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3. Use of GIS for Estimating Potential and Actual Forest Biomass for Continental South and Southeast Asia

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Abstract

A geographic information system (GIS) was used to estimate total biomass and biomass density of the tropical forests in South and Southeast Asia because available data from forest inventories were insufficient to extrapolate biomass-density estimates across the region. Initially, we modeled the biomass density that would be expected if no humans or natural disturbances were present. This value was derived from GIS data layers on elevation, soils, slope, precipitation, and an integrated climate index. Total forest biomass for nine countries was estimated to be 176 Pg (1 Pg = 10^{15} g), or an average potential biomass density (PBD) of 322 Mg/ha.

The potential forest biomass map was then masked with a map of forest locations for 1980, resulting in a map of the potential biomass density occurring on locations still in forest in 1980. The total potential biomass estimate for these locations was 63 Pg, representing a loss of 64% of the potential biomass, attributed to land conversion. Average potential biomass density of the forests, on the other hand, increased to 370 Mg/ha, indicating that much of the land converted before 1980 came from lower-biomass-density forests.

Finally, the influence of population density was factored into the estimate of PBD. The resulting estimate of total actual forest biomass in 1980 was 33 Pg, which represents a reduction of 52% of the potential biomass of the 1980 forested areas and 19% of the potential biomass across the entire subcontinent. The actual biomass density (ABD) for the South and Southeast Asian tropical forests of 1980 was estimated to be 194 Mg/ha, or 52% of the predicted biomass density of forests in the absence of human activity or other disturbances.

The method described appears to be capable of estimating biomass and biomass change across the tropics. The results highlight the importance of considering the degradation of intact forests as well as the outright conversion of forests to other uses when assessing the inputs of carbon to the atmosphere from tropical land-use change.

Introduction

A main source of uncertainty in models that are used for estimating carbon fluxes caused by tropical land-use change is the biomass density (biomass per unit area) of the forests undergoing change (Brown et al. 1991; Dale et al. 1991). The biomass density of forests being cleared and burned influences the potential amount of carbon that can enter the atmosphere. The principal reasons for the uncertainty are that many models have generally relied on regional averages of biomass density for a few forest types [e.g., closed and open or moist and seasonal forests (Houghton et al. 1987)] and that the data base on forest biomass density used for estimating these regional averages is poor. Recently, some uncertainty associated with modeling carbon fluxes has been reduced by adding country-specific biomass-density estimates for two forest groups to the models (Hall and Uhlig 1991). However, this level of geographic detail is still too coarse because within most tropical countries, particularly large ones, forest biomass density is still very variable (Brown et al. 1991; Brown et al., this volume).

Problems of Estimating Tropical-Forest Biomass Density

Biomass density of tropical forests varies considerably over the tropical landscape because of climatic, edaphic, and topographic differences; it also varies with the history of land use and human and natural disturbance. This variation cannot be encapsulated into regional or countrywide averages for use in models of tropical land-use change, as has been done in the past, without making some very large assumptions. Of obvious importance to the global carbon cycle is the biomass density of the forests being cleared.

Estimates from Ecological Studies

Many past estimates of tropical-forest biomass density have relied on results from ecological studies (Brown and Lugo 1982; Houghton et al. 1983). These ecological studies are used to characterize local forest structure and are appropriate for studying forests at a local scale. Because the selection of study sites is not random, these studies should not be used to make inferences about larger populations (Brown and Lugo 1992). Brown and Lugo (1984, 1992) and Brown et al. (1989) have shown that direct biomass determinations of a few small plots usually yield high biomass-density estimates because the plots are not randomly located and the number and size of the plots are small.

Another problem with using data from small, nonrandomly selected plots is the role of large-diameter trees. Brown and Lugo (1992) suggest that ecologists tend to adjust the placement of study plots in tropical forests to include large trees. Such sampling biases also occur in studies of old-growth forests in the midwestern United States (McCune and Menges 1986). The effect of adjusting plot placement to include large-diameter trees is to overestimate forest biomass density because biomass per tree increases geometrically with increasing diameter.

Estimates from Forest Inventories

To overcome the problems of using ecological studies, reliable methods have been developed for converting data in forest-inventory stand and stock tables (number of trees or volume per hectare by diameter classes) into estimates of biomass density (Brown et al. 1989; Gillespie et al. 1992). Data from forest inventories are generally more abundant and are collected from large sample areas (subnational to national levels) with a planned sampling method designed to represent the population of interest. However, this approach is not without its problems. 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 density. Typical problems include

- The minimum diameter of trees included in the inventory is often greater than 30 cm and sometimes is as large as 50 cm; this excludes smaller trees that can account for more than 30% of the biomass density (Gillespie et al. 1992).
- The maximum diameter class in stand tables is open-ended, with trees greater than 80 to 90 cm in diameter lumped into one class. The actual diameter distribution of these large trees significantly affects biomass density (Brown and Lugo 1992).
- Not all species of trees are included.
- Reports resulting from the inventories often leave out critical data, and the detailed field measurements are not archived and are lost.
- Many of the inventories are old (1960s or earlier), and the forests probably no longer exist or presently are in a very different condition.
- Very little descriptive information is given as to the actual condition of the forests; they are often described as primary, but diameter distributions and volume data suggest otherwise (Brown et al. 1991).

- Accurate spatial coordinates of the inventoried areas are often not given, and specific locations for individual plots are rarely available.

Although some of these problems can be overcome (Brown et al. 1989; Gillespie et al. 1992), the total forest area covered by such inventories is low. For instance, inventories completed by the early 1980s suitable for estimating biomass density in tropical Asia covered only about 9% of the total forest area. This areal coverage is insufficient to make generalizations across the entire, highly heterogeneous region. Furthermore, forests covered by these inventories had highly variable biomass-density estimates that ranged from <50 Mg/ha to >500 Mg/ha. To reduce uncertainties in biomass-density estimation and to improve the accuracy and precision of carbon-flux estimates from tropical land-use change, we need to improve our estimates in the noninventoried locations.

Human Impact on Tropical Asian Forests

The forests of most of tropical Asia have been subject to human disturbance for thousands of years, and great civilizations have come and gone (Whitmore 1984; Collins 1990). The disturbance of these forests has been so widespread that it is doubtful whether any virgin forest still exists except for small, protected areas, such as "sacred groves" (for more details on this topic see Richards and Flint, this volume). Furthermore, it is highly probable that the biomass density of most current forests is less than it would be in the absence of human or natural disturbances.

In the earliest period, humans lived in the forests as nomads and used the forests for hunting and gathering of food plants with no clearing for cultivation (Whitmore 1984). Later, great civilizations left their mark on the landscape. For example, the vast temples and irrigation systems built by the Khmer in Cambodia are now covered by the regrowing forest. In the dry zone of Sri Lanka, a complex network of irrigation reservoirs and canals is all that remains of a complex civilization whose population density at its height (between 300 BC and AD 1200) was greater than that in the 1960s (Rosayro 1962). Forests were certainly impacted during this period as they were cleared for cultivation of food crops to support the populations of these complex civilizations.

After Europeans arrived in tropical Asia, the pace of forest conversion and degradation accelerated as cash-crop agriculture and plantations of spices, tea, coffee, rubber, oil palm, etc. were introduced (Whitmore 1984; Brown et al., this volume; Richards and Flint, this volume). Most clearing and degradation occurred first in the lowland forests, then moved to higher elevations as demand for land increased. Continued increases in population and the conversion to cash crops of lands previously used for subsistence agriculture have increased the human impact on the remaining forests.

Forest exploitation for timber has a long history in the region (Collins 1990; Collins et al. 1991). However, the impact of logging was light until the end of World War II because few trees were cut and logs were extracted with elephants. Since then, mechanization has been introduced, and extraction has occurred over larger areas and at a greater intensity (Whitmore 1984). Many species of tropical Asian forests (e.g., teak and numerous species of dipterocarps) are highly valued in the tropical hardwood trade. Planned and unplanned (or illicit, cf. Brown et al. 1991) exploitation of tropical forests for timber clearly has the potential to significantly reduce their biomass density. It is usually the large-diameter trees, which account for a significant fraction of the biomass density (Brown et al., this volume), that are removed, and it can take centuries for replacement trees to reach these dimensions.

As a result of human activities, various secondary forests are present. Some are in young stages of low biomass density, whereas others have developed into late secondary forests with significantly higher biomass density. Repeated disturbance and over-exploitation have resulted in the conversion of forest lands to grasslands, scrub formation, and even badly degraded lands with little or no plant cover.

Purpose of This Study

A geographically referenced biomass-density database for the whole tropics would reduce uncertainties in carbon-flux estimates caused by biomass changes. Used in conjunction with a spatial representation of land-use change, it would allow the use of the appropriate biomass density with the corresponding rate of land-use change. The use of geographic-information-system (GIS) technology, along with modeling, offers an approach for developing such a biomass-density map. Unlike land-use change, biomass density cannot be determined by current remote-sensing technology even though attempts have been made to do this (Nelson et al. 1988; Sader 1988).

This study uses GIS to produce maps of forest biomass density for two points in time in the absence of human intervention or natural disturbance (potential biomass density, PBD) and with the inclusion of human influence up to the early 1980s (actual biomass density, ABD). Our hypothesis is that the current distribution of forest biomass density is 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, and degradation. Our approach, therefore, was to first generate a PBD map from a model of the biophysical parameters that most influence biomass density. Then with relatively recent forest inventories, recent vegetation maps, and population density data, the PDB map was "deforested" and "degraded," resulting in an ABD map.

This chapter describes in detail the procedures and assumptions used in obtaining our results. Because the GIS allows the incorporation of spatial heterogeneity into the process, we believe these procedures offer the best potential for estimating biomass density at continental scales. Judgements about how to use the data are made at many steps, and the GIS procedures offer a framework for uniformly making and recording these assumptions. We therefore include the detailed account so the reader can recognize and understand the numerous uncertainties and difficulties encountered in our analysis. As data and techniques improve, we can recreate and build on the effort established here to reduce the uncertainties and to improve the estimates of biomass density.

Methods

Study Area

Our area of interest consists of the continental portion of tropical South and Southeast Asia (Fig. 1). Most of Nepal is not tropical but was included because it is generally considered to be part of this region for other international reporting. Bounded by 0 and 36N latitude and 65 and 110E longitude, all or portions of the following countries were included: Bangladesh, Cambodia (Kampuchea), India, Laos, Myanmar (Burma), Nepal, Peninsular Malaysia, Sri Lanka, Thailand, and Vietnam. Insufficient information was available for Bhutan. General descriptions of the physical and biological features of the Southeast Asia region, especially with respect to their tropical forests, can be found in Whitmore (1984), for the Indian subcontinent in Champion and Seth (1968), and for the entire region in Collins et al. (1991).

The continental South and Southeast Asia region has diverse vegetation formations, ranging from the deserts of northwest India to the species-rich lowland forests of Peninsular Malaysia. At a regional scale, the total rainfall amount and its seasonality are the main factors influencing the spatial variation in vegetation biomass. The edaphic factor determines the spatial variation in biomass at a local scale (e.g., well drained sandy soils vs poorly drained clay soils). In the mountainous regions, elevation (which influences temperature) is an additional factor.

In the forested regions of South and Southeast Asia, the nonseasonal ever-moist regions have evergreen forests; with increasing climatic seasonality, the tendency towards deciduousness increases. As a result, evergreen, semi-evergreen, moist-deciduous, dry-deciduous, and open forests can be distinguished. In the Himalayan region, some coniferous forests exist, and the biophysical parameters regulating those forests may be different from those at work in the tropical broadleaf forests. In this paper, we do not address this issue directly and assume that all forests respond similarly to the biophysical factors that regulate biomass.

The occurrence of large-scale natural disturbances are not widespread in the region of study. Tropical cyclones or typhoons occur frequently in Bangladesh and parts of India and Myanmar (Burma) adjacent to the Bay of Bengal. To what degree the inland forests are affected by these events is poorly known.

Databases

The major effort for this project involved the acquisition, coregistration, and preprocessing of suitable digital data sets for the study area. Most of the following databases for this project were acquired from the United Nations Environment Programme's (UNEP) Global Resources Information Database (GRID) (Jaakkola 1990) or from various departments of the United Nation's Food and Agriculture Organization (FAO) in Rome.

