Geographical Distributions of Carbon in Biomass and Soils of Tropical Asian Forests

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Abstract

Estimates of geographically referenced carbon densities and pools in forest soils and vegetation of tropical Asia were modeled using a geographic information system. Spatial data bases of climatic, edaphic, and geomorphologic indices, and vegetation were first used to estimate the potential carbon densities (without human impacts) in above- and below-ground biomass of forests in 1980. The resulting map was then modified to actual carbon density estimates as a function of population density and three climatic regimes. Soil organic carbon estimates were generated by calculating mean carbon densities, to 100 cm depth, from pedon data for tropical forests, stratified by soil texture classes and climatic regimes. The means for each class were assigned to a texture/climate map for all of tropical Asia. The average carbon density for the tropical forests of Asia was 255 Mg ha^{-1} in potential biomass, 144 Mg ha^{-1} in actual biomass and 148 Mg ha^{-1} in soils, which correspond to total carbon estimates of 74, 42, and 43 Pg, respectively. Three out of the 14 countries considered (Indonesia, India, and Myanmar) accounted for about 70% of the total carbon pools in tropical Asian forests. Carbon densities and pools in vegetation and soil varied widely by ecofloristic zone and country.

Introduction

Recent estimates of the carbon source from changes in tropical land use to the atmosphere vary widely, from 0.4 to 2.5 Pg C yr^{-1} (1 Pg = 10^{15} g) for 1980 (Detwiler and Hall 1988, Hall and Uhlig 1991, Houghton *et al.* 1987) and from 1.2 to 2.2 Pg C yr^{-1} for 1990 (Houghton 1992). The uncertainty in these estimates is caused by high uncertanities in rates of land-use change, rates of forest degradation, the amount of carbon in vegetation and soil of the forests being cleared, and the allocation of carbon after clearing and burning (Brown and Iverson 1992). Many of these uncertainties could be resolved if maps describing the spatial distribution of land-use change and carbon in vegetation and soils were available. These coincident maps would enable changes in land use to be matched with appropriate vegetation and soil carbon.

High resolution satellite imagery, collected at more than one time interval for the entire tropics, will eventually allow for mapping and more precise estimates of land-use change. This mapping has been done already for a few countries, e.g., the Amazon Basin in Brazil (Skole and Tucker 1993). However, current technology in remote sensing has been shown to be incapable of reliably determining the biomass of complex tropical forests (Nelson *et al.* 1988). Alternative methods are therefore needed for this aspect of the effort. Recent work (Brown and Iverson 1992, Iverson *et al.* 1994) has demonstrated the feasibility of generating spatial distributions of tropical forest above-ground biomass density using a modeling approach in a geographic information system (GIS). To our knowledge no other similar attempts have been made.

We considered using maps of vegetation or life zones (e.g., Prentice *et al.* 1992, Emanuel *et al.* 1985) and average biomass carbon densities (e.g., Ajtay *et al.* 1979, Brown and Lugo 1982, Fearnside 1992, Olson *et al.* 1983, Whittaker and Likens 1973) to produce spatial distributions of forest biomass carbon density.

However, we rejected this approach because most of this work is concerned with potential vegetation and not actual, the data base for generating average biomass carbon densities is poor and generally does not represent the population of interest (i.e., all tropical forests of Asia), and the use of average values from a few forest types does not reflect the spatial heterogeneity of forest areas caused by differences in environmental factors and human impacts (cf. Brown and Lugo 1992, Brown and Iverson 1992 for further discussion).

A method is also needed to generate spatial distributions of soil carbon density because of the importance of soil to the global carbon cycle (Detwiler 1986). At present, estimates of carbon pools in soils for use in terrestrial carbon models are derived from highly aggregated life zone averages (Post *et al.* 1982) or on averages by pedons based on the Food and Agriculture Organization Soil Map of the World (FAO-UNESCO 1971-1981, Eswaran *et al.* 1993).

The goals of this paper are to present methods and results for producing spatial estimates of carbon densities (carbon per unit area, Mg ha^{-1} [1 Mg = 10^6 g]) and total carbon pools (product of carbon density and area, Pg) in vegetation and soils for tropical Asian forests. We build on the work of Iverson *et al.* (1994) for the carbon in forest vegetation and develop a new method for soil carbon densities. Area weighted average carbon densities and total carbon in vegetation and soils by ecological zones, country, and whole region are reported and compared. We conclude with a discussion of the implications of our results to the global carbon cycle.

Methods

Study Area

The area of study consists of the continental and insular portions of tropical Asia, including the following countries: Bangladesh, Brunei, Cambodia, India, Indonesia, Laos, Malaysia (Peninsular, Sabah and Sarawak), Myanmar, Nepal, Philippines, Sri Lanka, Thailand, and Vietnam. General descriptions of the forests of this region are given in Whitmore (1984) and Collins *et al.* (1991). The region is composed of very diverse forest formations ranging from very dry forests in parts of India to the moist evergreen forests of Malaysia and Indonesia. Most of this diversity of forest formations can be attributed to the very heterogeneous rainfall regimes, including total amount and seasonality (Whitmore 1984). Geomorphologic and edaphic patterns are responsible for further differentiation of the vegetation. Human use of the region adds another level of complexity to the forest landscape resulting in forests at different stages of degradation, including mature, logged, young to late secondary, and highly degraded.

The occurrence of frequent, large-scale natural disturbances are not widespread across the region. Tropical cyclones occur frequently in Bangladesh, parts of India and Myanmar, and the Philippines. To what degree the structure of forests over the long term are affected by these events is poorly known and are not explicitly included in the analysis.

General Procedure for GIS Processing

All data were processed with the ARC/INFO and Grid (raster) GIS, with the exception of the interpolation of climatic station data which was performed with GRASS (Construction Engineering Research Laboratory, Champaign, IL, USA). Processing involving areal calculations was performed separately on the continental and insular regions, projected into the Albers equal area projection, to reduce the distortion in pixel size near the east and west edges of the data sets. The pixel size was 3.75 km x 3.75 km. The data were converted into a geographic projection (i.e., latitude and longitude) for display purposes.

As with any overlay process involving highly generalized global data sets, there will be many sources of error and one cannot precisely locate or map the carbon density in any particular pixel. However, the general patterns across the regions or countries should be more reliable.

Carbon Density of Forest Vegetation

We estimate the carbon density of above-ground and below-ground biomass in trees with a diameter of ≥ 10 cm. In more open forests where trees are often smaller in diameter, the minimum diameter was lowered to 5 cm. We did not include the biomass of other living components such as saplings, shrubs, vines, and other understory plants because they represent a small fraction in closed forests (<5% of the above-ground biomass; Brown and Lugo 1992). These other components, however, could represent a larger proportion of the total biomass in open forests, but data are presently lacking to support this possibility. We did not include estimates for fine or coarse (woody debris) litter because the data base available is unsuitable for extrapolating to all the Asian tropics and we do not know to what extent this material is used by people for fuel, fodder, or other uses. A more detailed discussion of the significance of omitting these other vegetation components is given in Brown and Lugo (1992).

Above-ground Biomass Carbon Density

For producing a spatial distribution of forest biomass carbon density, we used the approach described in

Iverson *et al.* (1994). We extended the analysis detailed in Iverson *et al.* to include countries in insular Asia as well as in continental Asia, included an estimate for below-ground biomass density as well as above-ground, and converted the results from biomass units to carbon units (1 unit biomass = 0.5 units of carbon). Because of the paucity of data on forest biomass in the region (Brown and Iverson 1992), a modeling approach in a GIS was used. We assumed that the present distribution of forest biomass density is a function of the potential amount that the landscape can support under the prevailing climatic, edaphic and geomorphologic conditions and the cumulative impact of human activities such as logging, fuelwood collection, shifting cultivation, and other activities that reduce the biomass.

