Biomass of tropical forests of South and Southeast Asia

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Biomass of tropical forests of south and southeast Asia

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BROWN, S., GILLESPIE, A. J. R., and LUGO, A. E. 1991. Biomass of tropical forests of south and southeast Asia. Can. J. For. Res. **21**: 111–117.

Stand tables from forest inventories representing more than 22 × 10^6 ha of forests in tropical Asia were used to estimate aboveground biomass (point and 99% confidence interval). The mean inventory-based biomass for moist forests (225 Mg/ha) was lower than that reported by direct measurements for mature forests in the same region (350 Mg/ha), whereas the mean inventory-based biomass for dry forests (82 Mg/ha) was higher than estimates based on direct measurements (55 Mg/ha). Our analyses demonstrated that human use of the forests in tropical Asia is intense, leading to degradation. Between two national forest inventories of Peninsular Malaysia in 1972 and 1981, the total area and biomass of forests declined by 18 and 28%, respectively. Modeling land-use changes and carbon dynamics of tropical Asian forests must take into consideration human impact on vegetation because such use of forests reduces their biomass and may stimulate forest growth and carbon uptake.

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Des tables de peuplement construites à partir de données de l'inventaire de 22 × 10^6 ha de forêt en Asie tropicale furent utilisées pour estimer la biomasse aérienne (point et intervalle de confiance de 99%). La biomasse moyenne basée sur l'inventaire des forêts humides (225 Mg/ha) était plus faible que celle qui avait été rapportée suite à une évaluation directe dans les forêts matures de la même région (350 Mg/ha), tandis que la biomasse moyenne basée sur l'inventaire pour les forêts sèches (82 Mg/ha) était plus élevée que les estimés obtenus par une évaluation directe (55 Mg/ha). Nos analyses ont démontré que l'utilisation des forêts par l'homme en Asie tropicale est intense et entraîne sa dégradation. Entre deux inventaires réalisés en 1972 et 1981 dans les forêts nationales de la Malaisie péninsulaire, la superficie et la biomasse totales des forêts ont diminué respectivement de 18 et 28%. La modélisation des changements dans l'utilisation des terres et la dynamique du carbone dans les forêts d'Asie tropicale doit tenir compte de l'impact humain sur la végétation car une telle utilisation des forêts réduit leur biomasse et peut stimuler la croissance de la forêt et accentuer le prélèvement de carbone.

[Traduit par la Rédaction]

Introduction

Deforestation and other land-use changes that reduce the biomass of tropical ecosystems produce a source of carbon dioxide that exacerbates the rise in atmospheric carbon dioxide (e.g., Detwiler and Hall 1988; Houghton et al. 1985). The magnitude of this terrestrial carbon source, derived from models, is currently estimated to be between 8 and 47% of that produced from fossil-fuel combustion.

Carbon dioxide fluxes in terrestrial tropical ecosystems are estimated from models that calculate rates of release and uptake of carbon resulting from changes in land use. Carbon is released when forest lands are converted to agricultural uses (permanent and shifting cultivation), or are logged, and the biomass is burned or left to decay on the site. Uptake of carbon occurs in recovering forest vegetation and soils when agricultural lands or logged forests are abandoned or reforested.

A major source of uncertainty in the estimates of carbon fluxes due to changes in tropical land use is the biomass or carbon content of tropical forests being cleared or regrowing. Brown and Lugo (1982, 1984) made two estimates of the biomass of tropical forests from two distinctly different data bases. The two approaches gave markedly different biomass estimates for closed forests (*sensu* Food and Agriculture Organization 1981) but similar estimates for open forests (*sensu* Food and Agriculture Organization 1981).

The first estimate (Brown and Lugo 1982) was based on a synthesis of literature data on total forest biomass estimated by direct measurements on experimental plots (either by destructive harvest techniques or by applying regression equations obtained by destructively harvesting trees). All the data were for undisturbed or primary forests and represented a total area of <30 ha. The weighted average total biomass 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).