We, in turn, initially processed the data to be compatible with our ARC/INFO-ERDAS (Environmental System Research, Inc., Redlands, Calif.; Earth Resources Data Analysis, Inc., Atlanta, Ga.) system as well as to be geometrically com-

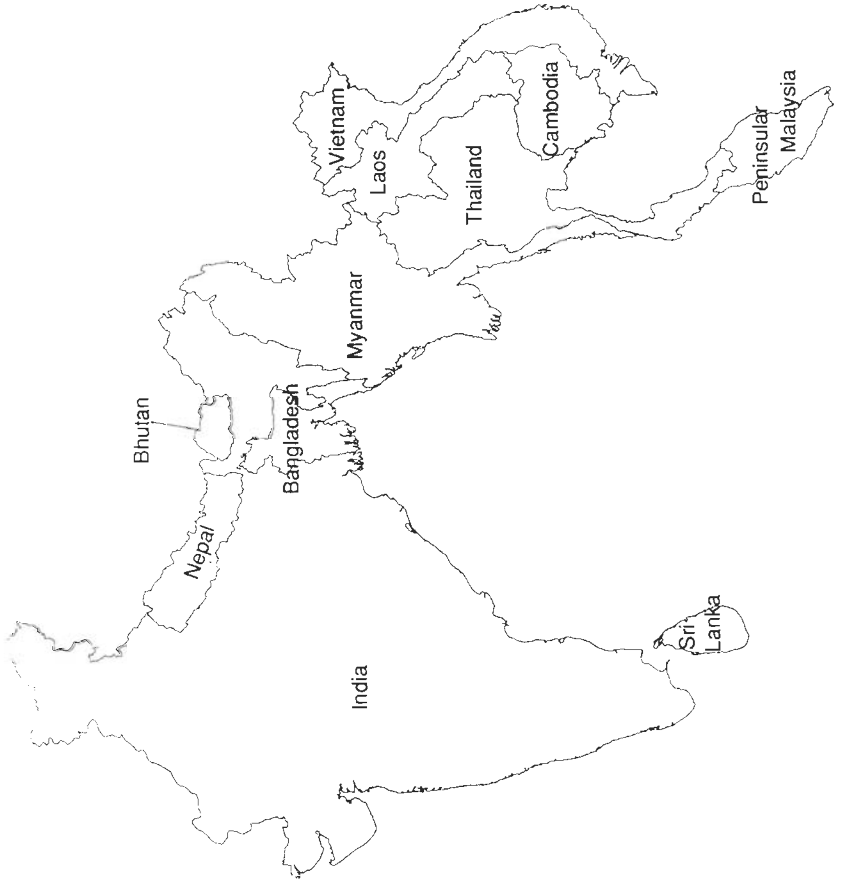

Figure 1. Map of the Study Area, Continental South and Southeast Asia. Forests in each of the noted countries were evaluated through our methods.

patible in geographic (latitude-longitude) and Albers conical-equal-area coordinates (meters).[1]

National Boundaries

Data delimiting national boundaries for the region were extracted from the World Boundary Database-II (WBDII, obtained from UNEP/GRID in Geneva). This set of vector files contains coastlines and national boundaries, which were combined into the national boundary coverage. WBDII used map scales of 1:1 million to 1:4 million; nominally, a scale of 1:3 million was used to achieve the amount of detail shown in the files.

Topography/Elevation

These data originated from the United States National Geophysical Data Center and were obtained from UNEP/GRID. The data set has a latitude/longitude resolution of 5 min and contains bathymetry as well so that the range of elevation is from about -10,000 to + 8,000 m, with a 1-m contour interval. The ocean bathymetric data were calculated to 0, and the positive elevation values were recoded to increments of 15 m. Inadequate spatial resolution of the data set precludes analysis of local terrain, but general surface tendencies and absolute elevation can be confidently evaluated.

Soils

This data set consists of the FAO soils map of the world (Food and Agriculture Organization 1974). The original soil maps were published between 1974 and 1978 at the 1:5 million scale. The data were originally digitized by ESRI, Inc., in Redlands, Calif., in Miller stereographic projection for South and Southeast Asia but were reprojected to geographic latitude/longitude by the FAO. The FAO also checked the quality of the digital data and updated the files as well as the soil legend before distribution.

The soil units show the dominant mapping (soil) unit, texture class, slope class, and associated soil units within the polygon. Text volumes accompanying the data discuss each soil type and provide typical profile descriptions so assessments and rankings can be made on soil quality (Food and Agriculture Organization 1974). Caveats in using the data primarily concern their coarse resolution and the general nature of soil maps. No soil map, regardless of scale, has boundary lines that can be considered hard and fixed. They are interpreted maps attempting to make discrete boundaries across multiple gradients.

Worldwide, the FAO classification has 26 main soil units and various combinations of subunits for each soil unit. These classifications are based on diagnostic horizon, parent material, moisture regime, chemical composition, etc. For example, the soil unit ferralsols is subdivided into subunits humic ferralsols, orthic ferralsols, plinthic ferralsols, rhodic ferralsols, and xanthic ferralsols. Each subunit is associated with a slope class and a texture class. For use in our GIS modeling effort, we prepared separate digital maps of soil subunits, texture class, and slope class.

Vegetation

The vegetation map we used was produced between 1981 and 1985 by the FAO in collaboration with the Institute of International Mapping of Vegetation, Toulouse, France (Food and Agriculture Organization 1989). The map was prepared by synthesizing data from different sources that included Landsat imagery; maps; and associated information on bioclimates, floristics, etc. The limits of different forest formations have been drawn by visual interpretation of Landsat imagery. About 450 images at 1:1 million scale were analyzed, covering all the countries of South and Southeast Asia. The maps were later photographically reduced to 1:5 million scale.

The map gives information on the main vegetation and land-use classes as well as their degradation status. In effect, it is a land-use map that reflects conditions from 1972 to 1980. Twenty-six vegetation and land-use classes were distinguished for 12 countries in the region. The vegetation map lends itself to various reclassification schemes that highlight different aspects of vegetation state and land-use types.

Meteorological Stations

Meteorological-station data were acquired from the agro-meteorological database of the FAO. The database reports various climatic parameters, such as mean monthly precipitation, maximum temperature, minimum temperature, temperature, day temperature, night temperature, evapotranspiration, and vapor pressure. Of the 3262 stations for the entire globe, 593 are in South and Southeast Asia. The reliability of the data depends on the station and the number of years of data collection; however, the FAO standards prevent highly unreliable data from being reported. For each station, latitude, longitude, and elevation are also reported, which enables the interpolation of data points to produce digital maps. This data set was used to derive the climatic parameter—a modified Weck's Climatic Index (see below)—and average annual rainfall, both of which were used in our model.

Ecofloristic Zone (EFZ)

A map of ecofloristic zones was developed by the Forestry Department of the FAO, with major contributions by the International Institute of Vegetation Mapping, Toulouse, France (Food and Agriculture Organization 1989; Singh 1990). Aerial photographs, as well as Landsat scenes, were used to produce the EFZ map. Thirty-six EFZs were distinguished for South and Southeast Asia based on floristic, climatic, physiographic, or edaphic factors at a resolution of 1:5 million. The bioclimatic limits were determined by the criteria of rainfall, its regime, the length of dry period, relative humidity, and temperature. The physiographic contours and the soils further defined the bioclimatic limits. The EFZ also defines the dominant or characteristic flora. The EFZ map can, therefore, be used as an approximate potential vegetation map, with the zonal boundaries defining the boundaries of characteristic vegetation. It was used as a cross-checking tool and for summarizing our results.

Population

Raw population data were acquired from the Demographic and Statistics department of the FAO. The reporting unit and reliability varies from country to country; therefore, the spatial resolution of the data also varies. For example, in India the reporting units are small districts, giving a very fine spatial resolution; whereas in Malaysia the reporting units are large states, giving a coarse spatial resolution. The data set reports the area of the administrative unit and the total population and population density for 1960, 1970, and 1980. A projected figure for 1990 is also given. Because most of the rapid population growth in the region has occurred since 1950 (McEvedy and Jones 1978), these data capture most of the dynamic trends.

Because of the problem of variable data resolution, we developed a map that more realistically distributed the population. First, the district or state data were converted to point data centered on the largest city of the respective subnational unit. The latitude and longitude of the largest city or town in the particular state or district was mapped, and then the data were interpolated to produce a map. (See later section on how interpolation was performed.) In this approach, the population density was spatially dispersed, decreasing away from the main town or city. Because we did not have the population reporting unit boundaries of some countries in our boundary database, this approach was necessary, and, we believe, more representative of reality. It should be noted that the interpolation of population density was not constrained by forest preserves, parks, or other forest-conservation or protected areas, nor was it "spread" preferentially along transportation corridors. Obviously, these factors are important, and errors occurred, especially when forested regions were located adjacent to one or more highly populated areas (e.g., the Western Ghats in India). However, constraints were not implemented here because of the complexity of the interpolation and because our scale of resolution was so coarse. The population-density map (as of 1980) was reclassified into 14 classes for use in this study.

Forest Biomass Density

We define forest biomass density as total above-ground biomass density (TAGBD) per hectare of all trees to a minimum diameter of 10 cm, including leaves, twigs, branches, bole, and bark. We do not include the biomass of other living above-ground components because the present database for them is insufficient to make extrapolations to a larger scale and they represent a small fraction of the total biomass density [understory biomass of shrubs, vines, herbs, saplings, etc. is generally <4% of the total (Brown and Lugo 1984, 1992)]. Nor do we include roots in our analysis because their biomass density varies considerably over the forested landscape (10 to >50% of above-ground [Brown and Lugo 1982]), most likely in response to soil type, soil fertility, and moisture regime. We propose to include below-ground biomass in a future generation of our biomass model as more information on this forest component becomes available.

Brown et al. (1989) developed methods for estimating TAGBD from stand and stock tables reported in forest inventories. The method using stand tables involves substituting the midpoint of a diameter class into a biomass regression equation to calculate biomass per tree and then multiplying this biomass by the number of trees per hectare in the class. This procedure is repeated for all classes, and the results are summed to give TAGBD; means and 99% confidence intervals were reported. Biomass density can also be estimated from data on volume per hectare as the product of volume, a biomass expansion factor, and wood density (Brown et al. 1989).

The major database used in this analysis is described in Brown et al. (1991). Data for the following countries were used in this analysis: Bangladesh, Peninsular Malaysia, Sri Lanka, Thailand, and Vietnam. These inventories were done at different times, spanning the period from the early 1960s to the mid-1980s. With the exception of one inventory, the minimum diameter of trees included was 10 cm. For the one exception, Peninsular Malaysia, the minimum diameter was 15 cm. Using the methods outlined in Gillespie et al. (1992), we estimated the number of trees per hectare in the 10- to 15-cm class and estimated biomass density from the stand tables as described above.

We obtained an additional forest-inventory database for more than 50 forest tracts (total forest area of about 631,000 km^2) spread over forest lands present in the late 1960s to early 1970s for most states of India (K. D. Singh, FAO, 1991, personal communication). We selected only those states that were represented by three or more inventories to ensure that the forests present at that time were well represented. This action reduced the database to about 40 inventories representing nine states (Andhra Pradesh, Assam, Bihar, Himachal Pradesh, Madhya Pradesh, Maharashtra, Orissa, Uttar Pradesh, and West Bengal).

Volume per hectare for all trees, including the volume of branches, to 7 cm in diameter, was reported. Biomass density (TAGBD) was estimated from these volumes as described above. New biomass expansion factors were calculated because those given in Brown et al. (1989) were based on the volume of tree boles per hectare for trees with a diameter of 10 cm or more. Using more detailed data for one of the inventories for a central state (Government of India 1972), we estimated biomass expansion factors (total above-ground biomass/volume-based biomass to 7 cm in diameter) of 1.50 for stands with volumes <90 m^3/ha and 1.35 for stands with volumes ≥ 90 m^3/ha. An average wood density of 0.64 Mg/m^3 was used, based on species lists in the same inventory (Government of India 1972) and a summary of wood densities reported in Reyes et al. (1992).

The inventories classified forests by a number of systems, such as their ecological type (e.g., evergreen, mixed deciduous, and swamps), commercial value (e.g., high yield, medium yield, nonproductive, and superior hill forest), or status (logged, disturbed, secondary, etc.). We calculated the biomass density of all these forest classes, and using the areas for each that were given in the reports, calculated an area-weighted mean biomass density for each inventory area.

Data Preparation, Manipulation, and Interpolation

The GIS processing of data was performed with two major software programs, ARC/INFO for the vector data and ERDAS and ARC/INFO's GRID for raster data. Data files were interchangeably converted between (1) ERDAS and ARC/INFO's GRID for raster processing and (2) ARC for vector processing to maximize the utility of each system. Interpolation of point data was performed with programs developed by our group.

Several maps needed additional preprocessing to create meaningful layers that could be incorporated into the model. First, the meteorological station data were converted to a climatological index. Second, the point data produced from meteorological data and from population data were interpolated into thematic maps with a thin-plate spline technique. Third, the vegetation map was modified to create a map depicting forest and nonforest. Finally, the EFZ map was reclassified to make useful categories, akin to life zones, for summarization and testing of results. These four procedures are now described.

Modified Weck's Climatic Index (mWCI)

Weck (1961) developed an empirical formula based on climatic data to assess the potential productivity of forest plots in various regions of West Germany. He later extended this work to the tropics and developed the following empirical relationship for his index (Weck 1970), referred to here as the Weck's Climatic Index (WCI). Unfortunately, he died before having a chance to modify and test the index.

$$WCI = \frac{dT(S)(P_1 + \sqrt{P_2})(G)(H)}{100(Tm)}, \qquad (1)$$

where dT (^{o}C) is the diurnal difference between average maximum temperature and average minimum temperature of the warmest month of the growing season; S (h) is the mean length of daylight during the growing season; P_1 (dm) is the average annual precipitation up to 20 dm; P_2 (dm) is the average annual precipitation exceeding 20 dm; G (months) is the duration of the growing season; H is the annual average relative humidity of the air; and Tm (^{o}C) is the mean annual temperature of the warmest month of the growing season.

The index is based on the following assumptions

1. In tropical areas, respiration is less if night temperature is low (dT).
2. Net production of organic matter is greater if the length of daylight is longer (S).
3. The relationship between the amount of precipitation and the net production of forests is not linear. A continual increase in precipitation above 2000 mm/year will correspond to a successively smaller increase in net production.
4. Net production is directly proportional to the length of the growing season (G). Months within the growing season must be free of frost and have a mean temperature of at least 10^{o}C. A month is considered to be in the growing season if $12P/(T + 10) > 20$, where P is the total monthly precipitation (mm) and T is the average monthly temperature.
5. Net production is linearly related to average humidity of the air (H). Vapor-pressure data were used to derive the average humidity.
6. The effect of precipitation on net production is less if the temperature of the growing season (Tm) increases.