The approach was to first develop a spatial distribution of potential (i.e., without the influence of humans) above-ground biomass density. This was accomplished using the following data layers, full descriptions of which are given in Iverson *et al.* (1994): (1) elevation was mapped by re-scaling, in 15 m intervals from sea level to about 4000 m, the US National Geophysical Data Center's elevation map, (2) five soil texture classes were mapped by reclassifying the FAO-UNESCO Soil Map of the World, (3) five slope classes were mapped based on the FAO-UNESCO Soil Map of the World, (4) annual precipitation was mapped by interpolation of meterological station data (about 600 stations) obtained from the agro-meterological database of FAO, and (5) integrated climate index was mapped by interpolation of a modified Weck's index (Weck 1970) using the same meterological station data as for precipitation.

The general methodology for processing these data layers follows that of Risser and Iverson (1988). A simple additive model of the data layers is used to arrive at a score for each pixel across the region. The scores are then calibrated with actual estimates of biomass density for mature forests.

The specific model that we used for mapping an index of potential biomass density combined the above data layers, weighted according to their effect on biomass density. The data layers of precipitation, climatic index, and soil texture were each assigned a maximum value of 25 points; elevation and slope classes together were assigned another 25 points. The maximum score for any pixel was thus 100 points. The initial weighting scheme for each layer was arrived at from information in Brown and Lugo (1982), Holdridge (1967), and Whitmore (1984). Model results were compared to known localities in the region, forest inventories, other literature sources, personal experience, and colleagues expert in the region (e.g., E. Flint and J. Richards, Duke University; cf. Flint and Richards 1994, Richards and Flint 1994). This process was repeated with the weight of climatic and edaphic factors adjusted within certain bounds to yield the most satisfactory map (Iverson *et al.* 1994).

Here we describe the weighting scheme for precipitation to serve as an example of our approach. Precipitation, ranging from less than 400 to more than 5000 mm yr^{-1}, was scaled to 12 classes, taking 400 mm yr^{-1} as the lower limit at which forests grow (Holdridge 1967). From 400 to 1200 mm yr^{-1}, each class interval was 200 mm yr^{-1}; from 1201 to 3600 mm yr^{-1}, each class interval was 400 mm yr^{-1}; and the last two classes were 3601 to 5000 mm yr^{-1} and > 5000 mm yr^{-1} (based on Brown and Lugo 1982, Holdridge 1967). The weighting factor for biomass density in the model was assumed to: (1) increase linearly from 3 points for the first precipitation class to the maximum of 25 points for the 9th class (2801-3200 mm yr^{-1}), and (2) decrease linearly to a minimum of 17 points for the 12th class (Brown and Lugo 1982). The details of assumptions and basis for the weighting schemes derived for the other layers are described in Iverson *et al.* (1994).

Overlaying all the data layers according to their weighting schemes resulted in a map of indices which was then calibrated to biomass density units using data from the literature for mature forest of the region. This posed a challenge because few measurements of mature forest biomass have been made in this region (Brown *et al.* 1991). Sufficient data were available to set the upper and lower limits of the potential biomass index (details of sources are given in Iverson *et al.* 1994). Once these were established, we assumed that biomass density was linear between these limits, using additional literature sources to establish intermediate biomass density classes. The two upper-limit classes for potential biomass density were 550-600 Mg ha^{-1} and >600 Mg ha^{-1}; the lower limit was <50 Mg ha^{-1}; and the ten classes in between were 50 Mg ha^{-1} wide (Iverson *et al.* 1994).

The distribution of potential above-ground biomass density was then "cut" with a map of forested areas as of about 1980 to produce maps of potential biomass density for forests lands only. The forest/non-forest maps used for this step were derived from two sources: (1) a vegetation map of continental tropical Asia produced by the Food and Agriculture Organization for its 1990 Tropical Forest Resource Assessment Project (Food and Agriculture 1989, K.D. Singh, FAO, pers. comm. 1990) and (2) a digital map of the forest areas for insular Asian countries reported in Collins *et al.* (1991; obtained from the World Conservation Monitoring Center [WCMC], Cambridge, England). The FAO vegetation and WCMC forest maps were developed from many multi-date sources (late 1970s to early 1980s), thus the exact year that they represent is not accurately known. We assumed that they represent the state of the vegetation in 1980 (K.D. Singh, pers. comm.). The forest/non-forest map when combined with the potential biomass density map produced a distribution of potential biomass carbon density in those areas remaining as forests as of 1980 (referred to as PCD-80).

The final step was to add the cumulative impact of human acitvity on reducing forest biomass from its potential. For this step, we assumed that population density could be used as a surrogate index to account for this reduction in biomass and that the impact of humans on forests varies by climate (Iverson *et al.* 1994, Flint and Richards 1994, Richards and Flint 1994). That is, the same human population density causes relatively more forest degradation in drier than in humid climates because of the inherent ability of humid forests to produce biomass more rapidly (Brown and Lugo 1982).

Degradation ratios for forests were calculated as the ratio of biomass density estimated from data given in forest inventories (Brown *et al.* 1989, 1991) to potential biomass density from the model (Iverson *et al.* 1994). These ratios were based on recent (since the 1960s) inventories suitable for converting to biomass, and were conducted in various subnational units of Bangladesh, India, Malaysia (Peninsular and Sarawak), Philippines, Sri Lanka, Thailand, and Vietnam (see Brown *et al.* 1991), for a total of 47 units. It was assumed that these inventories were done in a representative sample of the forests in a given subnational unit and that the weighted biomass density was the best estimate of the forest biomass density for the whole unit at that time. A weighted estimate of the potential biomass density for the same subnational unit was obtained from the PCD-80 map.

The calculated degradation ratios and their corresponding population density, taken at the time nearest to the time of the inventory for each unit, were stratified by three climatic regimes (aseasonally moist = >2000 mm yr^{-1}, seasonally moist = 1500-2000 mm yr^{-1}, and dry = <1500 mm yr^{-1}). These data were then subject to least squares simple linear regression analysis. The three resulting equations are shown in Figure 1. Default solutions to these equations at very high or low population densities were set at 0.06 (the lowest value obtained from inventories) and 1.0 (no degradation), respectively. These equations show that the rate of forest degradation, as indicated by the slopes of the equations, with increasing population is highest in the dry forests, followed by the seasonal and the moist as hypothesized above.

A population density map of the region was generated from population data reported by subnational units as obtained from the Demographic and Statistics Department of the Food and Agriculture Organization (see Iverson *et al.* 1994). The equations in Figure 1 were used with the maps of population density, rainfall, and PCD-80 to produce a spatial distribution of the actual biomass carbon density (ACD) of forests.