Forest volume data, reported by forest type for each of 76 tropical countries given by the Food and Agriculture Organization (1981), were used by Brown and Lugo (1984) for another estimate. Commercial wood volumes were converted to total biomass using average wood densities and expansion factors (ratio of total biomass to commercial biomass). The weighted average biomass for undisturbed closed forests by this method was 175 Mg/ha and for open forests was 60 Mg/ha, values that are significantly lower than those based on direct measurements.

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TABLE 1. Sources of data for biomass estimations for forests of south and southeast Asia

Country	Year	Area of inventory (ha)	No. of plots	Plot size (ha)	No. of forest types	Min. dbh (cm)	Source
Bangladesh	1964	2.4×10^3	3839	0.04–0.5	5	10	FORESTAL 1964
Bangladesh	1984–1985	8.7×10^4	4032	0.03	4	10	De Milde et al. 1985
Bangladesh	1986	3.3×10^3	640	0.03	2	10	Drigo et al. 1988
Burma	1982–1983	1.4×10^6	1343	1.05	4	5	Forest Department of Burma – Food and Agriculture Organization 1984, 1985
Cambodia	1970	2.4×10^2	2	22/2	1	10	Legris and Blasco 1972
Cambodia	1958–1961	3.9×10^6	1067	1.0	5	15	Rollet 1962
India	1970	Unknown	Unknown	Unknown	4	10	Government of India 1972
Malaysia							
Peninsular	1969–1972	8.2×10^6	4716	0.1	11	15	Food and Agriculture Organization 1973*a*
Peninsular	1981–1982	6.7×10^6					Government of Malaysia 1987
Sarawak	1972	1.2×10^6	5676	0.1	22	10*	Food and Agriculture Organization 1973*b*
Philippines	1983	2.4×10^6	5775	Variable	8	5	Kennel 1984
Philippines	1986–1988	Unknown	Unknown	Unknown	2	10	J. Schade, 1989, personal communication†
Sri Lanka	1958	3.4×10^5	6899	Variable	19	10	Andrews 1961
Sri Lanka	1966	1.6×10^4	—‡	—‡	4	10	Food and Agriculture Organization 1969
Thailand	1980	9.8×10^2	490	0.1	3	10	Royal Forest Department of Thailand 1980
Vietnam	1982–1983	6.1×10^6	1666	Variable (0.2–2.0)	8	10	Rollet 1984

*Inventory was based on a minimum dbh of 20 cm; number of stems in the 10–20 cm class was estimated by methods of Gillespie et al. (1991).
†Director, Philippine-German Dipterocarp Forest Management Project, Manila.
‡Sampled 4% of the area.

To attempt to resolve the discrepancy between the two biomass estimates, Brown et al. (1989) calculated new expansion factors (ratio of total aboveground biomass only to commercial biomass). These new factors were found to increase exponentially with decreasing quadratic stand diameter (QSD), ranging from 1.5–2.0 for undisturbed forests with high QSD to >7.0 for highly disturbed or recovering forests with low QSD. Brown and Lugo (1984) used a constant expansion factor of 1.4 for closed forests and 2.1 for open forests (original factors were based on above- and below-ground biomass but were converted here to aboveground biomass only to be consistent with Brown et al. 1989). Using the new expansion factors, Brown et al. (1989) revised the biomass estimates of tropical closed forests based on the Food and Agriculture Organization (1981) volume data, resulting in a 30–50% increase in the estimate depending upon the forest type.

Although progress has been made in reducing the discrepancy between direct measurement and volume-based estimates of tropical forest biomass, significant differences still occur (Brown et al. 1989). All the Food and Agriculture Organization volume data were unified to a common minimum diameter of 10 cm (using volume expansion factors), even though most of the volumes were measured to a minimum diameter of >10 cm (K. D. Singh and J. P. Lanly, Food and Agriculture Organization, 1989, personal communication). This attempt to standardize volume data introduces another error into the volume-based biomass estimates that has not been considered.