We have assumed that the index can be used as a climatic index for potential biomass density. This assumption is based on the evidence that, in mature tropical forests, the ratio of biomass production per unit area to biomass density (turnover rate) was found to be constant across all life zones or climate types (Brown and Lugo 1982). Moreover, standing biomass is the result of the integration of net production over the time to reach maturity.

When WCI was computed for all the climatic stations of continental South and Southeast Asia, we expanded the scope of the index beyond any previous efforts and uncovered a few problems. The term dT in the formula yielded values for the indices that, in some locations, did not make logical sense in comparison to other maps (e.g., EFZ). For stations that had a relatively low nighttime temperature, the value of dT was high, which raised the index value beyond reasonable levels. For example, Bombay, India, located in a region of potentially relatively lush vegetation, had a WCI of 136 and a mean annual rainfall of 1898 mm while Bangalore, India, located in a drier vegetation zone, had a WCI of 199 with less than half the mean annual rainfall (902 mm). The dT term in the equation was responsible for this incongruency. We believe that in the temperate zone, a greater difference in the dT term can increase production. However, in the tropics a large dT generally means a high maximum temperature, usually associated with moisture deficits and a resulting decrease in productivity caused by moisture stress. After examining additional stations and finding similar problems, we decided to eliminate the term by setting dT = 1 for all stations. This change yielded more-reasonable results at stations where low nighttime temperatures caused the WCI to be excessively high.

The calculation of growing-season length, based on the temporal distribution of rainfall and temperature (see Assumption 4 above), was also modified. Implicit in the function for a growing-season month is the soil-moisture status; that is, when the function is greater than 20, soil moisture was assumed adequate for growth. The modification was made to take into account the lag effect of accumulated soil moisture. We also considered a month with $12P/(T + 10) \leq 20$ to be a growing-season month provided the previous month was a growing-season month and monthly rainfall was above 200 mm. This change assumed the moisture accumulated in the previous month, along with the precipitation of the present month, would be sufficient to sustain the leaf biomass and thus net production. Again, the meteorological station results were examined, and the assumption was found to yield more-realistic values when compared to the EFZ map.

The resulting climatic index, referred to forthwith as the modified Weck's Climatic Index (mWCI), therefore has the following form, with variables the same as in Eq. (1) except that growing-season length (G) was extended:

$$mWCI = \frac{S(P_1 + \sqrt{P_2})(G)(H)}{100(Tm)} \quad (2)$$

Interpolation of Point Data

To obtain a map from point values of mean annual precipitation, mWCI, and population density, we assumed that the spatial distribution of these phenomena is continuous and smooth. Several bivariate interpolation methods fulfill these assumptions (Franke 1982; Hutchinson and Bischof 1983; Hutchinson 1991). Some methods use a smoothing procedure; smoothing was not used in this case because the FAO monthly average meteorological data are already smoothed over many years. However, the data used here posed a special problem because of their strongly heterogeneous spatial distribution with extremely high local gradients. The major problem encountered while interpolating the rainfall data, for example, was in regions with orographic rainfall. The Western Ghats in India, as an example, receive high amounts of rainfall on the windward side but are in a rain-shadow region on the leeward side. Within short map distances, the rainfall decreases, for example, from more than 3000 to 800 mm/year, creating problems with the interpolation (i.e., there is a tendency towards "undershoots" or "overshoots" in these areas). Also, some climatic stations had high rainfall on high-elevation points that were surrounded by relatively flat semiarid plains. To reduce the problem caused by high gradients, two special processes were used. First, the data were preprocessed by converting them to logarithmical transformation. Second, the transformed data were interpolated with a method using a completely regularized spline with tension. With the simple nonlinear transformation of input data together with accurate two-dimensional interpolation methods, we obtained results highly comparable to ancillary maps and other information about the region.

Creation of Forest/Nonforest Maps

The original 26 classes of the FAO vegetation map were reclassified to six classes: closed forest, secondary forest, shifting-cultivation forest, open forest, forest mosaic, and nonforest. The shifting-cultivation class included dense and secondary forests of varying ages intermingled with cultivated plots, while the forest-mosaic class included a mosaic of dense and open forests with scattered cultivation and tree crops. In our analysis, the reclassified vegetation map was mainly used to identify the forested regions of South and Southeast Asia as of circa 1980.

Reclassification of the Ecofloristic-Zone Map (REFZ)

The ecofloristic zone map, consisting of 36 zones, was reclassified into six zones approximating a life-zone classification. The resulting map was referred to as the reclassified ecofloristic-zone map (hereafter referred to as the REFZ map). The possible classes were montane (above 1500 m) vs lowland, and within each of these, moist (evergreen forests, high nonseasonal precipitation), seasonal (semideciduous forests, seasonal precipitation), and dry (deciduous forests, long dry season) types were distinguished.

Modeling Forest Biomass Density

Forest biomass density was modeled with a GIS in three stages: (1) the potential biomass density that would exist under no human or natural disturbances (hereafter referred to as PBD), (2) the potential biomass density for the areas in forest cover in

1980 (referred to as PBD-80), and (3) the actual biomass density estimated for those forests present in 1980 (referred to as ABD). The method is now presented for each; the general methodology follows that of Risser and Iverson (1988), where simple additive processing is used to arrive at a score for each cell of the map. In this study, the process was repeated many times, with continual adjustment of the relative weighting of the model parameters, before a satisfactory model was derived.

In the GIS models presented, we calculate the biomass density averaged across the entire cell (3.75 km x 3.75 km). Total biomass for a particular cell can therefore be made by multiplying the average biomass density of the cell by the area of the cell. The summation of total biomass for each cell yields total biomass for the region of interest.

To our knowledge, this is the first attempt to model forest biomass using such an approach. Below we make assumptions that are not always easily backed up by data at the scale in which we are working. Nonetheless, we believe that the incorporation of spatial heterogeneity of edaphic and climatic factors into biomass-density estimation improves greatly on previous estimates derived from tabular data. We further believe that this type of approach is the best method for estimating biomass density in regions where information is lacking and most, if not all, of the forest land has been disturbed by humans.

Potential Biomass Density Index

The model used to generate an index of potential biomass density (PBD) was an additive one that performed a weighted overlay of input layers according to our specifications (Fig. 2). Each of the individual layers was given a maximum value of 25 points so that the maximum score possible was 100 points (Fig. 3). The mWCI (Fig. 3a) and mean annual rainfall (Fig. 3b) together account for half the total possible weight in the model. Elevation (Fig. 3c) and slope class (Fig. 3d) together formed a layer, with elevation assigned a maximum weight of 13 and slope class a maximum of 12. Soil quality and texture (Fig. 3e) accounted for the remaining 25% of possible weight in the model. The final scheme was arrived at by first establishing general weighting from Whitmore (1984), comparing model results to known localities (inventories, other literature, and/or personal experience), and adjusting the influence (weight) of climatic vs edaphic controls to yield the most realistic map. The following paragraphs describe the assumptions and basis for the weighting schemes derived for each layer.

Modified Weck's Climatic Index

The values of mWCI ranged from 0 to more than 1400. The output map was nonlinearly reclassified into 20 classes. More classes were concentrated at the lower end because vegetation is more sensitive to mWCI at the dry end (a similar pattern was used by Holdridge [1967] in developing the life zone system); that is, the first eight classes were in increments of 25, followed by six classes with increments of 50, five classes incrementing in steps of 100, and the final class lumping all values above 1000 (Fig. 3a). We assumed a linear relationship between the index classes and the weight given for biomass density in the model (Fig. 3a) (Weck 1970).

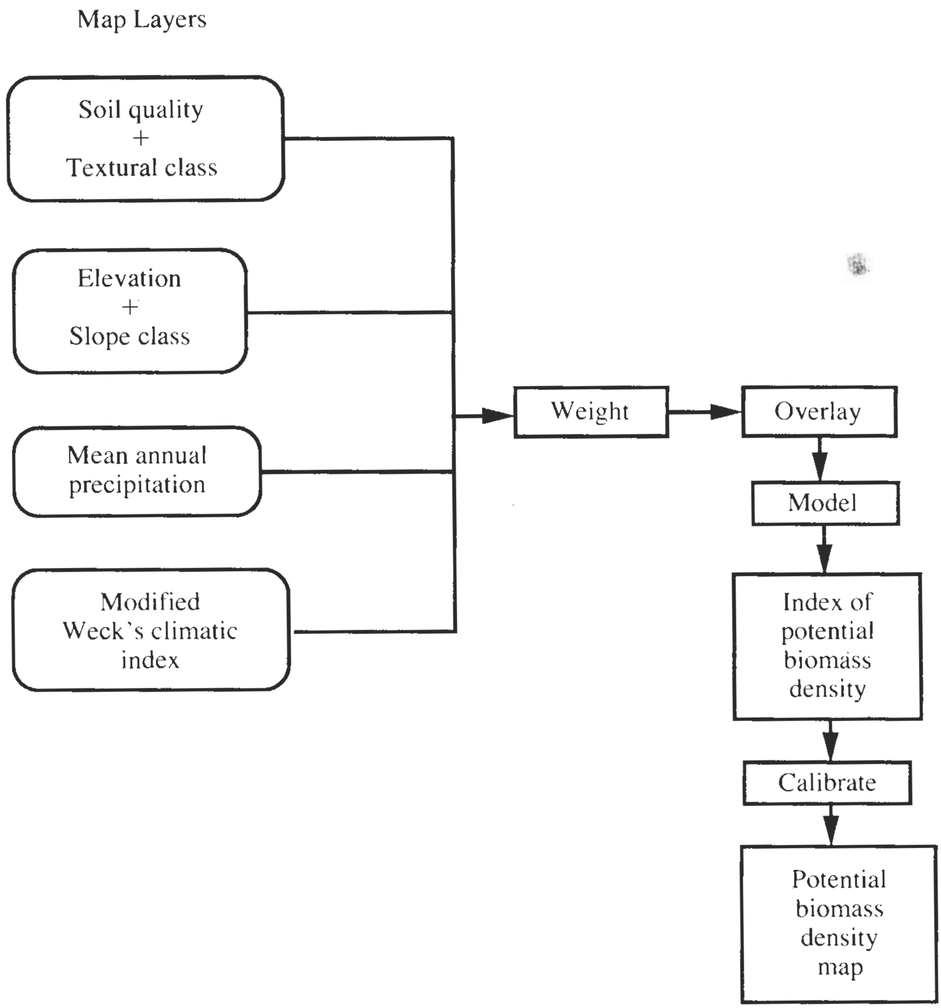

Figure 2. Flow diagram of GIS processing for potential-biomass-density (PBD) map.

Mean Annual Precipitation

A separate layer of absolute mean annual precipitation was also included to emphasize its relationship to biomass density. The relationship between precipitation class (incremented by 200 mm classes from 400 to 1200 mm, and by 400-mm classes from 1200 to 3200 mm) and weight for biomass density in the model was assumed to be positive from 400 mm/year to 3200 mm/year, after which increasing rainfall had a negative effect on biomass density (Brown and Lugo 1982) (Fig. 3b); 400 mm/year was taken as the lower limit for forests to grow, but it may support woody shrubs. This change in vegetation corresponds to the transition between thorn-woodland and very-dry-forest life zones of the Holdridge (1967) system. This lower limit was also used to mask out the nonforested region in our biomass-density maps.

Elevation/Slope Class

Large areas of hilly and mountainous regions are in our study area, including parts of the Himalayan Mountains. Such terrain can obviously affect the potential forest biomass density of the region, primarily operating through climatic influences. Therefore, the effect of elevation and slope on biomass density of tropical forests was considered in our model. We reclassified the elevation data into five classes (with 1 being the best) based on the descriptions of the forests of Southeast Asia by Whitmore (1984). The weighting classes used in the model for each elevation class are presented in Fig. 3c. The maximum value (for the lowland forests) is 13 out of the total of 100 possible points in the model. An elevation of 3750 m was considered the limit of the timber line; locations with elevations exceeding this value were considered nonforest land. The divisions were based on general variations of the structure of forests with elevation, as reported in Whitmore (1984): mangrove forests (1 to 15 m), lowland forests (16 to 750 m), upper lowland/lower montane transition (751 to 1500 m), lower montane forests (1501 to 2010 m), upper montane forests (2011 to 3000 m), and the very high elevation (subalpine) forests (3001 to 3750 m). The elevation range of 0 to 15 m was given Class 2 (a slightly lower rating than lowland forests) because the forests at or near sea level tend to be along the coast and are typically swamp formations that normally have lower biomass density than lowland forests.

The amount of slope (or, at this scale, the degree of dissection of the landscape) can also influence, to a limited degree, the capacity of the landscape to carry biomass. The FAO soil map also reported three main slope classes associated with each soil unit [(1) level to gently undulating, (2) rolling to hilly, and (3) steeply dissected to mountainous] along with two mixed classes that combine Classes 1 and 2 (1/2) or Classes 2 and 3 (2/3). This five-class map was given the weight classes shown in Fig. 3d. We did not consider slope to be a major limiting factor for forest biomass density because high-biomass forests have been found in each slope class. However, for consistently high biomass density over large areas, there is generally a higher biomass density potential on more level terrain. Therefore, the possible spread of points caused by various slope classes was set to 5 points (Fig. 3d).

