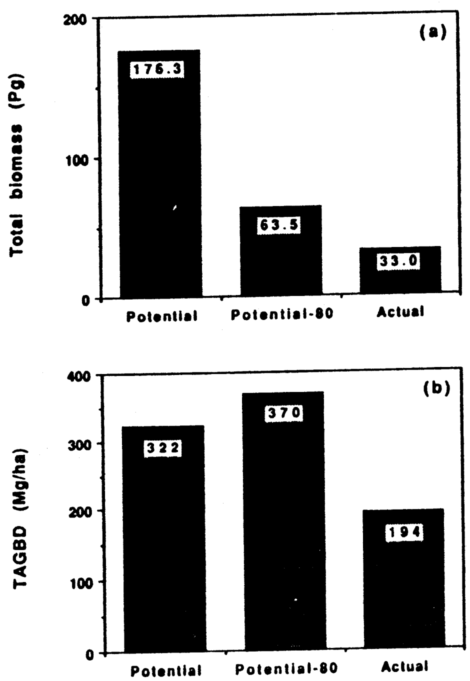

Figure 4 (a) Total aboveground biomass and (b) total aboveground biomass density (TAGBD) for forests under three conditions.

for 1980), stratified by ecoregions (Iverson et al., 1992). This approach yielded three estimates of the total quantity of aboveground biomass (Fig. 4 where potential = no human influence, potential-80 = biomass for forests as of 1980 with deforestation only, and actual = biomass for forests as of 1980 resulting from deforestation and degradation) and three maps of forest biomass density.

Total potential aboveground biomass for continental South/Southeast Asia was estimated at 176 Pg (176 x 10^{15} g of biomass, Fig. 4a). The range of TAGBD estimates was 50 to >600 Mg/ha, with a weighted average of 281 Mg/ha (Fig. 4b). The potential aboveground biomass estimate for the remaining forests in 1980 was about 64 Pg, or only 36% of the amount the region could support in the absence of humans. This reduction was caused by outright conversion of forests to nonforest, mostly occurring in drier forestlands that supported lower potential TAGBD. This extensive clearing of lower potential biomass forests is the main cause for the high weighted mean potential TAGBD of the remaining forests in 1980 (Fig. 4b).

A further decrease in forest biomass to account for degradation produced an estimated actual aboveground forest biomass of about 33 Pg. Thus, the long history of human impact (deforestation and degradation) on the forest lands of this region has reduced the total forest biomass to 19% of the potential amount the region could support.

Estimates of actual TAGBD ranged from <50 to about 400 Mg/ha (Fig. 5), with a weighted mean of 194 Mg/ha (Fig. 4b). In 1980, forests with the highest actual TAGBD were located in parts of Peninsular Malaysia, western Cambodia, northeast India, and parts of Laos. These are generally places of high potential biomass and relatively low population density.

Much of the continent has been deforested to essentially a non-forest condition (Fig. 5), especially where high population densities are present. The drier tropical forests, such as those occupying much of India, have had the most conversion and degradation. Apparently, humans prefer to occupy the drier sites, as they are more hospitable for human inhabitation and agriculture.

The TAGBD and total biomass estimates were also calculated by country for each of the three maps prepared for continental South/Southeast Asia (Fig. 6). Because of the size of the country, the most total biomass was and still is found in India and Myanmar(Fig. 6a). On the other hand, the