The purpose of this paper is to report new biomass estimates for tropical forests, independent of volume but still based on inventory data because of the large sample area that they typically encompass. We focus on the forests of tropical Asia because others in a joint research program of which our work is one phase have developed land-use models and extensive historical data bases on land use, vegetation types, and biomass for the same area (see other papers in this issue).

Methods

Brown et al. (1989) developed methods for calculating a point and interval estimate (mean and 99% confidence interval) of forest biomass based on stand tables (number of stems per hectare by diameter classes). We define forest biomass as mean total aboveground biomass of trees to a minimum diameter of approximately 10 cm; we do not include understory biomass (shrubs, herbs, saplings, etc.), which has been estimated to account for about 3–4% of the total aboveground biomass of closed forests (Brown and Lugo 1984).

We used only those forest inventories for tropical Asia that gave stand tables for trees down to a small minimum diameter (about 10–15 cm with one or two exceptions) and included all species (Table 1). The minimum diameter for the inventory of forests of Sarawak (Food and Agriculture Organization 1973*b*) was 20 cm, but because all species were included, the number of stems in the 10–20 cm diameter class was estimated by methods of Gillespie et al. (1991).

Inventory data were available for parts of 9 out of 13 tropical Asian countries (Table 1). All inventories were in the tropical moist forest life zone (*sensu* Holdridge 1967), with the exception of parts of India and Sri Lanka, which were dry. The total area of forest land that these inventories represent is $>22 \times 10^6$ ha or >8% of the total forest lands in tropical Asia (based on the 1980 area data given in the Food and Agriculture Organization 1981). Half of the inventories were completed since 1980, whereas the others were completed in the early 1960s (parts of Bangladesh, Cambodia, and Sri Lanka) or 1970s (parts of Cambodia, India, and Sarawak).

The number of forest categories within each inventory varied between 2 and 22. Some inventories classified forests into ecological types (e.g., evergreen, mixed deciduous, hill forests, freshwater swamps, etc.), whereas others used terminology that described their commercial value (e.g., superior hill forest, good hill forest, medium yield, low yield, nonproductive, etc.) or status with respect

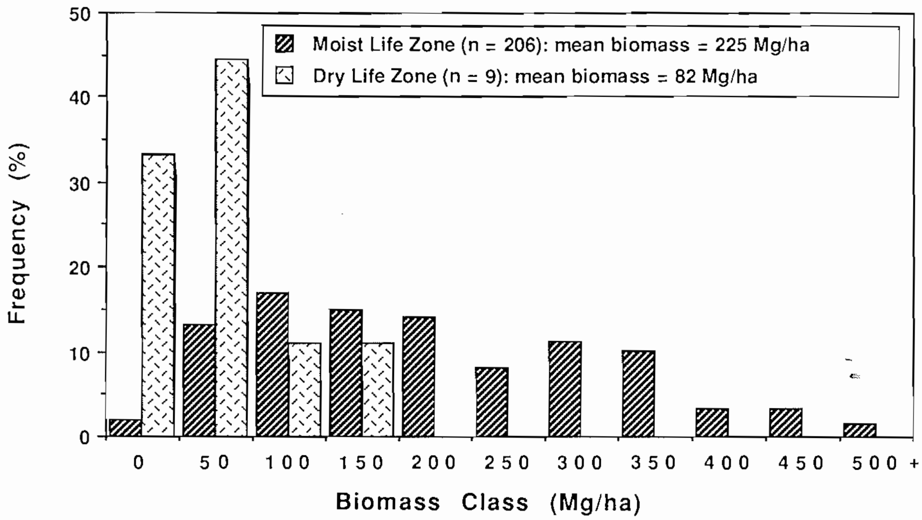

FIG. 1. Biomass frequency distribution (class size = 50 Mg/ha) for forests of tropical Asia in moist and dry forest life zones. Mean biomass was estimated from stand tables given in the forest inventories listed in Table 1.

to disturbance (e.g., logged, disturbed, shifting cultivation, secondary, etc.).