Soil Quality and Texture Class

Several edaphic and hydrological factors are known to affect biomass density in tropical forests (Whitmore 1984). We derived most of this information from the FAO soil maps (Food and Agriculture Organization 1974). Because the original purpose of the FAO soil maps was to evaluate the fertility and suitability of different soils for growing agricultural crops, we had to overcome this bias to evaluate their suitability for estimating the potential biomass density of forests. Long-lived tropical forests cannot

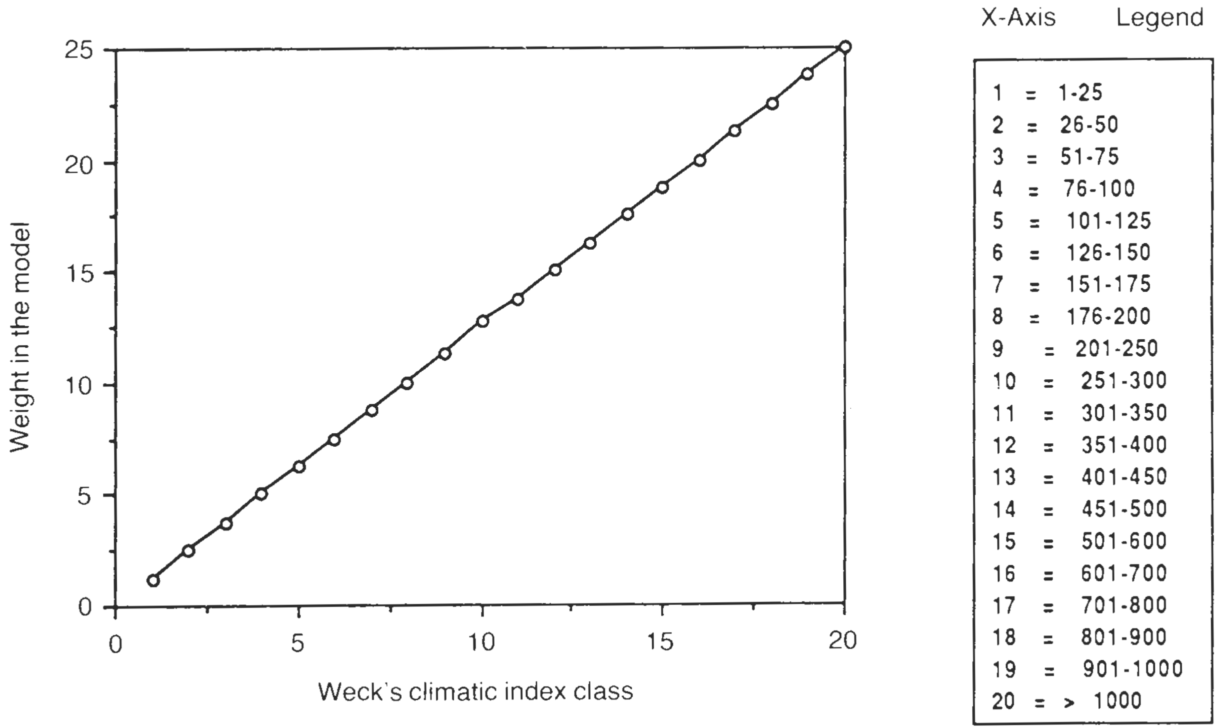

Figure 3a. Individual Weighting Factors for Data Layers Used in the Potential-Biomass-Density Model: Modified Weck's Climatic Index. (See text for explanations.)

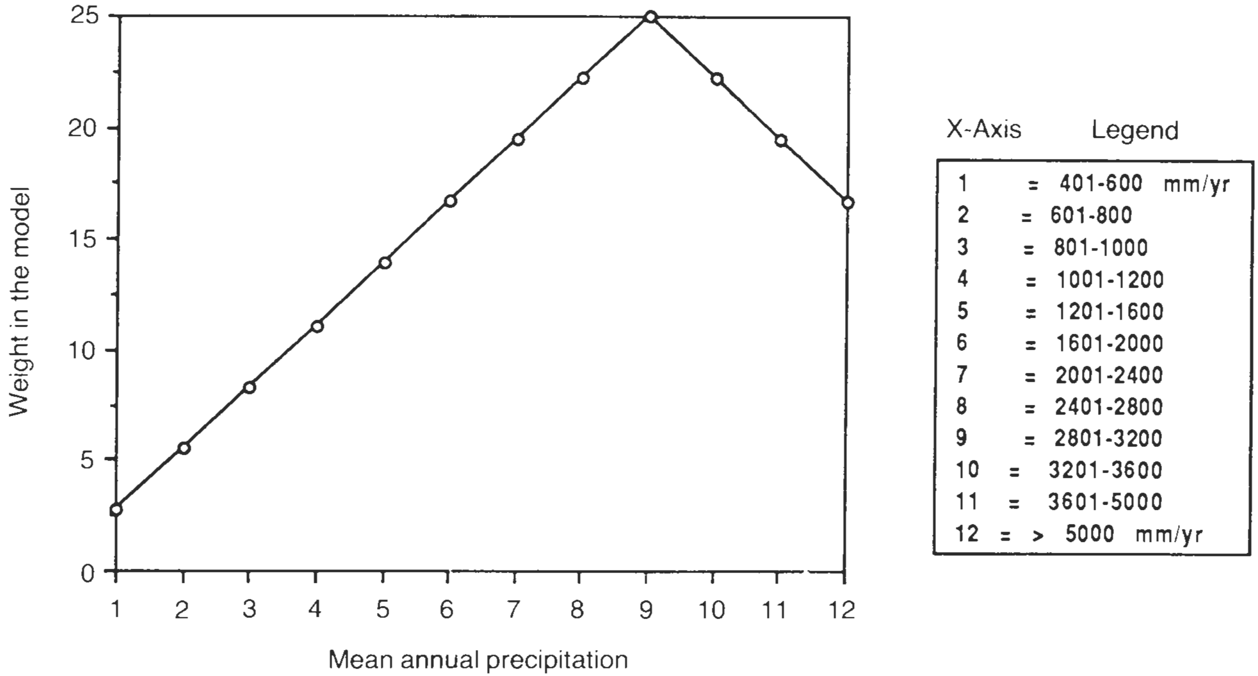

Figure 3b. Individual Weighting Factors for Data Layers Used in the Potential-Biomass-Density Model: Precipitation. (See text for explanations.)

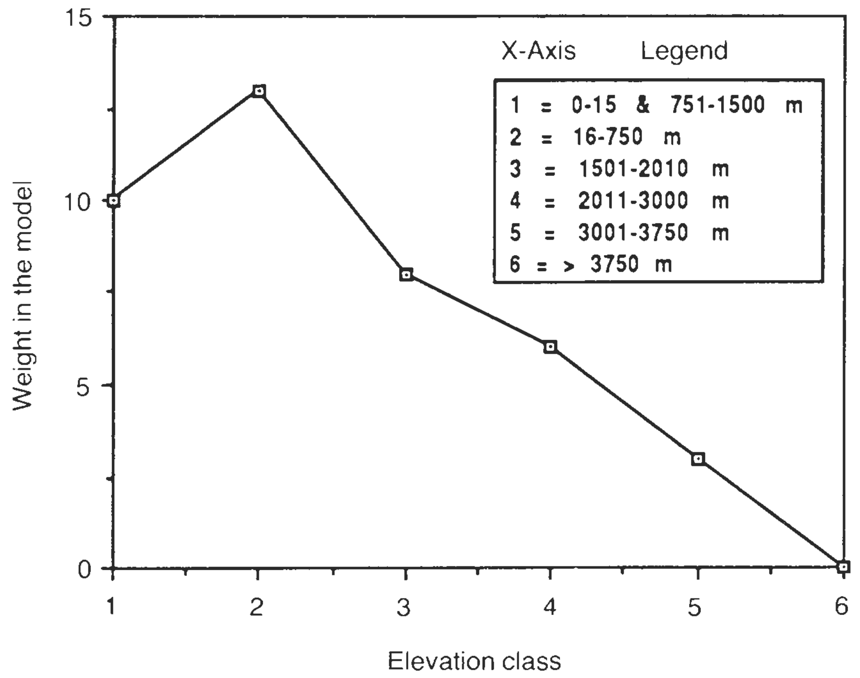

Figure 3c. Individual Weighting Factors for Data Layers Used in the Potential-Biomass-Density Model: Elevation. (See text for explanations.)

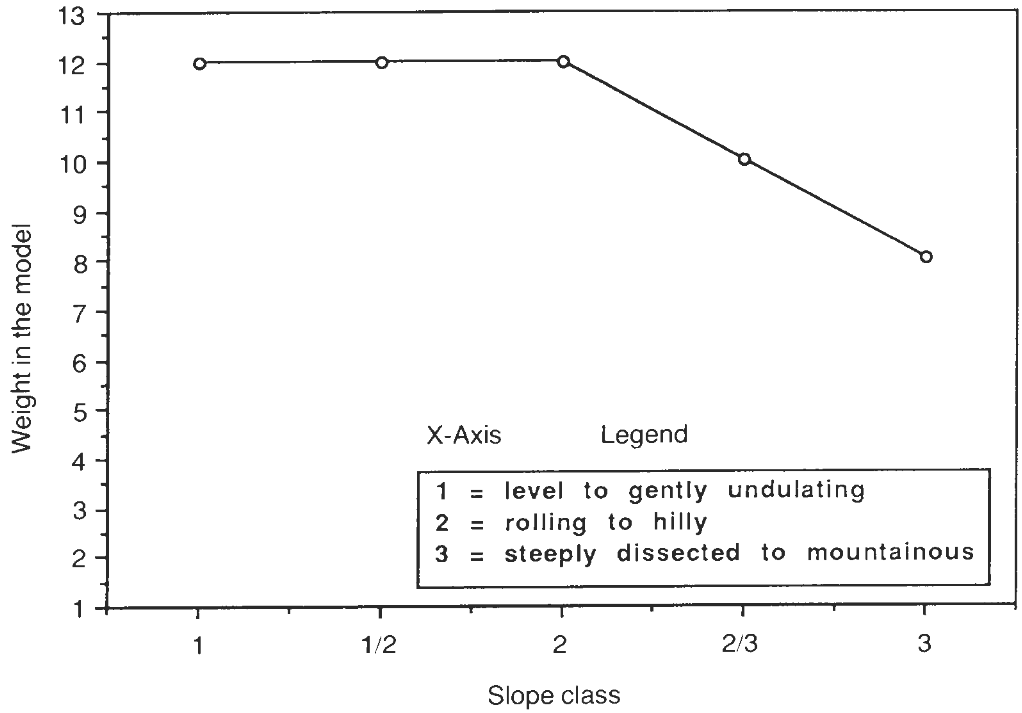

Figure 3d. Individual Weighting Factors for Data Layers Used in the Potential-Biomass-Density Model: Slope. (See text for explanations.)

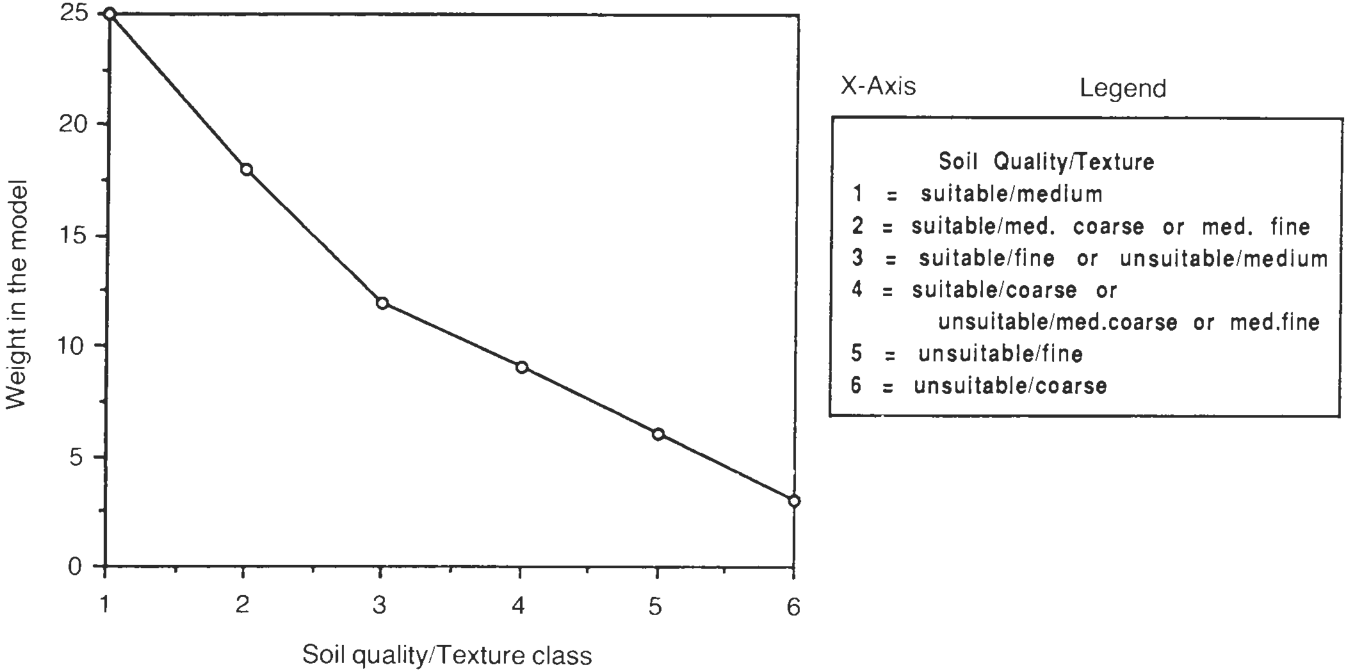

Figure 3e. Individual Weighting Factors for Data Layers Used in the Potential-Biomass-Density Model: Soil Quality and Texture. (See text for explanations.)

be considered in the same manner as short-lived agricultural crops with respect to soil fertility. Forest productivity generally is responsive to soil fertility, but potential biomass density is generally much less related to fertility than to climate, soil depth, and soil texture. Therefore, we could not rely on FAO assessments of soil fertility for crops as a major factor in the model. Instead, we performed a binary classification of the soil unit/subunit map into suitable and unsuitable soils. Only very shallow, stony, or salt-affected soils like lithosols and solenetz were given an unsuitable rating.