Below-ground Biomass Carbon Density

From the few pantropical data available on below-ground biomass (Brown and Lugo 1982, Fearnside

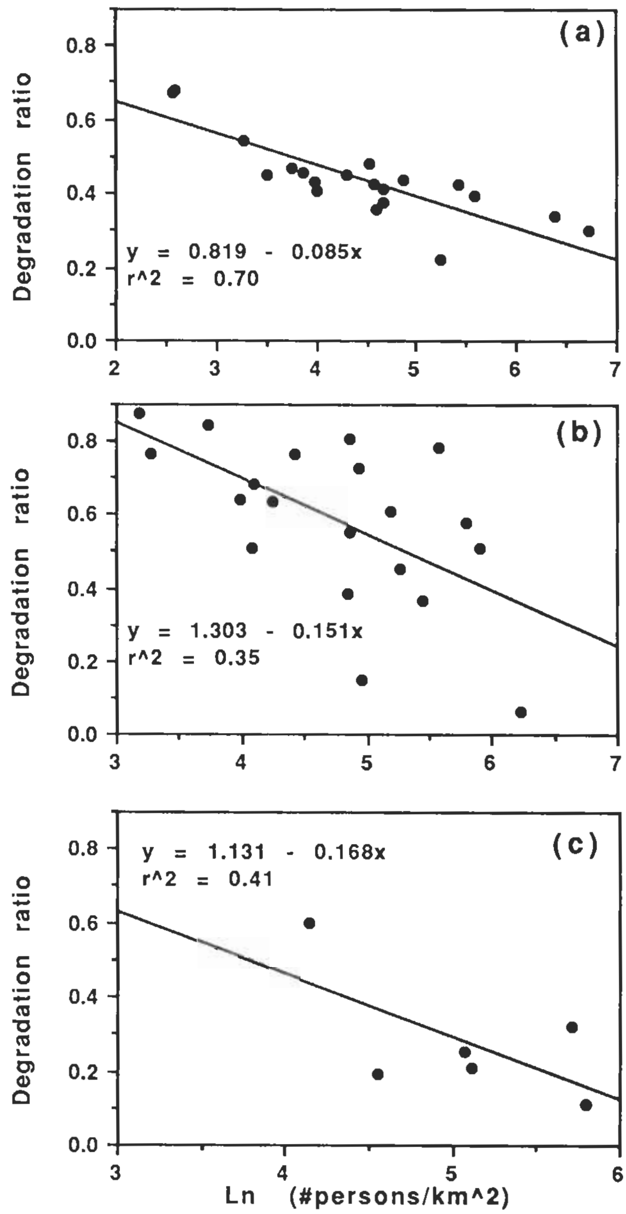

Figure 1 Relationship between biomass degradation ratios (actual to potential biomass density) and the natural logarithm (Ln) of population density for (a) moist, (b) seasonal, and (c) dry climatic zones (see text for description of these zones). The regression equation for (a) is for population densities > 12 persons km^{-2}; for population densities (PD) less than this, the degradation ratio = 1-0.015*PD.

1992, Olson *et al.* 1983), we calculated root:shoot ratios. We then stratified these ratios according to three climatic zones: (1) lowland dry = ≤ 1200 mm yr^{-1} and elevation ≤ 1000 m (no montane dry forests existed in 1980), (2) lowland and montane seasonal = > 1200-2000 mm yr^{-1} for elevation below 1000 m, and 500-1200 mm yr^{-1} for elevation above 1000 m, and (3) lowland and montane moist = >2000 mm yr^{-1} over all elevation ranges and > 1200-2000 mm yr^{-1} for elevation above 1000 m. These rainfall and elevation limits are generally based on those of the ecofloristic zones of the study area of FAO (1989) and the life zone system of Holdridge (1967). A climatic zone map was derived from the precipitation and elevation maps developed for the potential biomass density modeling.

The root:shoot ratios that we used are as follows: 0.18 for lowland and montane moist forests, 0.10 for lowland and montane seasonal forests, and 0.5 for lowland dry forests. Belowground biomass carbon density was then calculated for each pixel of the PCD-80 and ACD maps using these ratios and the climatic zones map.

Carbon Density of Forest Soils

There have been several attempts to estimate global soil carbon pools which include use of the FAO-UNESCO Soil Map of the World (Bohn 1982, Eswaran *et al.* 1993) and the life zone system (Post *et al.* 1982). None of these provide a suitable spatial distribution for estimating soil carbon pools for tropical forests because they have tended to lump the soil pedon data by map units or life zones without regard to vegetation cover or other variables that vary spatially.

The FAO-UNESCO (1971-81) Soil Map of the World is the only map presently available in digital form suitable for estimating the spatial distribution of tropical soil carbon pools. Unfortunately, the accompanying soil pedon descriptions are not suitable for estimating soil carbon densities because they do not report soil bulk density needed to convert the carbon concentrations to carbon contents, not all map units have pedon descriptions, and many of the soil pedons are for non-native vegetation. To overcome these problems with the pedon data base and previous studies, we developed an alternative approach for using this map.

Based on the available spatial data bases and the known factors that influence soil carbon, we chose soil texture and climatic regime (measured by mean annual precipitation coupled with effects of decreasing evapotranspiration due to increasing elevation) as the two most important factors for our analysis. It has been suggested that soil texture can play a significant role in determining the amount of organic matter in soil (Sanchez 1976, Lugo *et al.* 1986, Parton *et al.* 1987). Of all the environmental factors that affect the regional distribution of soil organix matter, mean annual precipitation has been shown to explain the most variance, followed by mean annual temperature (Jenny 1980).

We used the data base of Zinke *et al.* (1984) as a source of data on soil carbon density. This data set consists of pedon data containing information on organic carbon content (%C and bulk density to various depths), generally accompanied by information on soil texture, geographic location, climatic data, and land use. To this, we added data from other sources (Brown and Lugo 1990, and data from Venezuela and Costa Rica from ongoing research by S. Brown). We extracted all the data on soil carbon density for native tropical forests that met the following criteria: (1) reported carbon to 100 cm depth, and (2) had sufficient data to place the pedon in a rainfall, elevation, and soil texture class.

Because of the relatively few data points that met the criteria (a total of 171 points), we stratified the data set into the same three climatic zones as those used for the below-ground biomass (see above). We also assigned all the data to one of three texture classes based on the definitions used by the FAO-UNESCO Soil Map of the World. We then calculated the mean soil carbon density for each of nine classes (three climatic zones and three texture classes). This procedure resulted in a 3 x 3 matrix of mean soil organic carbon densities (Table 1). Because the soil

Table 1 Mean soil organic carbon contents to 100 cm (Mg ha^{-1}, with one SE and sample size in parentheses) stratified by texture and climatic regimes, to generate the spatial distribution of soil carbon density in forest soils of tropical Asia. See text for further details on sources.

Texture classes	Climatic regime*		
	Dry	Seasonal	Moist
Coarse	94 (30, 4)	63 (9, 10)	77 (19, 10)
Medium	97 (9, 18)	136 (21, 20)	147 (27, 20)
Fine	150 (24, 11)	151 (14, 25)	116 (9, 53)
Medium-coarse§	96	100	111
Medium-fine§	124	144	131
Histosols¶		------------675------------	

*Dry (lowland) = ≤1200 mm yr^{-1} with elevation below 1000 m, seasonal (lowland and montane) = >1200-2000 mm yr^{-1} and elevation below 1000 m or 500-1200 mm yr^{-1} and elevation above 1000 m, and moist (lowland and montane) = >2000 mm yr^{-1} over all elevation ranges or >1200-2000 mm yr^{-1} and elevation above 1000 m.
§These are mixed classes, and are calculated as the arithmetic average of the two corresponding classes
¶From data in Anderson (1983); we used a bulk density of peat soils of 0.15 g/cm^3, a carbon concentration of 45%, and a depth of 100 cm.

map also contained two mixed texture classes (medium-fine and medium-coarse), we estimated their carbon density as the arithmetic average of the two corresponding classes. There are also fairly extensive areas of histosols in tropical Asia, usually associated with peat swamps (Anderson 1983). These peat deposits generally exceed 100 cm in depth. We estimated their carbon density from data given in Anderson (1983, cf. Table 1).