The 9 countries were grouped into three regions to determine whether differences in forest biomass exist at this scale. The groupings, based on similarities in geographic location and forest types present, were as follows: (*i*) Bangladesh group, including Bangladesh, Burma, India, and Sri Lanka; (*ii*) Malaysia group, including Peninsular Malaysia, Sarawak, and the Philippines; and (*iii*) Cambodia group, including Cambodia, Thailand, and Vietnam.

The method for estimating biomass from stand tables basically involved substituting the midpoint of the diameter class into a biomass regression equation (based on diameter only, given in Brown et al. 1989) to calculate biomass per tree and then multiplying the biomass by the number of trees in the class. This was repeated for all diameter classes, and the sum produced a point estimate for biomass of the forest represented by the stand table. The 99% confidence interval around the point estimate was calculated from the covariance matrices of the coefficients of the biomass regression equations.

Results and discussion

Biomass estimates

Most (>61%) of the tropical moist forests in Asia covered by the inventories had biomass estimates less than 250 Mg/ha (Fig. 1), with a mean of 225 Mg/ha. This is far less than the mean of 350 Mg/ha (n = 4, SE = 28) for mature tropical humid forests in Asia or 300 Mg/ha (n = 25, SE = 18) for all mature tropical humid forests based on direct measurements (Brown and Lugo 1982). A few mature forests in tropical Asia (about 6%) had biomass estimates >400 Mg/ha, some of the highest values reported for tropical forests (Fig. 1).

The estimated biomass of most (78%) of the dry forests was <100 Mg/ha (Fig. 1), and the mean of 82 Mg/ha is about 1.5 times the 55 Mg/ha (n = 4, SE = 12) from direct measurements of dry forests (Brown and Lugo 1982). The discrepancy between the two methods for the dry forests may be due to a limited data base of direct measurements of dry forest biomass, biases in plot selection for direct measurements, and all of the direct measurement study areas being located in forests in higher tropical latitudes (subtropical, *sensu* Holdridge 1967).

Biomass was plotted against basal area for forests in each of the three regions to determine if there were regional trends (Fig. 2). We expected biomass to be highly related to basal area because the graph is basically a way of showing the biomass regression equation (biomass is a function of diameter squared); we use these graphs merely as a means of showing the variation in biomass by region. Total aboveground biomass ranged from <50 Mg/ha to >500 Mg/ha in all regions (Fig. 2). The biomass estimates for the dry forests, for a given basal area, were considerably lower than those for the moist forests (Fig. 2*a*).

Many of the forests included in the inventories have been subject to human disturbance, resulting in large areas of degraded forest land and a wide range of biomass estimates. This appears to have been most prevalent in the Bangladesh group (Fig. 2*a*; note the high number of low biomass forests), where the widest range of biomass is exhibited (9–533 Mg/ha). Some of the disturbance has been due to commercial logging, but most has been due to illicit felling and clearing for subsistence agriculture (references are made to this in most of the inventory documents).

The effect of human intervention on forest biomass is illustrated by an example from Sri Lanka: medium-yield moist forests in two reserves that were very inaccessible had average biomass values of 366 and 468 Mg/ha (from data in Food and Agriculture Organization 1969) compared with 194–270 Mg/ha for similar forests that were subject to human disturbance (Andrews 1961). The reduction in biomass due to disturbance is reflected in (*i*) higher numbers of stems in the smallest diameter classes and (*ii*) fewer larger trees (>40 cm) than in undisturbed forests. The numerous small trees tend to account for less than 20% of the total biomass (Gillespie et al. 1991). In contrast, larger trees (>50 cm) in undisturbed forests can account for as much as 40–50% of the stand's biomass. It is these larger trees that are usually cut illicitly.