We then combined this binary soil-quality classification layer with the textural class map (created directly from the FAO soil map) to create a soil-quality/texture map, which was then used as a layer in our model. Soil texture was considered to be the major soil factor influencing the biomass density of forests because it is highly related to the soil-moisture condition as well as to the nutrient-storage capacity and the soil-organic-matter content (Sanchez 1976).

The FAO classification has three main classes of soil texture (coarse, medium, and fine) along with two mixed classes (coarse-medium and medium-fine). For our model, the medium (loam) class was considered the best soil for carrying forest biomass, followed by the two intermediate classes (coarse-medium and medium-fine). The fine-textured class (clay, which causes poor drainage and waterlogging) and the coarse class (sand, which causes excessive drainage and high leaching) were considered the worst soils. This texture-class map was overlain with the binary soil-quality map to produce an eight-class map that gave unique combinations of soil quality/texture (Fig. 3e). The best soil type (suitable quality, loamy texture) could contribute 25 points out of a total of 100, whereas the worst soil type (unsuitable quality, sandy texture) contributed only 3 points (Fig. 3e).

Calibration of Potential Biomass Density Index

To convert the map depicting indices of PBD into real biomass-density values requires the assignment of biomass-density values to a particular range of index values. Because so few forests in continental tropical Asia can be considered to be in a primary state (presently or at the time of inventory), this calibration posed a challenge (Brown et al. 1991). To tackle this problem, we used a combination of approaches to set the upper and lower limits of the PBD range and several values in between. Once the upper and lower limits were established, we assumed linearity of biomass density between these ranges, using the values in between to set the width of the biomass-density classes.

Upper Biomass-Density Limit

The highest PBD indices were located in many parts of Peninsular Malaysia, the wet zone of Sri Lanka, the southwestern and northeastern parts of India, and a small region of Cambodia. We used two major sources to set the upper limit of PBD for these areas: (1) literature data from ecological studies and (2) relationships between biomass density and proportion of the biomass in large trees (Brown and Iverson 1992; Brown et al., this volume). Although biomass-density values from ecological studies are to be used cautiously for global or regional estimates because of the problems outlined in the introduction of this chapter, they would seem appropriate for estimating the upper limit to potential biomass density. We also developed relationships of total above-ground biomass density (TAGBD) vs percentage of TAGBD in trees with diameters >70 cm using the stand table data. These relationships were then used to extrapolate the TAGBD estimates to those more appropriate for mature forests with the approach given in Brown et al. (this volume).

Peninsular Malaysia is dominated by dipterocarp forests (Brown et al., this volume), which are known to have some of the highest forest biomass densities in the tropics. The highest PBD indices for Peninsular Malaysia were located mostly in the lowlands where forests no longer exist. However, ecological studies done in similar forest types in Kalimantan and Sarawak give a range of biomass densities of 510 to >1000 Mg/ha (Brunig 1983; Proctor et al. 1983; Yamakura et al. 1986). Results of our own work for Peninsular Malaysia (Brown et al., this volume) suggested that some regions of hill forests had biomass densities of almost 500 Mg/ha in the 1980s, and that these have probably been disturbed (by the removal of large trees) and could have had >600 Mg/ha in an undisturbed state.

For the moist forests of Sri Lanka, extrapolation of the relationship between TAGB and the proportion of TAGB in large trees resulted in biomass-density estimates of greater than 650 Mg/ha. Biomass density of mature forests in southwestern India (Karnataka) have been estimated at 450 to 650 Mg/ha (Rai and Proctor 1986). These values and those above for Peninsular Malaysia established the two upper-limit biomass-density classes of 550 to 600 Mg/ha and >600 Mg/ha.

Lower Biomass-Density Limit

The lowest potential biomass indices were generally located in the northern and northeastern parts of India at the transition zone to semidesert/desert. For these areas, we assumed that the biomass density would be 50 Mg/ha or less (Brown and Lugo 1982).

Midrange Biomass-Density Values

Data for mature forests in between the extremes are limited. Two sites in western Cambodia yielded biomass densities of 400 to 450 Mg/ha and 450 to 500 Mg/ha for dense moist forests (Legris and Blasco 1972). A biomass-density estimate for a mature dry evergreen forest in northeast Thailand was 200 to 250 Mg/ha (Sabhasri et al. 1968). These few data points correspond well with the linearly interpolated values that we assigned to the PDB indices.

Potential Biomass Density of 1980 Forested Area (PBD-80)

The PBD map was masked, by the use of an overlay process, to the forested portions of the vegetation map (Fig. 4). This process yielded a PBD map of the forest areas still in existence circa 1980, the PBD-80 map. This intermediate biomass-density map depicts the change in forest area caused by deforestation only but not by degradation (the removal of biomass from the remaining forests by human disturbances).

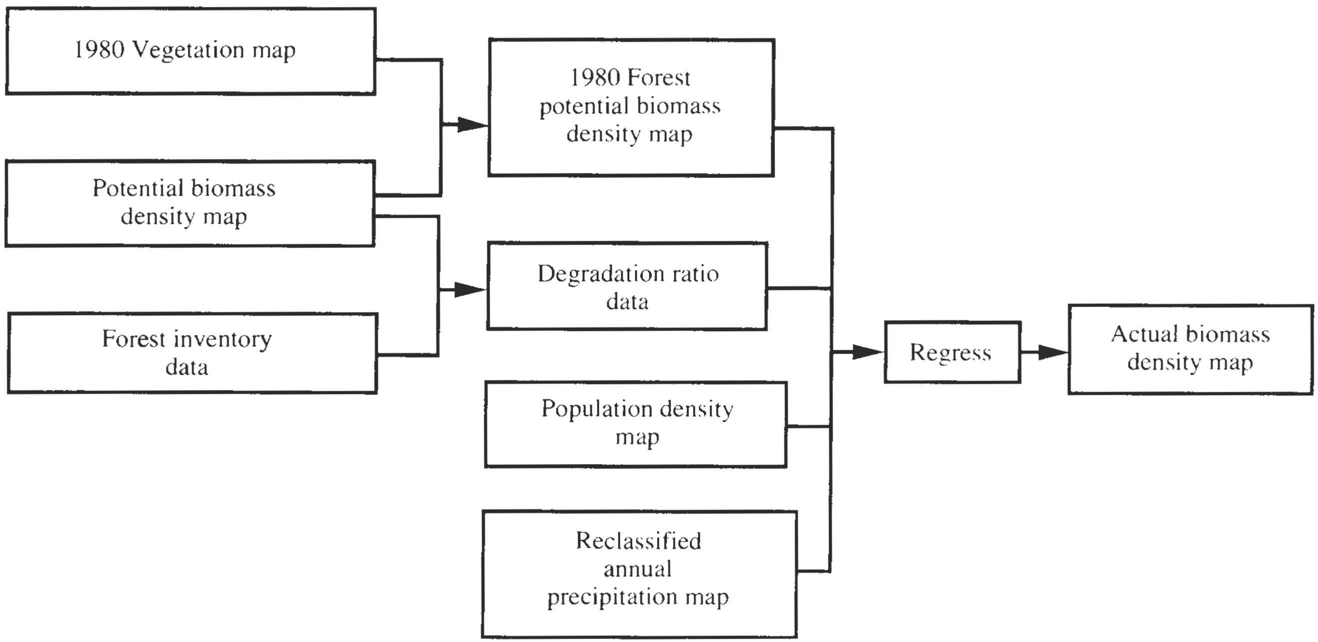

Figure 4. Flow Diagram of GIS Processing to Create Potential-Biomass-Density Map of 1980 Forests (PBD-80) and Actual-Biomass-Density (ABD) Map of 1980.

Actual Biomass Density of 1980 (ABD)

Our approach in estimating the actual biomass density extant in 1980 was to start with the PBD-80 database and to apply estimates of biomass degradation factors. We hypothesized that the degree to which forests are degraded or reduced from their potential biomass is mainly a function of the population density, with differently shaped functions for different ecofloristic zones. Higher population densities will tend to result in more-degraded forests caused by the high use of products from the forest. At a given population density, we expect forests in drier zones to be degraded more severely than those in humid zones because of the inherent ability of humid-zone forests to produce biomass more rapidly (Brown and Lugo 1982).

To estimate ABD, we used the following databases: estimates of biomass density from the forest inventories: population density data in tabular and map form; and maps of PBD-80 and precipitation. The first step (Fig. 4) was to estimate forest degradation ratios (DR), defined as actual biomass density from the inventory divided by the modeled potential biomass density. The DRs were calculated at the subnational level (except for Sri Lanka, which was calculated at the national level). We assumed that the inventoried areas were a representative sample of the forests present in that subnational unit and that the weighted biomass density from the inventory was the best estimate of the actual biomass density of those forests. The subnational breakdown of the forest inventories resulted in the following number of data points per country: Bangladesh, 2; Peninsular Malaysia, 9; Sri Lanka, 1; Thailand, 4; Vietnam, 17; and India 9 for a total of 42. A weighted estimate of the PBD-80 for the corresponding subnational unit was obtained from the PBD-80 map. Degradation ratios were then calculated from the inventory data described above.

Corresponding population-density statistics for each subnational unit for the decade closest to the time when the inventory was done were obtained from the population database described above. We then stratified the database according to annual precipitation patterns, roughly equivalent to moist (>2000 mm/year of rainfall with a short to no dry season), seasonal (1500 to 2000 mm/year of rainfall with a dry season of up to 6 months), and dry (<1500 mm/year of rainfall with a dry season lasting longer than 6 months). We then used least-squares regression analysis to fit these data to the following exponential model:

$$DR = a + b \ln(PD) \quad , \qquad (3)$$

where DR is the degradation ratio, PD is the population density (people/km^2), and a and b are regression coefficients.

Our final equations for converting the PBD-80 map to one of ABD are given in Fig. 5 for dry:

$$DR = 1.131 - 0.168 \ln(PD),\ p < 0.01,\ r^2 = 0.41,\ n = 6 \quad ; \qquad (4)$$

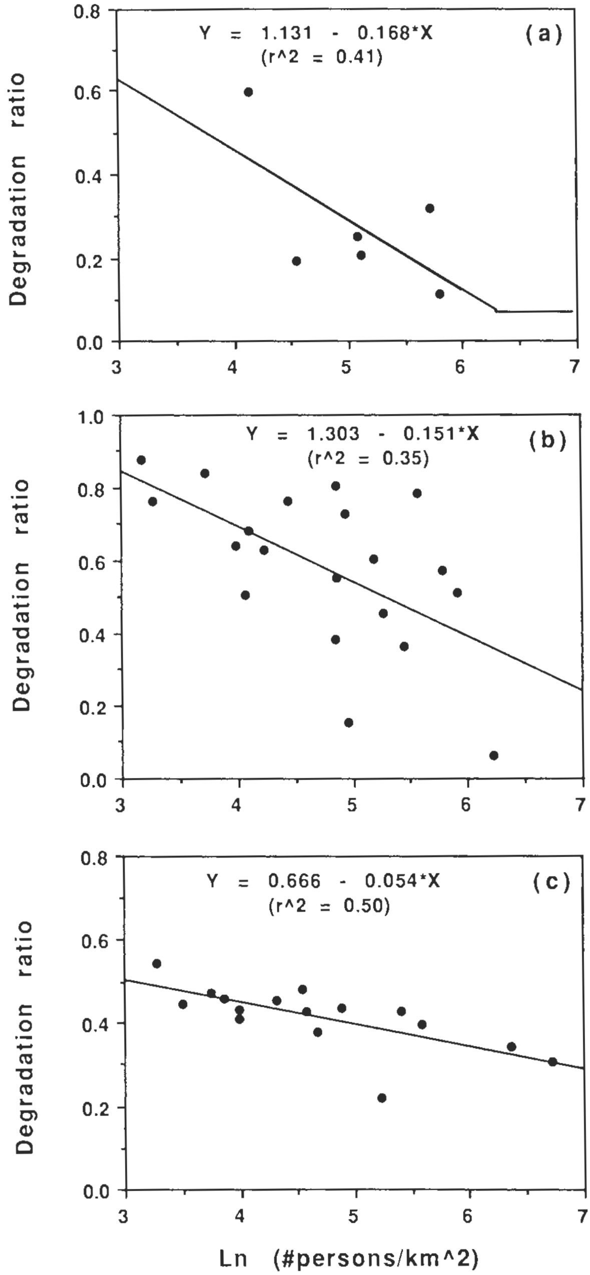

Figure 5. Relationship between degradation ratios (actual biomass density from inventory/PBD-80) and the natural logarithm (ln) of population density (ln 3 = 20, ln 4 = 55, ln 6 = 403, ln 7 = 1097 persons/km^2) for continental South and Southeast Asia under (a) dry, (b) seasonal, and (c) moist regimes. Data are at the subnational or administrative-unit level of scale. (See text for details.)