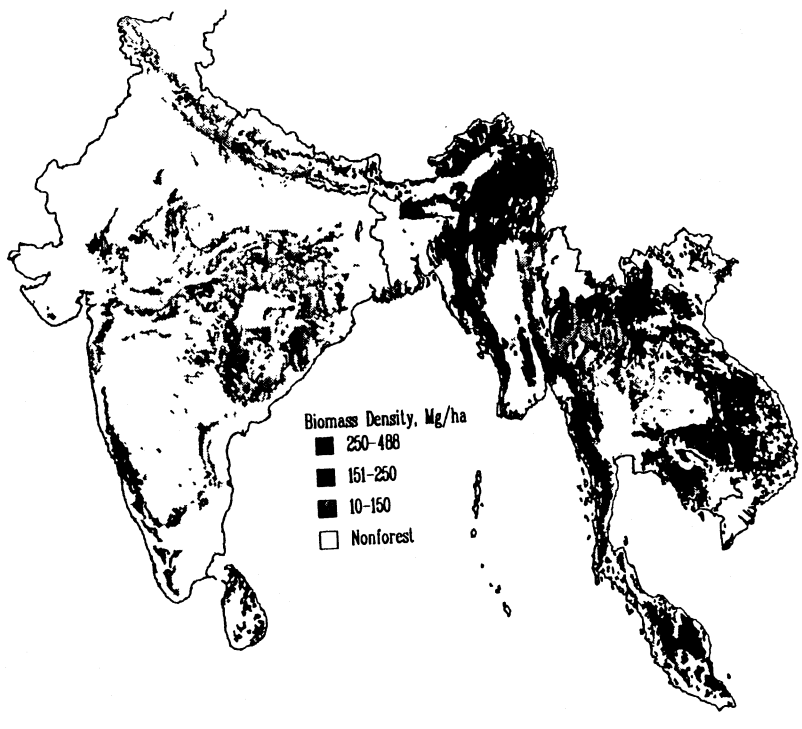

Figure 5 Map of actual total aboveground biomass density (TAGBD, Mg/ha) for forests of continental South/Southeast Asia, aggregated into three classes.

actual TAGBD values were quite low for India, with other countries yielding about twice the Indian value, including Cambodia, Laos, Myanmar, and Vietnam (Fig. 6b).

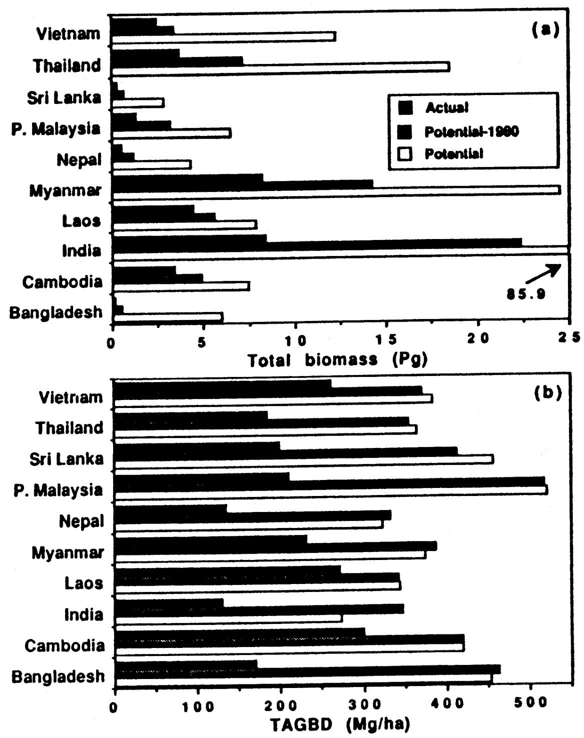

Figure 6 Individual south and southeastern Asian country estimates of (a) total aboveground biomass and (b) total aboveground biomass density (TAGBD).

We are continuing to estimate potential and existing forest biomass through the application of GIS for tropical America and eventually tropical Africa. This work is part of an overall effort, funded by the U.S. Department of Energy to several institutions, to improve the spatial and temporal estimates of carbon fluxes from the tropical landscape. The analysis considers carbon sinks (see Brown et al., 1992b; Lugo and Brown, 1992) and sources. The goal is to generate maps of carbon fluxes through time, using detailed historical data on biomass and land use combined with GIS and remote sensing, that can be cross-checked with atmospheric carbon measurements (e.g., Tans et al., 1990).

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