The inventory of the Burmese forests was done near townships along one of the major railway lines from Rangoon to Mandalay, in an area that has been under human pressure for years. Such use reduced the biomass to the present-day low values. Most of the evergreen forests of Vietnam were classified as medium to poor yield, with

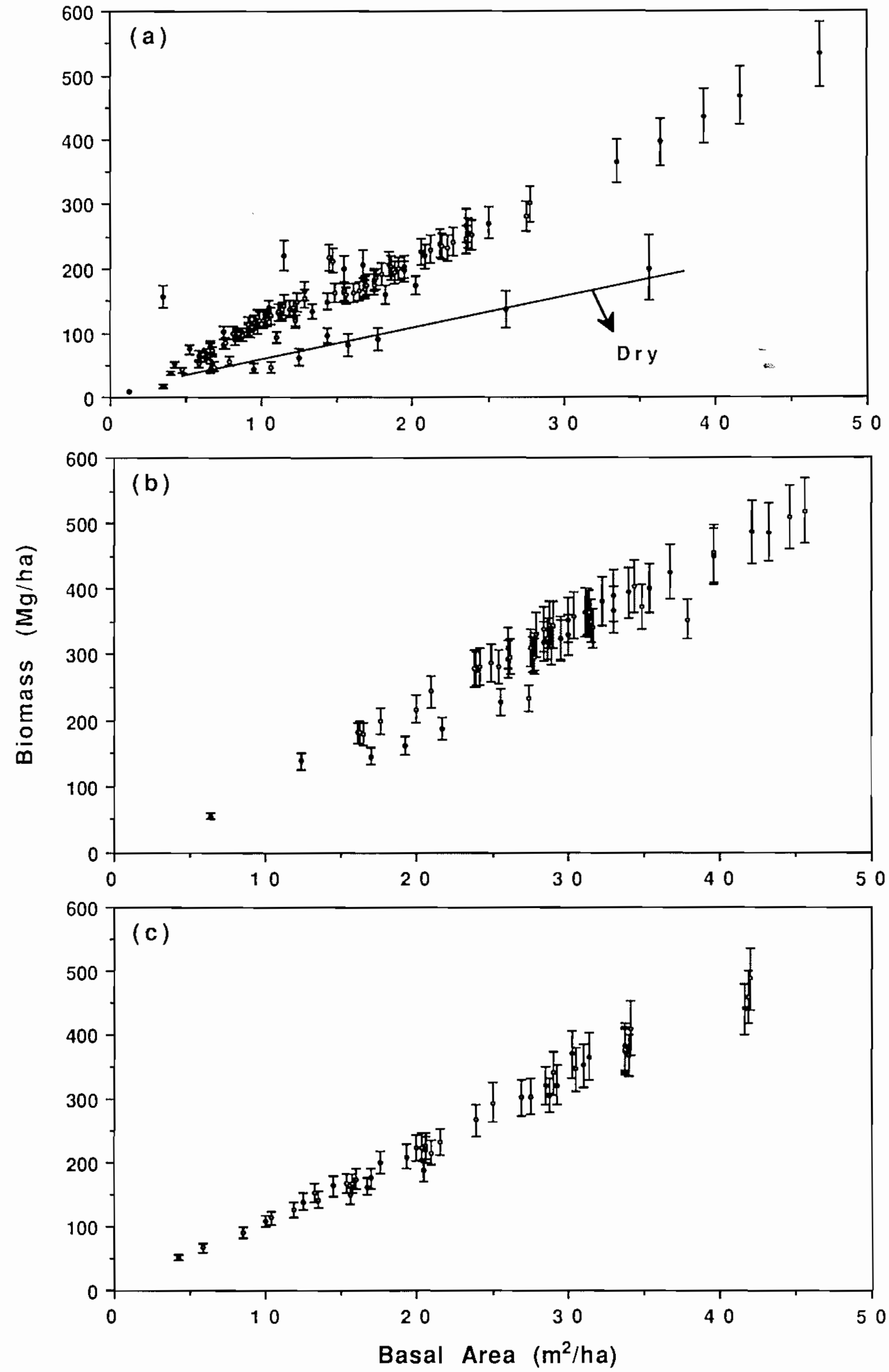

FIG. 2. Mean (±99% confidence interval) biomass versus basal area for all forests included in the inventories given in Table 1, divided into three regions based on similarities in location and forest types. (*a*) Bangladesh group, including Bangladesh, Burma, India, and Sri Lanka. (*b*) Malaysia group, including Peninsular Malaysia, Sarawak, and the Philippines. (*c*) Cambodia group, including Cambodia, Thailand, and Vietnam. All points adjacent to the line in Fig. 2*a* are estimates for dry forests.