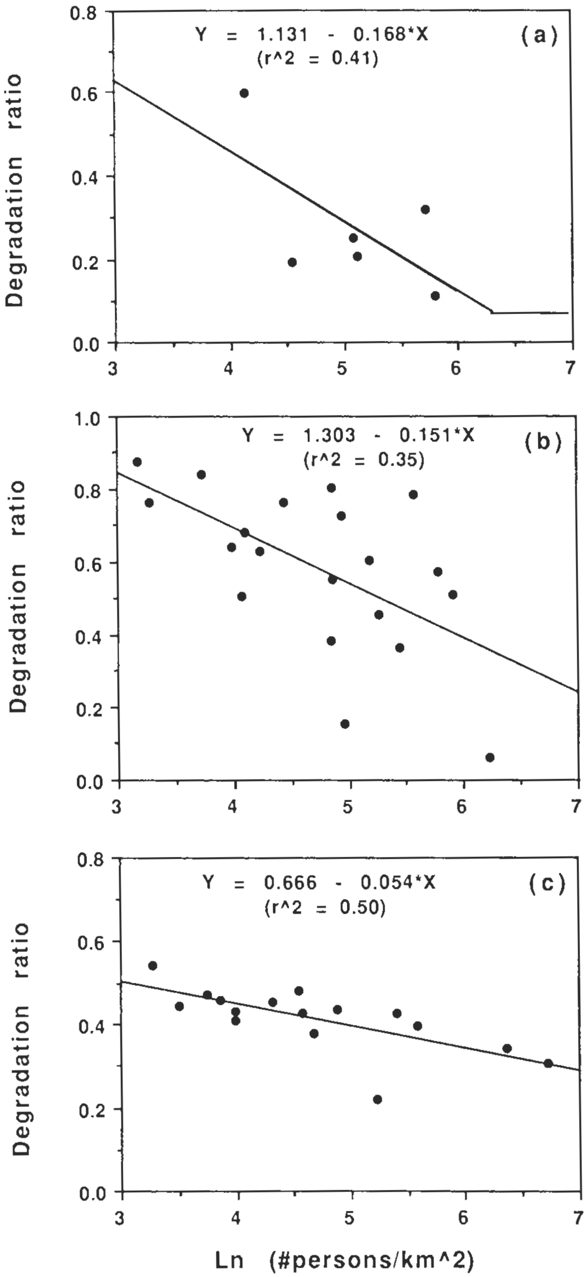

Figure 5. Relationship between degradation ratios (actual biomass density from inventory/PBD-80) and the natural logarithm (ln) of population density (ln 3 = 20, ln 4 = 55, ln 6 = 403, ln 7 = 1097 persons/km^2) for continental South and Southeast Asia under (a) dry, (b) seasonal, and (c) moist regimes. Data are at the subnational or administrative-unit level of scale. (See text for details.)

for seasonal:

$$DR = 1.303 - 0.151 \ln (PD), p < 0.01, r^2 = 0.35, n = 20 \quad ; \tag{5}$$

and for moist:

$$DR = 0.667 - 0.054 \ln (PD), p < 0.01, r^2 = 0.50, n = 16 \quad . \tag{6}$$

These equations were used with the maps of PBD-80, population density, and precipitation to produce the map of ABD (Fig. 4). If the solution to Eq. (3) in any zone yielded a DR of less than 0.06 (the lowest value obtained from inventories) for any cell, that cell was given a DR value of 0.06. Similarly, if any equation estimated a DR > 1, we used a default of 1.0. This situation occurred at population densities of less than $8/km^2$ in the seasonal and dry zones. In the moist zone, very low population densities would result in a degradation ratio of about 0.7 according to our model. However, no areas of continental South and Southeast Asia in any zone had population densities less than $8/km^2$. The rate of forest degradation with increasing population density (slope of the equations) is steeper in the seasonal and dry zones than in the moist zone (Fig. 5). This result most likely reflects a greater use of the forests for their products and slower rates of recovery, as hypothesized above.

Results and Discussion

Biomass Mapping

Distribution of Potential Forest Biomass Density by Forest Type and Ecofloristic Zone

Corroborative evidence and expert opinion substantiate the map at PBD (Fig. 6) as being realistic. Peninsular Malaysia, northeast and western Ghats of India, eastern Bangladesh, western Cambodia, southern Thailand, and southwest Sri Lanka show high values of PBD, as can be expected from their climate patterns and historical descriptions of vegetation. The only truly arid region is in northwest India, and the semiarid zone extends south of this to the central part of the Deccan Plateau in India. Central Myanmar is also relatively dry compared to the other parts of Southeast Asia and shows lower PBD. The PBD estimates of the mountainous regions of Nepal and the northern state of Himachal Pradesh in India may be lower than expected for those mountainous (mainly coniferous) forests.

By overlaying the PBD map (Fig. 6) with the reclassified vegetation map, some general observations can be made with respect to expected trends in biomass density (Fig. 7a). For example, the open forest class on the 1980 vegetation map has lower PBD classes (primarily in the range 225 to 425 Mg/ha, with a mode of 325 Mg/ha, Fig. 7a) than the other forest classes, suggesting that they mostly originated from lower-biomass-density forests, rather than from extreme degradation of closed, dense forests. The present-day secondary and shifting-cultivation forests came primarily from formerly

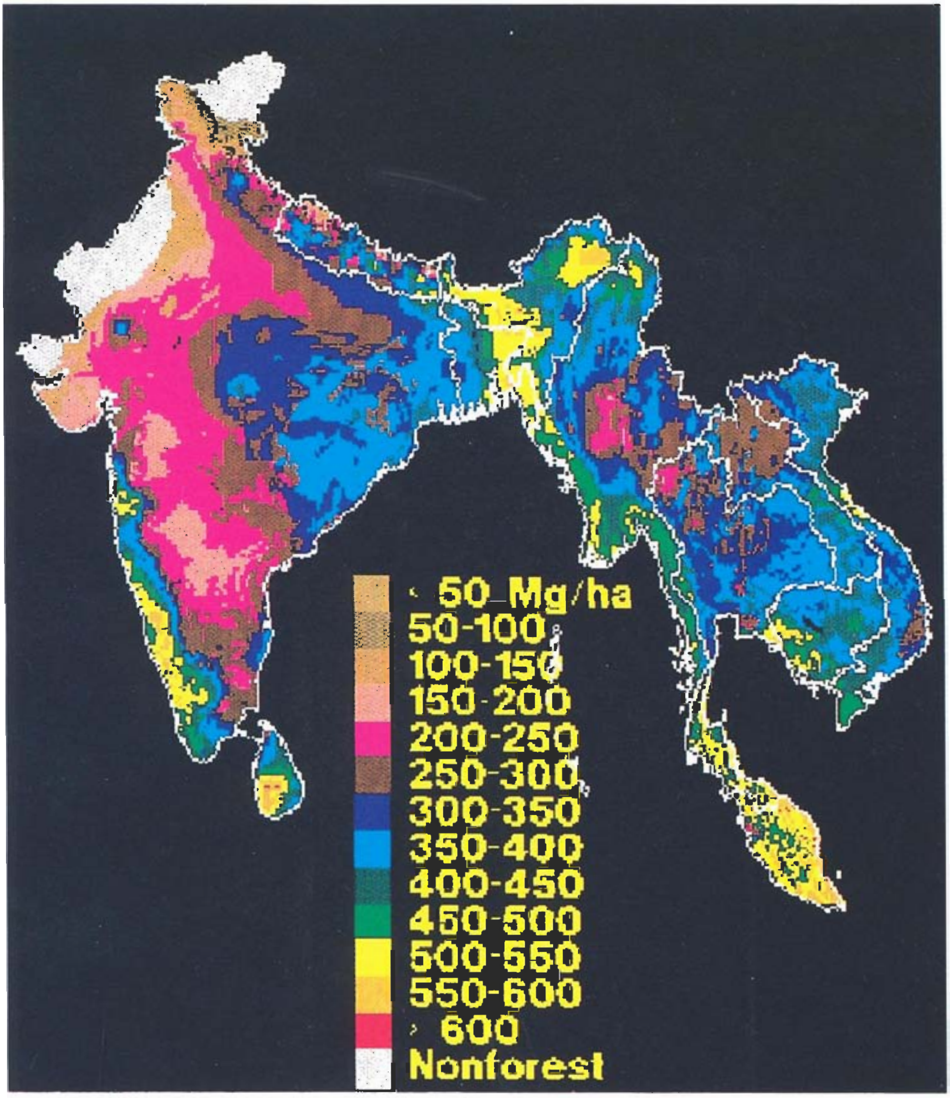

Figure 6. Map depicting potential biomass density (PBD) for continental South and Southeast Asia (prehuman influences).

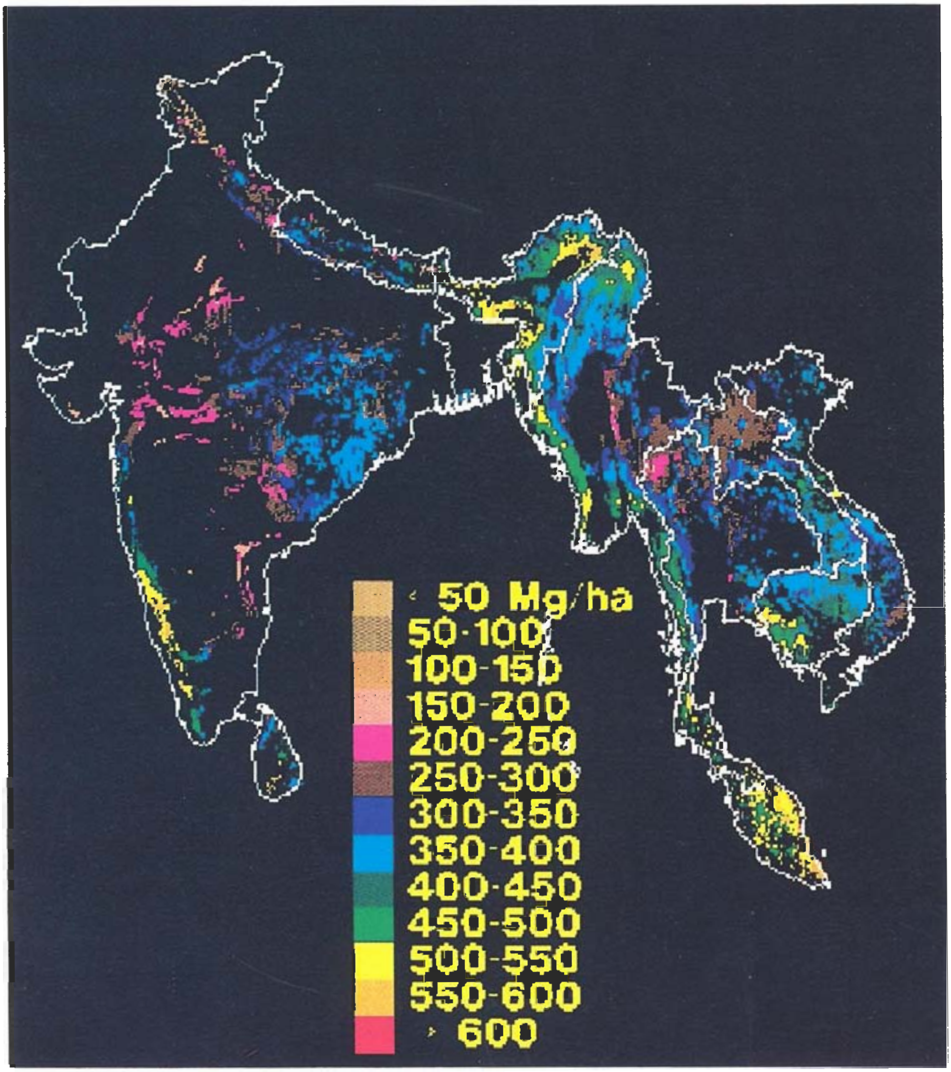

Figure 8. Map depicting estimated potential biomass density for areas forested as of 1980 (PBD-80).

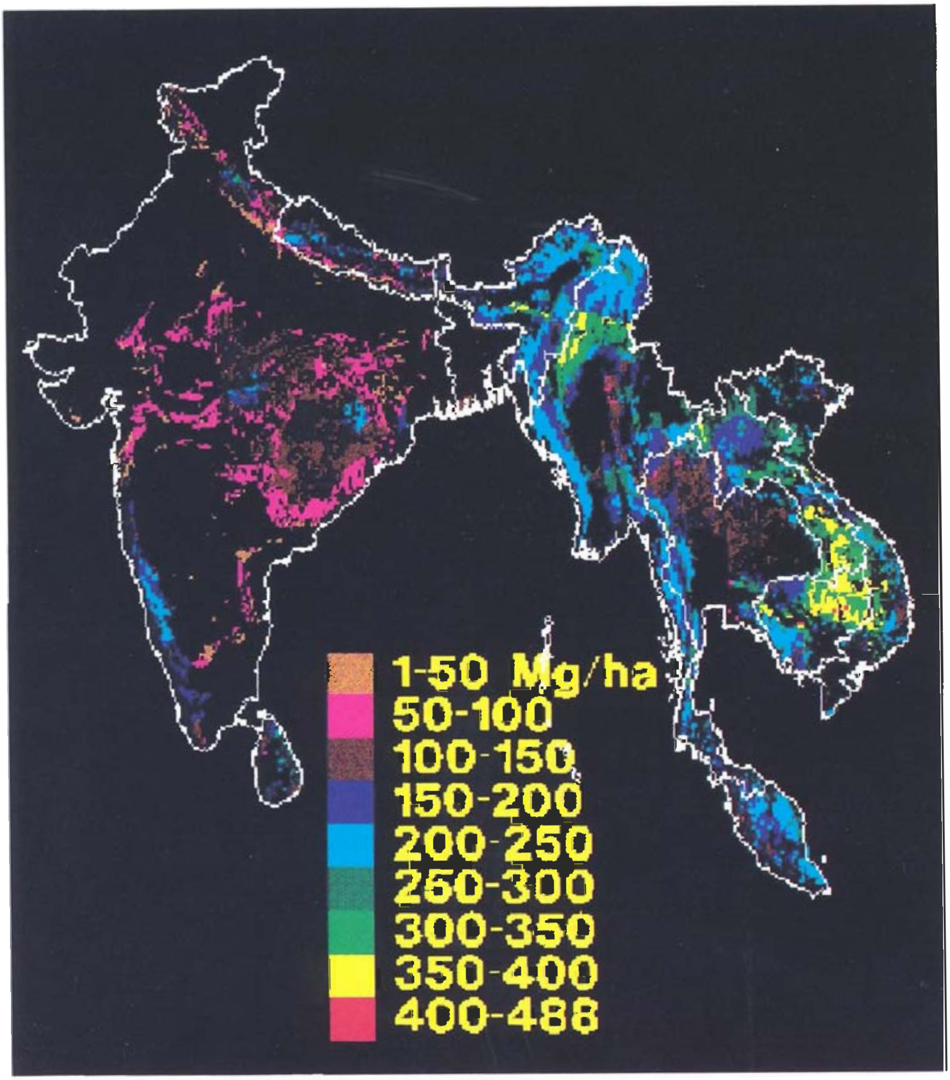

Figure 9. Map depicting estimated actual biomass density (ABD) for areas forested as of 1980.