We then used the map of soil texture classes derived from the FAO-UNESCO Soil Map of the World, the climatic zone map, and the values in Table 1 to assign each pixel the corresponding soil carbon density. Finally, we overlayed the forest maps derived above to produce a spatial distribution of soil carbon density in the forest existing in 1980. We assumed that soil carbon density under forests did not change as a result of degradation of biomass carbon density.

Results and Discussion

Validation of the Models to Estimate Carbon Densities

As few forests of any significant extent in tropical Asia are undisturbed by humans (Brown *et al.* 1991, Collins *et al.* 1991, Whitmore 1984), it is difficult to validate our estimates of potential biomass carbon density. The only suitable data for validating our model are large-scale inventories in mature forests and such data do not exist. Furthermore, small-scale field data would not be suitable for validating our model because many of the input data are of coarse resolution. To determine if our results seemed reasonable and gave expected trends across the region, we aggregated our estimates by the ecofloristic zones (EFZ) for the region (FAO 1989). These zones served as an independent data base for testing our results because we have not used this map in any of our analysis.

An EFZ is based first on bio-climatic factors such as rainfall and its seasonality, the length of the dry season, relative humidity, and temperature. Elevation, soils, and dominant characteristic flora add further levels of detail. This map serves as an approximate potential vegetation map for the region. The FAO map (obtained in digital form from K.D. Singh, FAO, Rome) was prepared by the Forestry Department of the FAO and the International Institute of Vegetation Mapping in Toulouse, France. We reclassified the original 36 zones into six zones. These consisted of three lowland (<1500 m) and three montane (>1500 m) zones, subdivided further into moist- evergreen forests with high non-seasonal rainfall, semideciduous forests with seasonal precipitation, and dry- deciduous forests with a long dry season and low rainfall.

Overlaying the reclassified EFZ map with the one of PCD-80 produced expected trends (Table 2). Our potential biomass carbon density estimates were higher for forests in lowland than in montane zones for a given moisture regime, and higher in moist followed by seasonal and dry for a given elevation belt. These expected patterns of potential biomass carbon density with EFZ increase our confidence that the methodology described here does produce reasonable estimates at this regional scale.

As so few forest inventory data were available for

Table 2 Estimates of mean biomass carbon and soil carbon density (to 100 cm depth) (Mg C ha^{-1}) potentially (PCD-80) and actually (ACD) in forests of tropical Asia by ecofloristic zones, for 1980. Coefficients of variation (CV, in %) are given for total potential and actual biomass carbon and soil carbon densities.

Ecofloristic zone*	PCD-80				ACD						Total
	Above	Below	Total	CV	Above	Below	Total	CV	Soil	CV	1980
					CONTINENTAL						
L-moist	224	41	265	16	117	21	138	25	133	11	271
L-seasonal	175	18	193	19	94	9	103	54	121	25	224
L-dry	124	63	187	29	38	19	57	61	121	22	178
M-moist	176	32	208	21	115	20	135	25	135	7	270
M-seasonal	152	16	168	39	83	8	91	51	125	23	216
Wtd mean	**184**	**28**	**212**		**99**	**14**	**113**		**126**		**239**
					INSULAR						
L-moist	270	49	319	9	162	29	191	23	187	102	378
L-seasonal	232	22	254	15	88	8	96	46	142	65	238
M-moist	251	45	296	16	152	28	180	27	114	21	294
Wtd mean	**268**	**48**	**316**		**162**	**28**	**190**		**178**		**368**
Wtd mean for region	**219**	**36**	**255**		**124**	**20**	**144**		**148**		**292**

*Forests were not found in all zones in 1980; L = lowland, M = montane.

developing the degradation models, we were forced to use all of them which left none for validating our estimates of actual biomass carbon density. However, because other data bases were used, in addition to the degradation ratio/population density regression equations, to develop the actual biomass carbon density estimates, we believe that we can use the inventory data to check the overall validity of the results. We fit a linear regression equation between the actual biomass carbon density from the inventory data and the predicted carbon density from the model. A significant relationship was obtained with an r^2 of 0.7, a slope of 0.91, and an intercept of 7.2. The reduction in r^2 was caused mainly by five points from the dry and seasonal zones of continental Asia where the model predicted higher biomass carbon densities than was obtained from the inventories. This pattern could be expected because the original regression equations for these two zones had the lowest r^2 (Fig. 1). Overall, the model tended to overestimate the biomass carbon density by <5% for densities <250 Mg ha^{-1} and up to 8% for densities between 250-400 Mg ha^{-1}.

Despite the coarse resolution of many of the data layers, the imperfect regression equations, the problems with inadequate biomass density data, and the many assumptions used, we believe that the map of actual biomass carbon density is a realistic spatial representation of the situation in 1980 and the best that can be produced with current technology and data. For the first time, we have produced a spatially explicit estimate of carbon density which considers distributions of environmental and anthropogenic factors.

Geographical Distribution of Biomass and Soil Carbon Densities

Actual biomass carbon densities range from less than 50 to more than 360 Mg ha^{-1} for the forests of tropical Asia (Fig. 2). Most of the forests of the region have biomass carbon densities that range from 100 to 200 Mg ha^{-1}. Forests with low biomass carbon densities (< 100 Mg ha^{-1}) are generally located in India and Thailand, while forests with high biomass carbon densities (>250 Mg ha^{-1}) are located in the countries on the island of Borneo and Irian Jaya.

Carbon densities of soils range mostly from 60 to 160 Mg ha^{-1} (Fig. 3). In general, the soils of continental Asia have higher carbon densities (120-160 Mg ha^{-1}) than those in insular Asia (100-120 Mg ha^{-1}), with the exception of patches of peat soils (675 Mg ha^{-1}). Furthermore, for most of the forested areas, the soil carbon densities are similar in value to the biomass carbon densities.

Biomass and Soil Carbon Densities

By Ecofloristic Zone

Potential and actual biomass carbon density. The average biomass carbon density by ecofloristic zones ranges from 168 to 319 Mg C ha^{-1} for the total potential and from 57 to 191 Mg C ha^{-1} for the total actual (Table 2). The total potential biomass carbon density for a given ecofloristic zone is about 1.5 times higher in insular than in continental Asia, a trend caused by the generally more favorable environmental conditions in the insular region. The coefficients of variation for the potential biomass carbon density (CV, Table 2), indicate that the variability in carbon densities is less in lowland than in montane zones, less in the insular than in the continental region, and decreases from dry and/or seasonal to moist zones within the same elevation belt. The zones with the low CVs suggest that they are relatively environmentally homogeneous. On the other hand, lowland dry and montane seasonal ecofloristic zones are relatively more variable environmentally, and thus contain forests that are more variable with respect to biomass carbon density.

Below-ground biomass carbon density accounts for 14% of the total biomass carbon density under potential and actual conditions (Table 2). However, proportionally more of the potential and actual biomass carbon density is below-ground in insular Asia (15% of the total) than in continental (12-13% of the total), caused by the dominance of moist forests (root:shoot ratio of 0.18) in the former versus dominance of seasonal forests (root:shoot ratio of 0.10) in the latter area. Even though forests in the dry zone have a high root:shoot ratio (0.5), they contribute very little to the regional totals because the percent of the total continental forest area in this ecofloristic zone in 1980 was small (about 5%) and nonexistent in the insular area.