biomass estimates ranging from 127 to 306 Mg/ha, compared with a range of 320–460 Mg/ha for high-yield forests that once covered these areas (Rollet 1984).

Forests in Sarawak (Fig. 2*b*), covering $>1 \times 10^6$ ha, appeared to have undergone little human disturbance based on land-use maps produced at the time of the inventory (Food and Agriculture Organization 1973*b*). Very small areas of the eight inventory units were remnant forests from previous logging and shifting cultivation. In the Sarawak dipterocarp forests, the biomass estimates were relatively uniform within a stocking class and ranged from 280 to 325 Mg/ha for medium stocking and from 325 to 405 Mg/ha for heavy stocking (Food and Agriculture Organization 1973*b*).

Changes in forest biomass and area in Malaysia: a case study

Two similar national forest inventories done 9 years apart in Peninsular Malaysia (Table 1) allowed us to address the effect of forest degradation on biomass. During the 9-year period, forest area declined by 18% (Fig. 3*a*). The decline occurred in most categories, but the largest reduction was in the disturbed hill forests (all commercially important

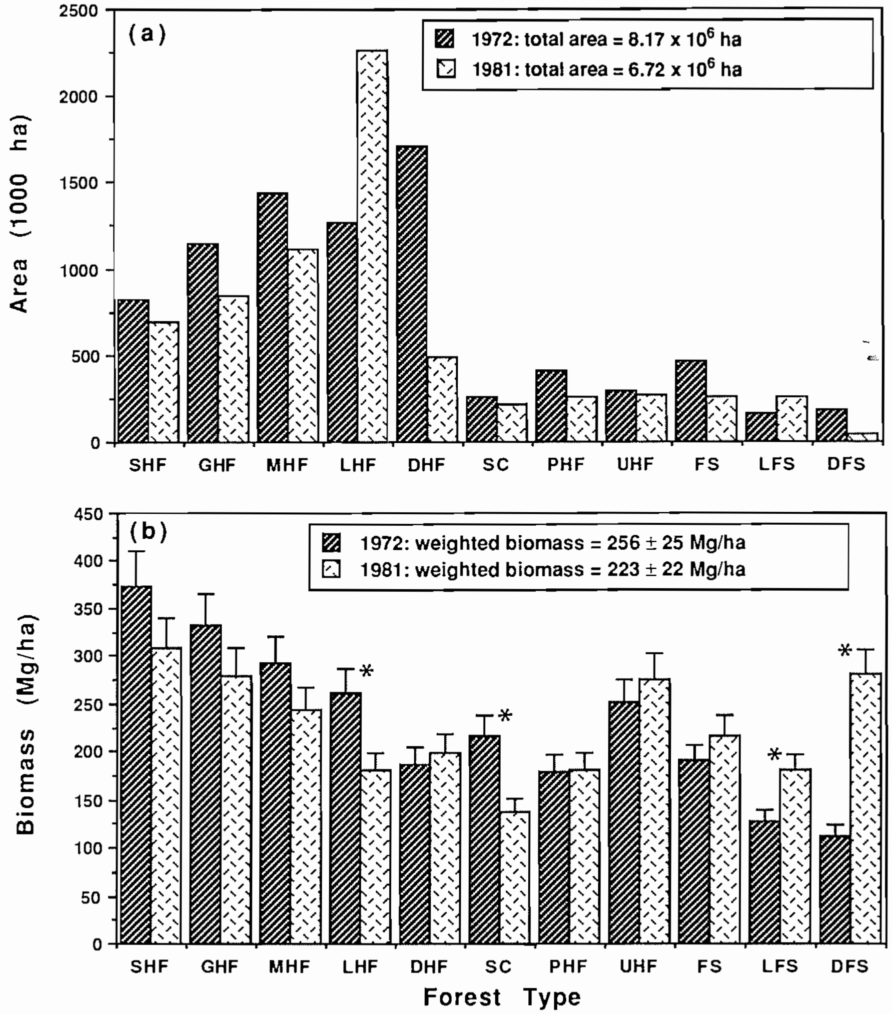

FIG. 3. Change in (*a*) area and (*b*) biomass of tropical forests in Peninsular Malaysia between 1972 and 1981 (data are from Food and Agriculture Organization 1973*a* and Government of Malaysia 1987). Biomass values are the mean and 99% confidence interval. Significant differences in biomass during the 9-year interval are shown by asterisks, based on 99% confidence interval. HF, hill forest; FS, freshwater swamp forest; S, superior; G, good; M, moderate; L, partially logged (since 1966); D, disturbed (all commercial species logged before 1966); P, poor; U, upper; and SC, shifting-cultivation forest (mixture of cleared plots, secondary forests, and patches of primary forest).

species selectively logged before 1966), from about 1.7×10^6 ha in 1972 to 0.5×10^6 ha in 1981. Most of this decrease was due to conversion to agriculture or rubber and palm oil plantations under a program of planned rural development (Food and Agriculture Organization 1973*a*).

The area of shifting-cultivation forest (mixture of cultivated areas, secondary forests, and patches of primary forest) changed little during the 9 years. The only forest category that exhibited an increase in area was the partially logged hill forests (logged since 1966). More than 90% of this increase in logged forest area can be accounted for by the decrease in relatively undisturbed hill forest. As with the hill forests, the area of freshwater swamp and disturbed freshwater swamp forests decreased, whereas the area of partially logged swamp forests increased.