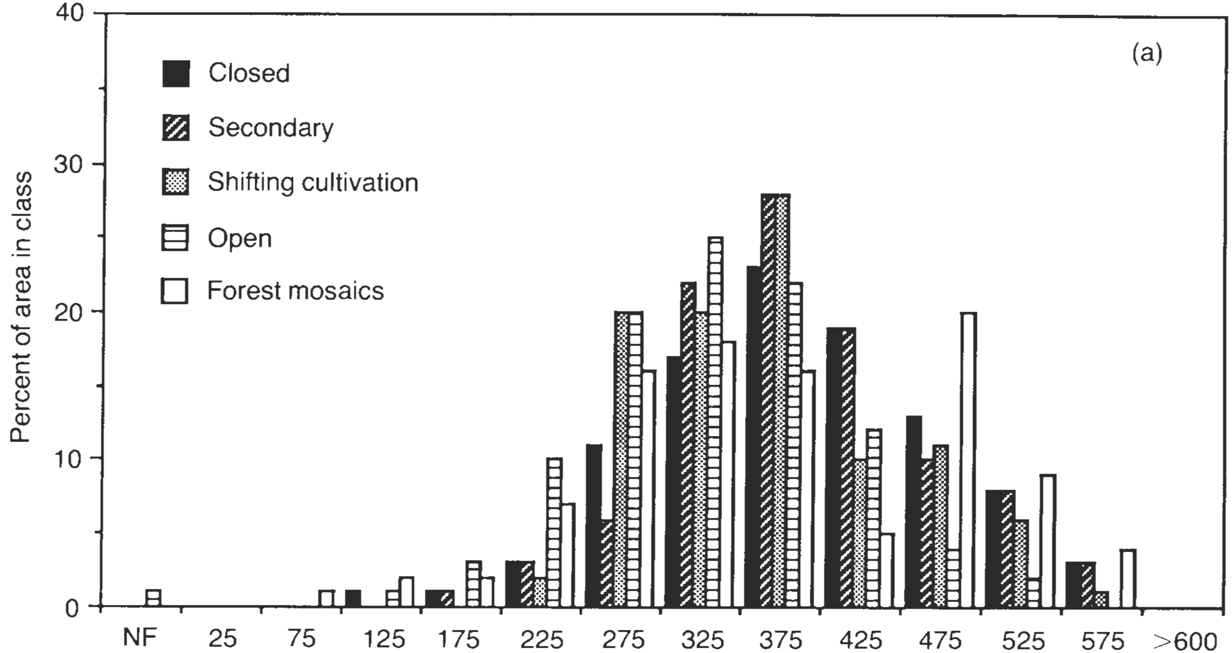

Figure 7a. Percentage Distribution of Total Area in a Given Vegetation Class by Potential-Biomass-Density (PBD) Class. Bars are plotted at the midpoints of 50-Mg/ha classes.

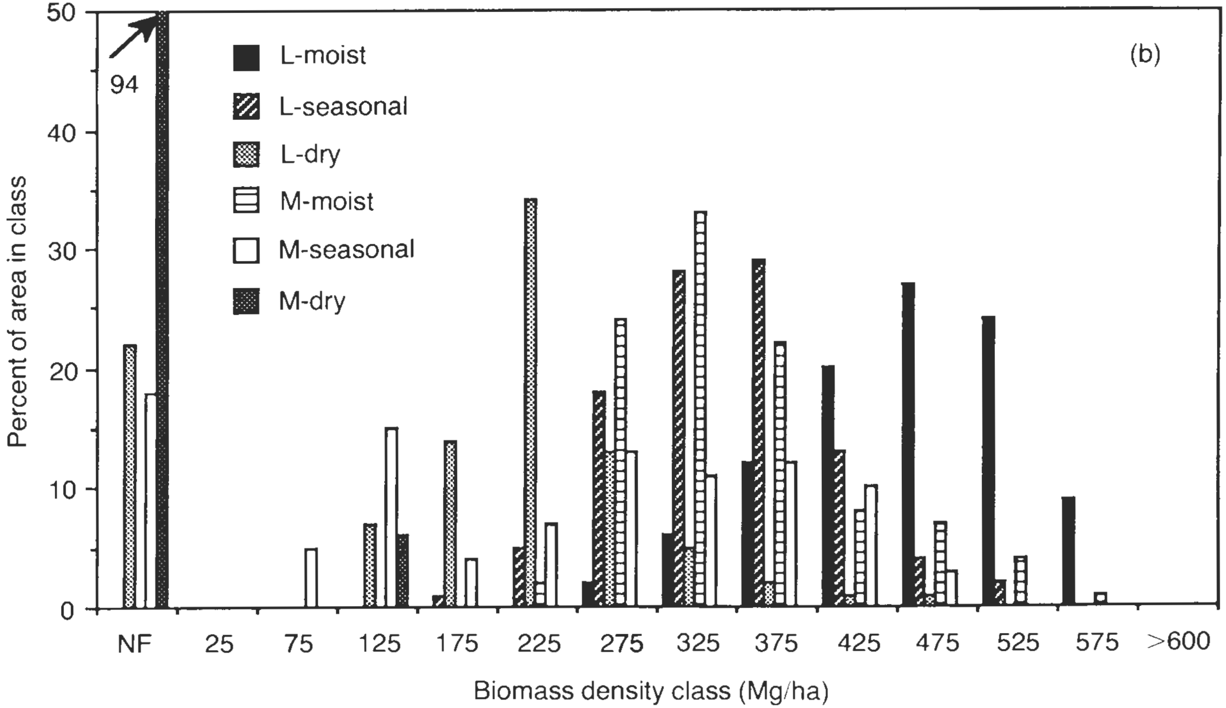

Figure 7b. Percentage Distribution of Total Area in a Given Reclassified Ecofloristic Zone (REFZ) by Potential-Biomass-Density (PBD) Class. Bars are plotted at the midpointsof 50-Mg/ha classes.

closed forests, as indicated by the close association of the three types in the PBD distribution. The present-day forest-mosaic class (mixtures of forests and nonforests, usually agriculture) had the highest variability in the PBD distribution, and originated mostly from forests in the 275- to 525-Mg/ha range.

The overlay of the PBD with the REFZ map again yields results that are reasonable and expected (Fig. 7b). The lowland moist zone dominates the highest PBD classes, as expected from the literature (Whitmore 1984). The lowland seasonal and montane moist zones have roughly equivalent PBD distribution with a mode value several classes lower than that for the lowland moist zone. The lowland dry zone is typified by very low PBD, again as expected (Fig. 7b). These results help us gain confidence in our method for estimating PBD of tropical forests at this coarse, subcontinental level of mapping. However, we cannot espouse high accuracy at the local level because of the coarse resolution of input data sets and their inability to capture specific local anomalies.

Potential Biomass Density of 1980 Forested Areas (PBD-80)

The massive deforestation that has occurred historically in the region is readily apparent by comparing the area of forest in Fig. 8 to that in the PBD map of Fig. 6. Hundreds, even thousands, of years of inhabitation (McEvedy and Jones 1978) with dense populations of humans and livestock (especially in India) have reduced the forestland area to only 33% of what it once was, according to the 1982 vegetation map. Much of the area that was converted from tropical forest fell in the lower (drier) potential biomass classes (potential biomass <250 Mg/ha). This trend is especially apparent in central and north-central India, central Myanmar, and southern Thailand. Much of the high biomass forest has also been converted, however, especially in Sri Lanka, western and southern Peninsular Malaysia, southern Vietnam, and much of Bangladesh (Figs. 6 and 8).

Actual Biomass Density as of 1980 (ABD)

The ABD map shows a scattered distribution of forests with about a third of the remaining forests of low-biomass-density classes (biomass-density values of 150 Mg/ha or less, Fig. 9), especially in India and Thailand. A long history of high population pressure is responsible for the degraded nature of those forests, especially because they also generally fall in regions that are drier, with lower potential biomass density. The highest-biomass-density (biomass density >300 Mg/ha) forests present in 1980 are mapped for northern Cambodia, southern Laos, the northern edges of Thailand and Laos, northern Myanmar, parts of Northeast India, and central Vietnam (Fig. 9). The largest area (44%) of forest lands, however, had intermediate biomass-density values in the 151- to 250-Mg/ha range (Fig. 9).

An overlay of the ABD map with the vegetation map shows a prominence of low biomass-density values for the open and forest-mosaic classes. The distribution of closed, secondary, and shifting-cultivation forests were more normally distributed across ABD classes (Fig. 10a). Several anomalies exist in this overlay, however, including the relatively high percentage of open forests (low expected ABD) in high-ABD classes and the relatively high percentage of closed forests (high expected ABD) in low-ABD classes. Most of these anomalies are likely caused by errors in the vegetation map as well as by errors in our biomass-estimation techniques. For instance, we know that many of the forests in Vietnam classified as open in the vegetation map are classified as closed in their national inventory (Rollet 1984).

The overlay of the ABD map with the REFZ map shows the highest biomass-density classes (>250 Mg/ha) coming from three ecofloristic zones: lowland moist, lowland seasonal, and montane moist zones (Fig. 10b). The montane moist forests, which initially had lower PBD relative to lowland moist forests (Fig. 7), also had relatively high biomass density in 1980, possibly a result of greater inaccessibility (and less population pressure by humans) of those forests relative to many of the lowland forests. The lowland seasonal REFZ class followed the two moist classes in biomass density and was generally equally distributed across the higher-biomass-density classes, but relatively larger areas were in the 75- to 175-Mg/ha classes. As expected, the lowland dry forests generally occupied the lowest biomass-density classes (mostly <100 Mg/ha, Fig. 10b). No montane dry forests were present in 1980.

Another way to help understand and check the validity of the results is to compare the ABD map with actual inventories in the region. Although data from the actual inventories were used in developing the degradation models (Fig. 5), we believe that we can use them here to check the overall validity of our ABD map.

The graph of predicted ABD to inventory ABD showed a reasonable relationship, with an r^2 of 0.62 (Fig. 11). The slope of the regression line (solid line in Fig. 11) is slightly less than 1 (0.91) and has an intercept of 12. The result is an overestimate of biomass density of about 15% at low biomass densities and an underestimate of about 10% at the high biomass densities. At the intermediate biomass-density classes, the model and inventory estimate were very close (Fig. 11). The points existing as outliers in the lower portion of the graph were mostly from the dry and seasonal zones of India and from one subnational unit of Vietnam in the seasonal zone. Our model predicted a much higher biomass density than was inventoried for these locations. Possible causes for these discrepancies include the inability of our model to account for the long duration of high population pressure for the Indian points, and the inability of the model to account for the effects of the Vietnam War.

Biomass-density estimates for the subnational units of Peninsular Malaysia, on the other hand, were underestimated by an average of 9% in our model as compared to the inventory data (a weighted average over all subnational units of 210 Mg/ha calculated here vs 230 Mg/ha in Brown et al., this volume). This difference could be explained partially by an inadequate population-density map (population densities were reported only at the large state level, which limited accuracy of the interpolated population-density map). This interpolated population-density value was therefore exaggerated in sparsely populated areas like the national parks. The estimates could probably be improved by higher-resolution population-density data and/or by restricting the population interpolations from entering national parks, etc.