Actual biomass carbon density of existing forests in the insular and continental areas is reduced to about 60% and 53%, respectively, of their potential amount (Table 2), caused by the human activities described earlier. Coefficients of variation for actual biomass carbon densities are higher than for potential densities, reflecting the uneven impact of humans on the forested landscape. The differences in the way humans impact the forests in the region is further illustrated by the differences in the degree of forest degradation that exists among ecofloristic zones between the two areas. In the continental area, lowland dry forests are the most degraded (degradation ratio of 0.30 and CV of 61%), whereas in insular Asia, where the lowland dry zone is missing, the lowland seasonal forests are the most degraded (degradation ratio of 0.38 and CV of

46%). This trend has been observed in other tropical forest zones, where the drier zones tend to be preferentially inhabited by humans and are often the first to become degraded and cleared (Tosi and Voertman 1964).

Existing forests in montane moist and seasonal zones of continental Asia are less degraded than their lowland counterparts with degradation ratios of 0.54-0.65 and 0.52-0.54, respectively. In insular Asia, however, the lowland and montane moist forests are degraded by the same amount (60%) and less than or almost equal to the same zones in the continental area. The overall lower degradation of lowland moist forests in insular than in continental Asia is most likely caused by two factors: the population density in insular is less than in continental Asia (82 person km^{-2} versus 187 person km^{-2}), and lowland insular forests have higher potential biomass carbon densities than continental forests (Table2).

Actual soil carbon densities. Soil carbon densities range from 114 to 187 Mg ha^{-1} (Table 2). Coefficients of variation in soil carbon densities are generally small, with the exception of the high values for the lowland moist and seasonal zones in insular Asia. The high CVs found in insular Asia are caused by the presence of peat deposits that have considerably higher soil carbon contents than any other soil class (Table 1).

In general, soil carbon density is higher than or about equal to the actual biomass carbon density in a given ecofloristic zone, except for the montane moist zone of insular Asia (ratios of soil carbon to actual biomass carbon density of 0.63-2.12). This overall correlation is to be expected as the environmental conditions that favor high plant biomass are the same as those that produce high soil carbon. Furthermore, as expected, soil carbon density in moist zones is higher than in seasonal or dry zones (Post *et al.* 1982), and a tendency to be higher in montane zones than in lowland zones of the continent. The exception is the montane moist zone of insular Asia which has the lowest soil

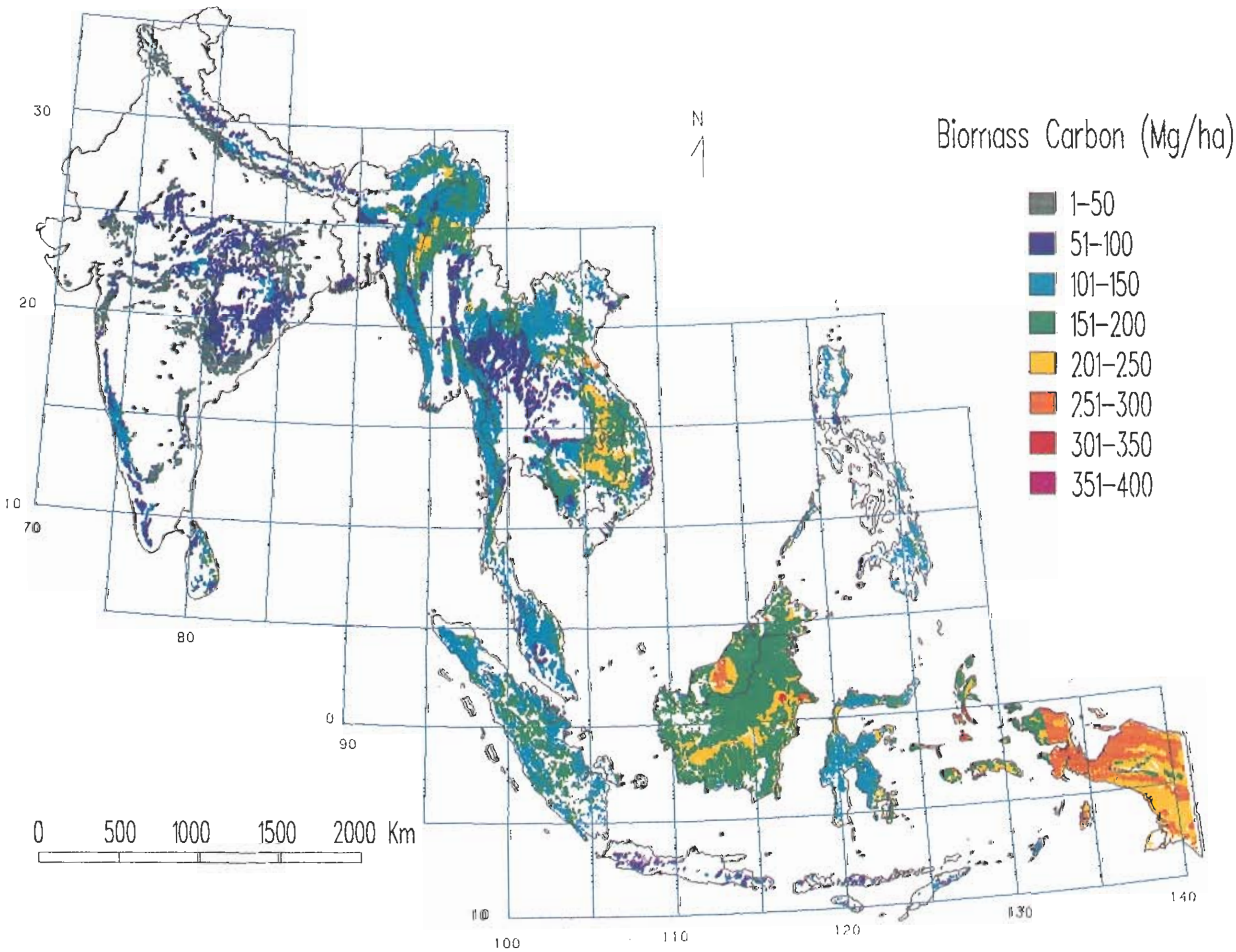

Figure 2 Spatial distribution of biomass carbon density, above- and below-ground in 50 Mg ha^{-1} classes, for forests of tropical Asia in 1980.

carbon density of all, a value that corresponds to the mean carbon content for fine textured soils in this ecofloristic zone (cf. Table 1).

The higher soil carbon density of the lowland moist zone in insular compared to continental Asia is caused by the relatively large areas of peat forests in the former area which have very high soil carbon densities (cf. Table 1 and Fig. 2). The difference between the lowland seasonal zone of the continental versus insular areas reflects differences in the common texture class; soils in this zone in insular Asia are dominated by fine textured soils whereas those in continental Asia are dominated by coarse to medium-coarse soils.

As we assumed no reduction of soil carbon density caused by forest degradation, the soil carbon contents in Table 2 could be lower, particularly in those zones where biomass carbon density is reduced the most from its potential (e.g., lowland dry in continental and lowland seasonal in insular). From data given in Detwiler (1986) for shifting cultivation forests, we estimated that the reduction could amount to about 5 to 10% of the mean soil carbon density in these two ecofloristic zones. But as the forests in these two zones occupy a small proportion of the total area, the effect of our assumption on the total soil carbon pools is very small (<0.5%).

Total carbon density of vegetation and soil in 1980. When the soil carbon density is included, the variation in the total carbon density (vegetation plus soil) among ecofloristic zones is reduced, ranging from 178 to 378 Mg ha^{-1}. The difference between the minimum and maximum biomass carbon density by EFZ for the whole region is more than a three-fold factor, but the difference between the minimum and maximum total carbon density is about two-fold (Table 2). The area-weighted mean total carbon density in forests of insular Asia (368 Mg ha^{-1}) is more than 1.5 times higher than that in forests of continental Asia (239 Mg ha^{-1}).