Not only did the area of forest change in this 9-year period, but also the total biomass of the whole forested region declined by 28%, or 10% more than the decline in forest area. Although significant decreases occurred only in two forest types (partially logged hill forest and shifting-cultivation forest), there was a general trend of decreasing biomass in most commercial hill forests (Fig. 3*b*) due to a reduction in the number of trees in the larger size classes. This most likely resulted from illicit felling.

The area of partially logged forests increased, but the biomass was only about 70% of the 1972 value. The decrease in biomass of these forests during the 9-year period could be due to more intensive logging, indicated by a noticeable reduction in the number of large stems, or logging occurring in lower quality forests. Shifting-cultivation forests exhibited only a slight decline in area, but the average biomass declined to 64% of the 1972 value. This suggests that little new land was added to this category but that land already in this use had shorter fallow periods, as indicated by a lower frequency of large trees and a higher frequency of small trees.

All the noncommercial hill forests showed either no significant change (poor hill forests) or a nonsignificant increase (disturbed and upper hill forests) in biomass between the two inventories. Apparently these remaining forests have undergone no further degradation.

Biomass of the primary, logged, and disturbed freshwater swamp forests increased, the latter two significantly so, during the 9-year period. In fact, the biomass of the disturbed freshwater swamp was significantly higher than that of the primary freshwater swamp in 1981. The area of the disturbed freshwater swamp in 1981 was a fraction of its extent in 1972 (Fig. 3*a*), but these residual stands contained significantly more biomass. This implies that lower biomass swamp forests were eliminated, perhaps because of accessibility, leaving small pockets of high-biomass forests.

Most present models of land-use change in the tropics (e.g., Detwiler and Hall 1988; Houghton et al. 1985) have dealt only with changes in forest to nonforest area because the data for addressing forest degradation have not been available. The data on changes in biomass over time presented here for Malaysia demonstrate that not only are forest areas declining but also the remaining forests are gradually, or in some cases rapidly, being degraded. Decreases in forest area and degradation of remaining forests could both produce a source of carbon dioxide. Conversely, carbon dioxide sources from decreases in forest area may be partially offset by increases in biomass (due to regrowth) of residual stands (e.g., the freshwater swamps in Malaysia) or by the growth of forest fallow following abandonment.

The detailed data set that we have presented here for Peninsular Malaysia underscores the importance of repeated national forest inventories and knowing the history of forest area, biomass, and human use for modeling the global carbon cycle more accurately and precisely. This also emphasizes the usefulness of and the need for permanent plots with periodic, consistent evaluation.

Reconciliation of biomass estimates for closed tropical forests of south and southeast Asia

The biomass range of 50–530 Mg/ha presented in this paper encompasses the range of 310–430 Mg/ha from direct measurements (Brown and Lugo 1982). It appears, therefore, that both methods give comparable estimates for undisturbed forests (>350 Mg/ha). However, the estimates based on inventory data represent a more realistic picture of biomass of undisturbed forests (i.e., those in Sarawak and parts of the Philippines, Sri Lanka, and Cambodia) because of the larger area sampled (a few hectares for direct measurements versus thousands of hectares for inventories), which reflects the spatial heterogeneity of the tropical forest landscape. Reliance on the direct-measurement biomass values, extrapolated across all of tropical Asia for use in models of deforestation (e.g., Houghton et al. 1985), cannot be justified because most of the forests there have been degraded.

Estimates of biomass based on Food and Agriculture Organization (1981) volume data and expansion factors (Brown et al. 1989) resulted in an area-weighted biomass of 159 Mg/ha for all closed tropical Asian forests, including those that are undisturbed, logged, and nonproductive. Results from this study, although not area weighted but including values for the same forest types as the Food and Agriculture Organization (1981), suggest that the average biomass is higher (225 Mg/ha). In addition to the errors inherent in the respective calculations, the discrepancy between biomass based on volume versus that based on this study suggests that the errors associated with unifying the volume data in Food and Agriculture Organization (1981) to a common minimum diameter (discussed earlier) are the cause. Further research is needed to resolve the importance of these potential errors in volume so that more accurate and precise biomass estimates may be made for modeling present and past global biogeochemical cycles.

Implications for modeling

Our results have several implications for modeling carbon fluxes to the atmosphere from changes in land use in tropical Asia:

(1) Higher biomass estimates (>350–400 Mg/ha) most likely reflect forests in tropical Asia as they existed prior to incursion of human pressures, past or present (e.g., forests in Sarawak or in very inaccessible areas). This emphasizes the need to know historical land-use patterns and cultural practices (see Flint and Richards 1991) to better determine the initial conditions of forests being modeled.

(2) Models of forest clearing over time (>100 years as is typically done) need to address the changes in biomass due to degradation. Higher biomass estimates could be used at the start of the models, but progressively lower initial biomass values need to be used in more contemporary times as forests are degraded.

(3) Forest degradation by humans in tropical Asia is rampant; it reduces biomass and may also stimulate forest growth, depending upon the intensity of human use. The net implication to the carbon budget needs to be explicitly addressed in land-use models.

(4) The steady-state assumption used to describe the carbon balance of most undisturbed forests (Lugo and Brown 1986) is further weakened as forest degradation may induce net carbon uptake as the forest regrows to its initial condition.

(5) Because all biomass estimates are reported as a point and confidence interval estimate, range and sensitivity analysis in carbon flux models should be based on these interval estimates. In the past, the effects of uncertainty in biomass estimates were evaluated by using different published estimates of biomass (e.g., Brown and Lugo 1982, 1984; Whittaker and Likens 1973), which are mostly based on direct measurement methods. This approach resulted in an unrealistic range of conditions because high values were erroneously extrapolated worldwide.

The analysis presented here is for forests in tropical Asia only. We do not know whether similar trends exist in the forests of tropical Africa and America, but suspect that they are similar because recent studies suggest that few undisturbed tropical forests exist (Lugo and Brown 1986; Brown and Lugo 1990).

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