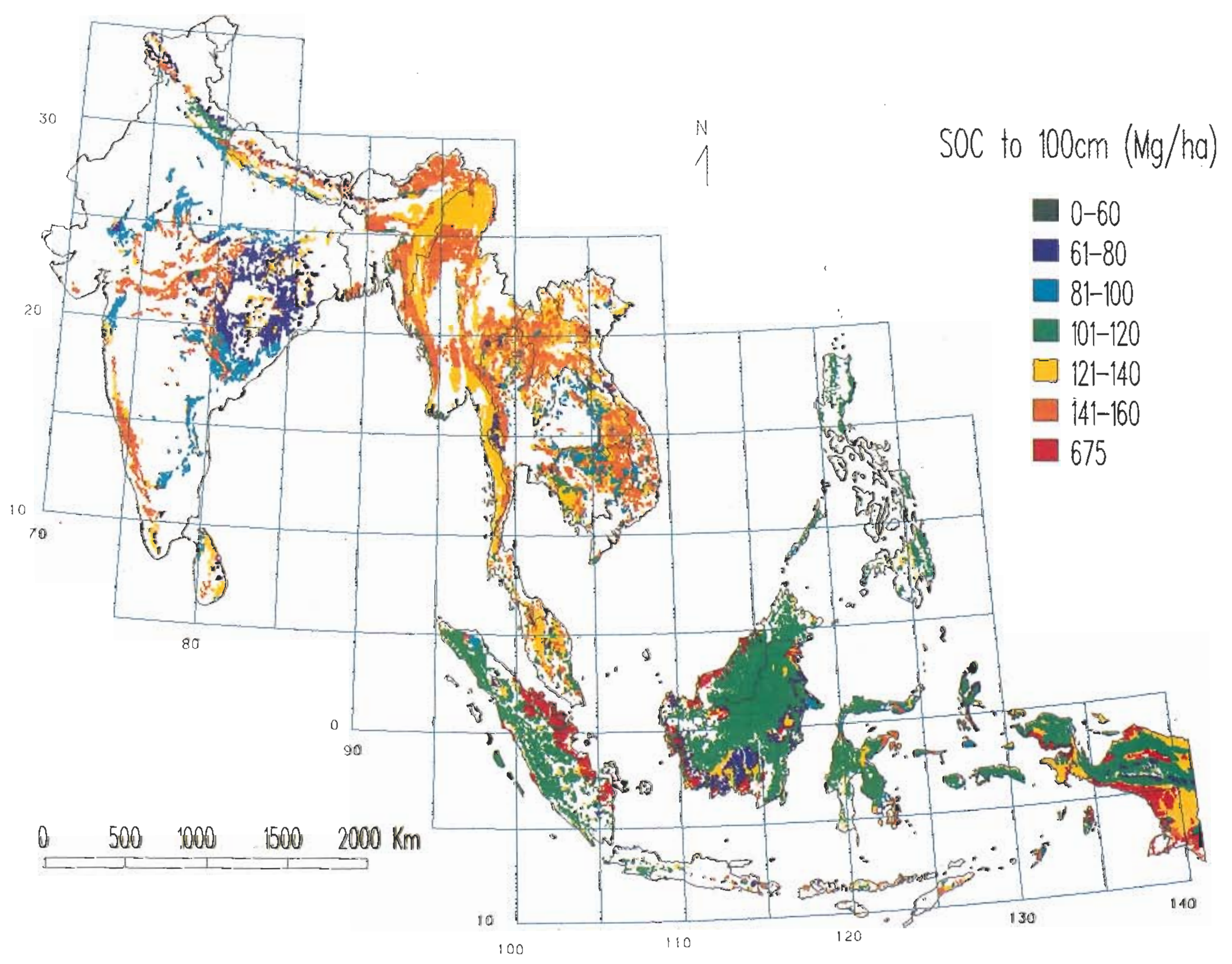

Figure 3 Spatial distribution of soil carbon density (SOC) to 100 cm depth in 20 Mg ha^{-1} classes for forests of tropical Asia in 1980.

By Country

Potential and actual biomass carbon density. Potential biomass carbon density averages 255 Mg ha^{-1} for all of tropical Asia, and ranges from a low of 188 Mg ha^{-1} in Nepal to a high of about 340 Mg ha^{-1} in Brunei (Table 3), reflecting the differential spread of environmental factors. The corresponding CVs by country tend to be low (4-25%) with India being the most variable as expected for this large country with a wide range of environmental conditions.

Highest potential carbon density values are in those countries which contain forests dominated by species of dipterocarp: Brunei, Indonesia, Malaysia (Peninsular, Sabah and Sarawak), and the Philippines (Whitmore 1984) and whose climate is dominated by moist conditions. Countries with low biomass carbon densities, e.g., India, Laos, Nepal, and Thailand, are dominated by seasonal to dry climates.

Countries where the biomass carbon density of forests is reduced the most from their potential by human activities are Bangladesh, India, Nepal, and Peninsular Malaysia (a degradation ratio of about 0.38-0.41). The degradation ratios for the first three countries are caused by the high population densities (132-629 persons km^{-2}) within and around the relatively few remaining forests (cf. Fig. 1) and their forests have low biomass carbon densities (77-101 Mg ha^{-1}; Table 3). Although the carbon density of forests in Peninsular Malaysia is considerably lower than its potential because of a high population density (205 persons km^{-2}, the fourth most densely populated country of the whole region), compared to the other three countries the forests still contain a considerable quantity of biomass carbon (125 Mg ha^{-1}). The above-ground value for Peninsular Malaysia is well within the 95% confidence interval of the average carbon density based on a nation-wide forest inventory in 1980 (Brown *et al.* 1994). Most of the reduction in forest biomass in this country is caused by extensive logging and log poaching.

Countries whose forests are the least degraded from their potential are Brunei, Cambodia, Indonesia, Laos, Myanmar, Sabah/Sarawak, and Vietnam (degradation ratios of 0.6-0.8). The carbon density of the forests of the remaining countries is 50% or less of their potential. The different rankings of actual compared to the potential biomass carbon density by country can be attributed to differences in the distribution of human populations and potential biomass carbon density.

Two other estimates of actual biomass densities of forests have recently been made for the countries in tropical Asia. The first one is part of the Tropical Forest Resource Assessment 1990 Project of the Food and Agriculture Organization. Their estimates of above-ground biomass carbon density (we converted their biomass estimates to carbon units) for the same countries that we include range from about 47 to 148 Mg ha^{-1} for 1990 (K.D. Singh, 1993, FAO, pers. comm.) comared to our range of 66 to 169 Mg ha^{-1} for 1980. The FAO estimates were obtained by converting average forest volumes obtained from partial-country forest inventories to biomass units and extrapolating to the whole country. On average the FAO values are about 75% of ours. The lower values obtained by FAO could

Table 3 Estimates of mean biomass carbon and soil carbon density, to 100 cm depth, (Mg C ha^{-1}) potentially (PCD-80) and actually (ACD) in forests of tropical Asia by country, for 1980. Coefficients of variation (CV, in %) are given for total potential and actual biomass carbon and soil carbon densities.

	PCD-80				ACD						Total
Country	Above	Below	Total	CV	Above	Below	Total	CV	Soil	CV	1980
Bangladesh	232	35	267	16	87	14	101	32	143	8	244
Brunei	289	52	341	6	160	29	189	8	305	88	494
Cambodia	209	24	233	13	153	17	170	24	129	15	299
India	173	28	201	28	66	11	77	58	115	29	192
Indonesia	266	49	315	11	162	28	190	24	183	101	373
Laos	171	23	194	17	137	19	156	24	136	10	292
Malaysia:											
Peninsular	258	47	305	10	106	19	125	20	127	12	252
Sabah/Sarawak	285	52	337	4	169	31	200	13	162	100	362
Myanmar	193	30	223	23	120	18	138	25	136	6	274
Nepal	167	21	188	21	70	8	78	47	125	20	203
Philippines	255	46	301	12	110	19	129	16	112	6	241
Sri Lanka	206	24	230	18	102	12	114	34	124	20	238
Thailand	177	23	200	23	94	12	106	31	128	16	234
Vietnam	186	26	212	15	132	19	151	23	134	14	285
Wtd mean	219	36	255		124	20	144		148		292

partially be explained by continued degradation of the forests by the increasing population in the intervening period as well as by differences in methods.

A study by Flint and Richards (1994) produced weighted estimates of total biomass carbon density for forests and woodlands for 1980 of 74 Mg ha^{-1} for continental countries and 124 Mg ha^{-1} for insular countries. These are both 65% of our corresponding values, and about 80-90% of FAO's corresponding values, after subtracting below-ground biomass. Flint and Richards' estimates are based on compiling data from the forestry literature for the regions and applying degradation factors based on human populations, similar to but not the same as our approach.

Although differences exist among ours and the other two estimates, the three sets of values are similar in magnitude to each other. Differences in methodology, sources of input data, and time of the assessment are most likely the causes for the differences. Despite these differences in approach, the general similarity of estimates provides compelling evidence that the forests of the tropical Asian countries have generally low biomass carbon densities.

Actual soil carbon densities. Countries with the highest soil carbon densities (162-305 Mg ha^{-1}) are those with proportionally large areas of peat swamps, e.g., Brunei, Indonesia, and Sabah/Sarawak (Fig. 3). Soil carbon densities vary little among the other countries (115-143 Mg ha^{-1}). As a result, the differences in the total carbon density (soil plus vegetation) among countries is reduced to a two-fold factor between the minimum and maximum value, excluding Brunei which has the highest soil and a high biomass carbon density.

Total Carbon Pools

The distribution of total carbon by ecofloristic zone is shown in Figure 4. The total carbon pool is concentrated in only one to two ecofloristic zones in each region. For continental Asia, most of the total carbon in soil, potential biomass, and actual biomass (about 80% for each) is concentrated in the lowland seasonal and moist forests (Fig. 4a). This distribution is caused mainly by (1) the large area of seasonal forests in the continental region (54% of the total forest area) and (2) the high carbon densities along with the relatively large area of lowland moist forests (25% of the total forest area). For the lowland seasonal zone in 1980, the carbon in soils represents a slightly larger proportion of the total carbon pool (54%) than the carbon in biomass (46%). In the lowland moist zone, the carbon is about equally divided between soil and biomass. With respect to the total potential carbon pool (soil plus potential biomass carbon), soil accounts for only 39% and 33% of the total in the lowland seasonal and moist zones, respectively.

The third most important ecofloristic zone in continental Asia, the montane moist, accounts for only 14% of the total soil and potential and actual biomass carbon (Fig. 4a). Once again, the total carbon pool in this zone in 1980 is divided equally between the soil and biomass. Forests in lowland dry and montane seasonal zones contribute very little to the total pool.

Insular Asia is dominated by the lowland moist zone, which accounts for 86% of the total area and 89 to 92% of the total carbon pool in biomass and soil (Fig. 4b). The remaining area and carbon is located in the montane moist zone; other lowland and montane zones are practically non-existent. The carbon pool in the lowland moist zone in 1980 is divided equally between biomass and soil. However, with no forest biomass degradation (potential biomass), the soil carbon pool would comprise 37% of the total pool, a lower proportion than the actual. In the montane moist zone, more of the carbon is located in the actual (61%) and potential (72%) biomass than in the soil.

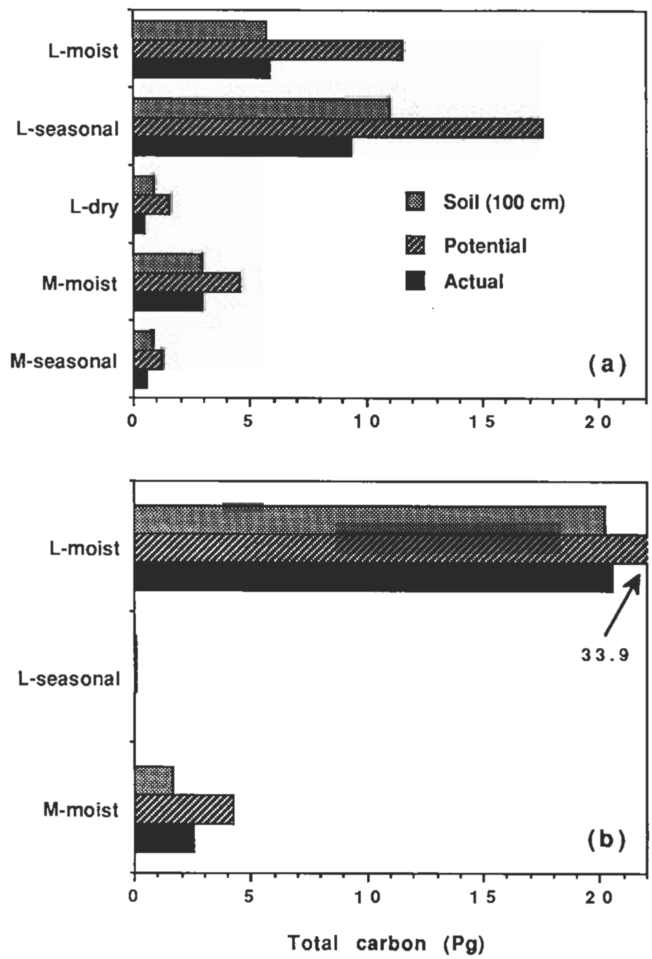

Figure 4 Total carbon content in soils and and potential and actual forest vegetation for (a) continental and (b) insular Asia by ecofloristic zones for 1980. L = lowland and M = montane.

Although it is often stated that tropical soils contain low amounts of soil carbon (or organic matter), our results clearly show that it is of equal importance to the total 1980 carbon pool as the forest biomass (Fig. 4). In fact, the soil carbon content generally exceeded that in the vegetation in zones where precipitation was low or seasonal in nature (Table 2 and Fig. 4a). Compared to the potential carbon pool however, soil carbon is of lesser importance.

Three countries of tropical Asia (Indonesia, India, and Myanmar) account for about 71 to 75% of the total carbon pool in potential biomass (a total of 53 Pg), actual biomass (a total of 30 Pg) and soil (a total of 32 Pg) (Fig. 5). However, there are differences in the allocation of the carbon between actual biomass, potential biomass, and soil among these three countries. In Indonesia, the country with by far the largest amount of total carbon in 1980 (40 Pg), and Myanmar, soil carbon accounts for 50% of the actual total and 39% of the potential total. For the drier country of India, 60% of the 1980 total and 36% of the potential total is in soil.

The next most important countries to the regional total are Cambodia, Laos, Sabah/Sarawak, and Thailand, which together account for 19-24% of the total soil and potential and actual biomass carbon. In these countries, the contribution of soil to the total actual pool is generally less than the biomass, except for Thailand (Fig. 5). The remaining seven countries compose about 7% of the total pools.

Total Region

The region as a whole has a carbon pool of 43 Pg in soil, 74 Pg in potential biomass, and 42 Pg in actual biomass of forests (Fig. 6). The distribution is split remarkably even between continental and insular Asia. Even though continental Asia contains 58% of the the total forest cover in 1980, these forests contain somewhat less than their actual and potential share of the carbon. Continental Asian countries account for 50% of the soil pool, 49% of the potential biomass pool, and 45% of the actual biomass pool. This distribution of carbon is, of course, caused by the geographic variations in climatic regimes and soil texture classes, which influence the biomass and soil carbon densities, as well as the distribution of human populations.

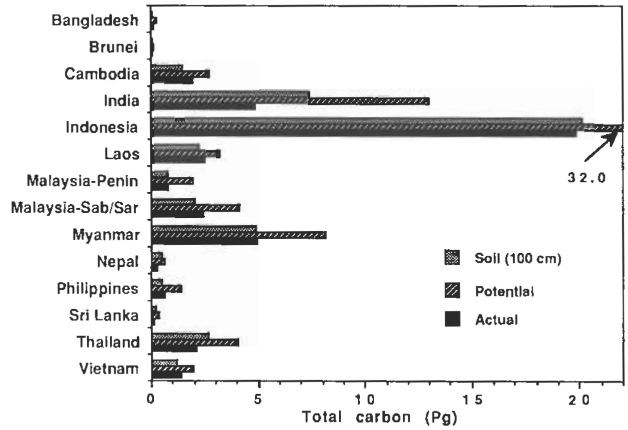

Figure 5 Total carbon content in soils and potential and actual forest vegetation for continental and insular Asian countries for 1980. Malaysia-Penin = Peninsular Malaysia, and Malaysia-Sab/Sar = Sabah and Sarawak, the western states of Malaysia.

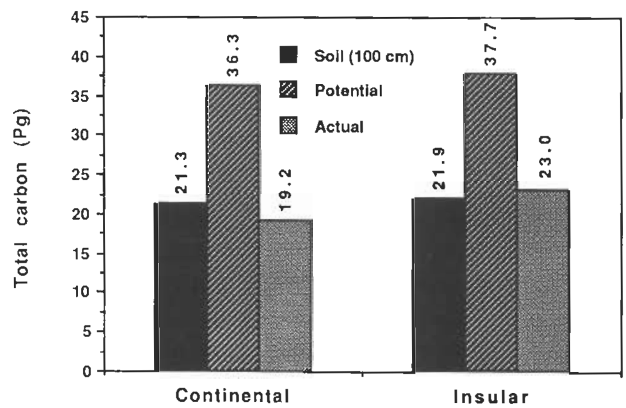

Figure 6 Total carbon content in soils and potential and actual forest vegetation of the continental and insular Asian forests for 1980.

Sources of Error

In this paper we have presented estimates of the amount and distribution of carbon in vegetation and soils for the forest area in tropical Asia. These estimates are subject to error owing to both methodology and data limitations. As new data (quality and resolution) become available, we can build on our approach to reduce further the uncertainties and to improve the accuracy and precision of our carbon density estimates.

At this stage in the analysis, we recognize that errors originate from several sources. First, there is the inherent error in the spatial data bases caused by inaccuracies in the maps, or maps of insufficient detail (e.g., vegetation and soil maps). We have limited control over these errors, and foresee little improvement in these data bases in the near future because of the large-scale effort needed to revise and update vegetation and soils maps. However, when improved data are developed, we expect that the methodology presented here can be repeated to obtain improved spatially explicit estimates of biomass density.

A second potential source of error is in the production of maps from the interpolation of point data (e.g., precipitation, climate index and population density maps). However, we believe that these errors are minimal because of the two-dimensional interpolation methods that we used that produced results comparable with other ancillary maps and information about the region (Iverson *et al.* 1994).

Third, there is the potential for systematic errors in the modeling of potential biomass carbon density caused by inappropriate weighting schemes for the input variables. However, we scale several of our input variables into varying-width classes before we weight them which we believe minimized this source of error.

There is also the potential that we have overlooked other factors that may be important in regulating potential and actual forest biomass. For example, we did not consider differences between broadleaf and conifer species, distances from roads and other access points, differences among human impacts (e.g., logging versus shifting cultivation), and the effects of natural disturbances. For the tropical Asian region, we believe that most of these other factors are of limited importance at the scale at which we are modeling.

Finally, there is error associated with applying imperfect regression equations across the region. This type of error applies to the degradation index versus population density equations where r-squares were low in some cases. We expect this source of error to be reduced as new forest inventories suitable for estimating biomass density become available.

Although forest biomass and soil carbon are the major contributors to the total carbon densities and carbon pools, we have not included other forest components and processes which influence these totals (e.g., understory and fine and coarse litter). Including these other components could add up to an additional 20-30% of the total biomass carbon density, particularly in dense forests in the moist zones (Brown and Lugo 1992). What effect the common human practice of using these components for fuel and fodder have on their quantities is unknown, but would likely be highly variable depending on the culture, economics, and density of the population. Also, these minor components would be expected to differ by status of the forest, e.g., mature or slightly degraded forests would probably contain more carbon in these components than highly degraded or secondary forests. Futhermore, we did not degrade the soil carbon pool under degraded forests which could reduce the total soil pools, but as discussed above, we expect this error to be small.

Taking all these sources of error into consideration, we believe that the estimates for carbon densities and pools in the forests of tropical Asia presented in this paper are conceptually correct and the best available in map form at this time.

Implications for the Global Carbon Cycle

The most obvious value of our results to the global carbon cycle is that carbon densities are represented spatially and thus can be "matched" to spatial representations of land-use change determined from satellite imagery. Progress in developing better data bases on changes in forest cover is being made as more countries are being analyzed with high resolution satellite imagery (Skole and Tucker 1993, J. Townshend, University of Maryland, 1992, pers. comm.). Improved land-use change data with our spatial estimates of carbon densities will definitely reduce the uncertainties associated with flux from the tropics as has been shown for Latin America (Houghton *et al.* 1991).

Our research also shows that in addition to outright forest clearing, there is another mechanism that reduces the carbon content of forests, namely biomass degradation. Most forests being cleared are not mature or primary as is often assumed, but they generally have considerably lower carbon densities than the values that have been used in terrestrial carbon models (e.g., Houghton *et al.* 1987). The impact of forest biomass degradation on carbon flux estimates from the tropics depends on whether the biomass removed is burned as fuel or is going into long-term storages as wood products. As most of the activities that cause forest degradation are illicit, it will be difficult to resolve this issue.

Another important implication of our results for the global carbon cycle is in the area of carbon mitigation. As stated above, it is generally assumed that tropical forests are mature and thus in steady state with respect to carbon accumulation (Lugo and Brown 1992). When mitigation options through forest management are sought, attention is usually given to the notion of establishing plantations on degraded lands (Grainger 1990). Establishing sufficient areas of plantations to significantly reduce atmospheric carbon dioxide would entail planting vast areas, which would probably not be feasible at this time (Grainger 1990). However, because we have shown that many forests in tropical Asia are far from their maximum carbon stock, protection of these forests could sequester significant quantities of carbon by natural regeneration and regrowth (Iverson *et al.* 1994). How feasible this forest management option will be in the future depends on the global willingness and commitment to reduce fluxes and levels of atmospheric carbon dioxide.

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