In general, the trend shown in Fig. 11 is significant between the two estimates of biomass estimates. Clearly, further investigations are needed, including the inclusion of other factors regulating biomass. We believe that, given all the problems and assump-

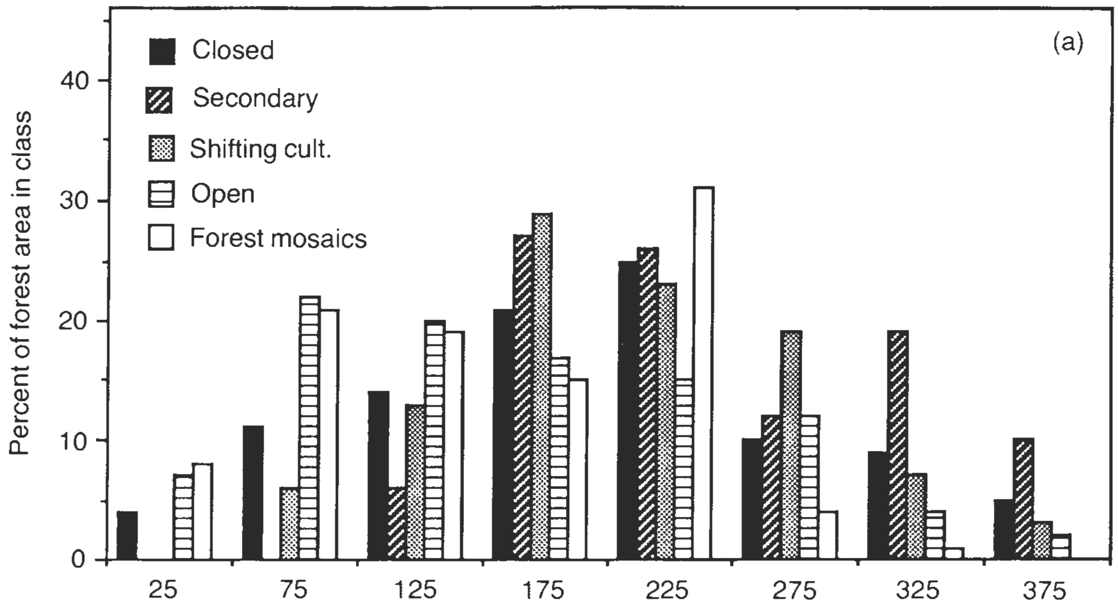

Figure 10a. Percentage Distribution of Forest Area in a Given Vegetation Class by Actual Biomass-Density Class. Bars are plotted at the midpoints of 50-Mg/ha classes.

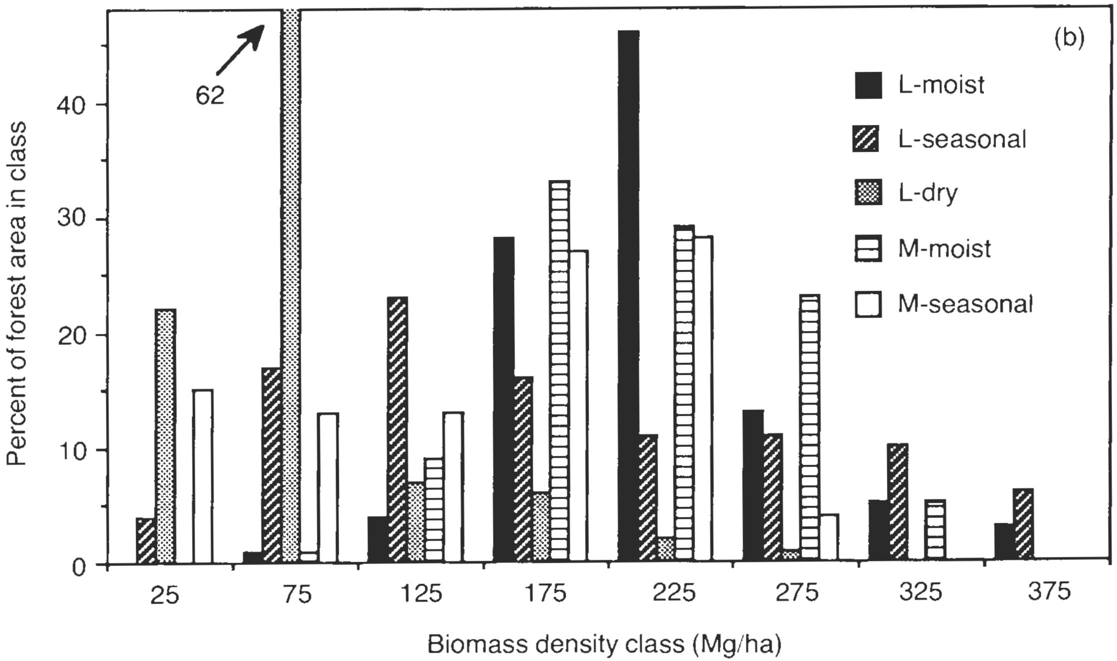

Figure 10b. Percentage Distribution of Forest Area in a Given Reclassified Ecofloristic zone (REFZ) by Actual Biomass-Density Class. Bars are plotted at the midpoints of 50-Mg/ha classes. L is lowland, and M is montane; no M-dry forests remained in 1980, and thus none are plotted.

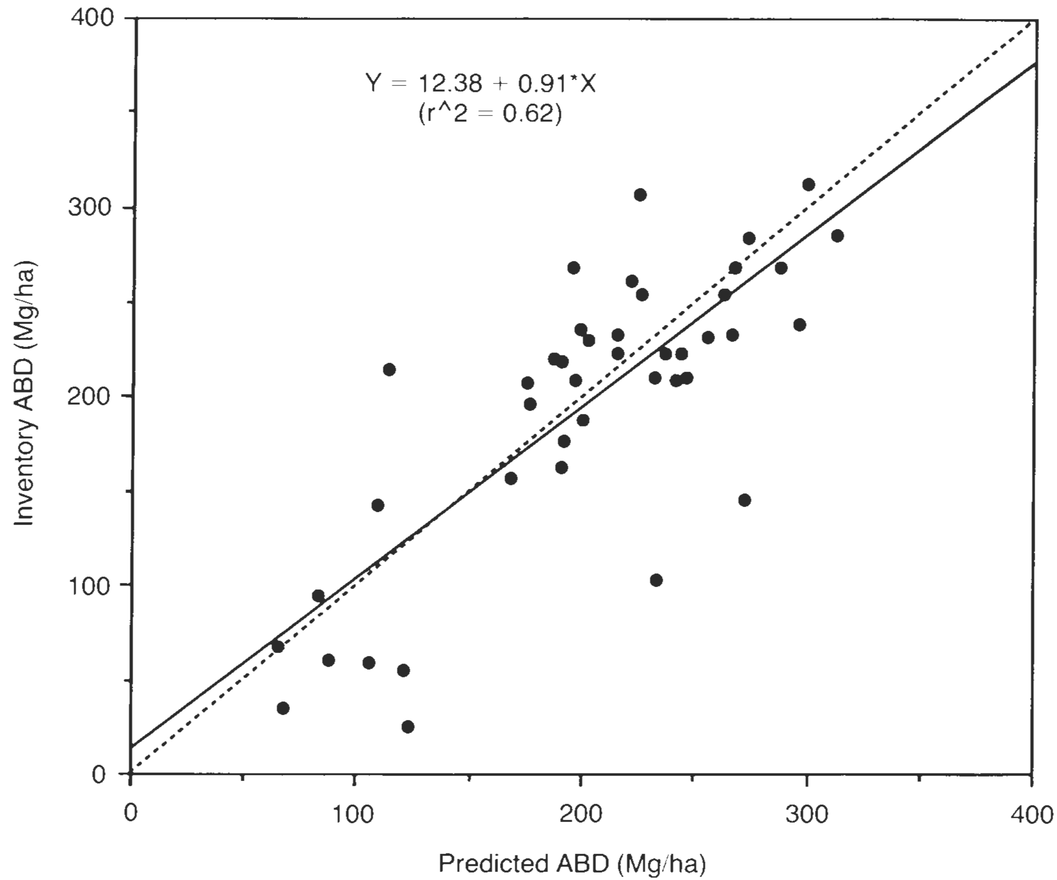

Figure 11. Actual Biomass Density Predicted by the Model vs Actual Biomass-Density Estimates for Inventoried Areas at Subnational Levels in Continental South and Southeast Asia.

tions with both inventory data and this coarse-resolution GIS effort, the map of actual biomass (Fig. 9) is both realistic and the best that can be done with current technology and available databases. Of course, no such map is static, and as data improve in quality and are updated, better biomass maps will evolve.

Changing Land Use and Biomass

Dramatic changes have occurred in tropical-forest area and biomass in South and Southeast Asia because of the influence of humans during hundreds of years of activity. The total area assessed in this study accounted for 559 million hectares, with 518 million hectares (92.7%) projected to have been forested prior to human intervention, according to our assumed minimum requirement of 400 mm of annual precipitation for forest. As of circa 1980, the amount of forestland was estimated to be 170.3 million hectares or 30.5% of the land area and 32.9% of the original forestland.

The distribution of forest lands among the REFZ classes also changed significantly in the region (Fig. 12). Of the original forested (potential) landscape, almost 80% was in the lowlands, and about half of these were seasonal forests, followed by dry and moist. Of the forests remaining in the 1980s, more than half were in the lowland seasonal zone, and about 25% were in the lowland moist zone. Only about 5% of the remaining forests were in the lowland dry zone, down from nearly 30% of the original area.

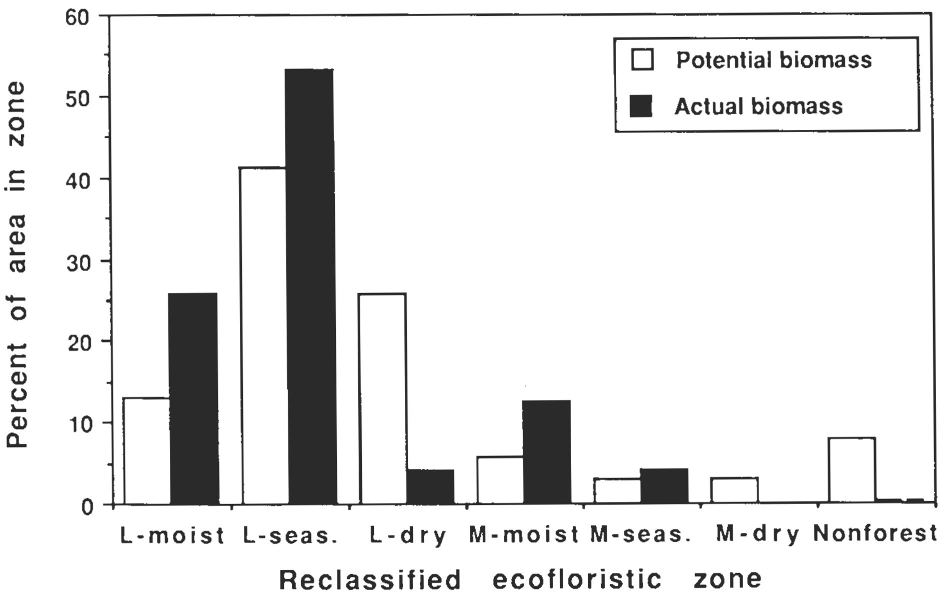

Figure 12. Percentage of total land area (potential biomass density, PBD) and forest area (actual biomass density, ABD) by reclassified ecofloristic zone.

Total above-ground biomass and biomass density of forests in the region also changed dramatically (Fig. 13). The difference between the total potential biomass and the total potential biomass in 1980 represents a total biomass loss of about 64% caused by land conversion only (Fig. 13a). Furthermore, the model estimates a dramatic biomass reduction between the total potential biomass in 1980 and total actual biomass. The combined effect of biomass removals for human use from the remaining forests in 1980 reduced the total biomass by about half of what the forest could have sustained if left in an undisturbed state. The net result is that the actual biomass present in 1980 was only 19% of the biomass capacity of the region because of the combination of deforestation and degradation. This change represents a severe degradation in biomass; more attention should be given to the importance of degradation of the world's tropical forests.

Apparently, lower-biomass-density forests were preferentially removed over the centuries; we say this because the average PBD for the continent (322 Mg/ha) was lower than the PBD-80 (370 Mg/ha) (Fig. 13b). We believe that this can be attributed in part to the general inaccessibility and low population densities in areas where the high-biomass forests grow. For example, in India, the high-biomass-density forests of the Western Ghats and Northeast India were inaccessible to conversion compared to the drier and heavily cultivated areas of the Ganges Plain. In 1980, the average actual biomass density for the continent was estimated to be 194 Mg/ha, 60% of the PBD and 52% of the PBD-80 (Fig. 13b).

Changes by Ecofloristic Zone

Certain tropical zones (dry and seasonal lowland) are preferentially inhabited by humans (Tosi and Voertman 1964), and the drier forests are often among the first to be exploited and are the most severely degraded. Support for this finding can be found in Fig. 5, where, as precipitation decreases, the regression line becomes steeper. It is probable that future deforestation in the tropics will likely occur first in those remaining drier zones that are more hospitable to humans. More-humid tropical forests, where biomass and species richness are the highest, are likely to be cleared last when choices exist.

Initially, and still in 1980, the greatest total biomass was found in lowland seasonal forests, followed by lowland moist forests (Fig. 14a). Montane zones contributed very little biomass to the total estimate, both in the past and as of 1980, although some of the montane forests may have their biomass densities underestimated in our model. Lowland dry forests initially contributed about 17% to the total potential biomass, but their contribution in 1980 (total potential or actual biomass) was insignificant because of their small area (cf. Fig. 12).

The lowland moist forests had the overall highest PBD with more than 450 Mg/ha, followed by the lowland seasonal and montane moist with about 350 Mg/ha and the montane seasonal with only about 270 Mg/ha (Fig. 14b). However, in 1980, the ABD averages for the moist and seasonal forests were similar (215 and 190 Mg/ha, respectively). The dry forests, as expected, had the lowest PBD and ABD (Fig. 14b).

The amount of biomass degradation, as indicated by the ratio of ABD to PBD-80, was greater overall for lowland forests than for montane forests. For example, the mon-

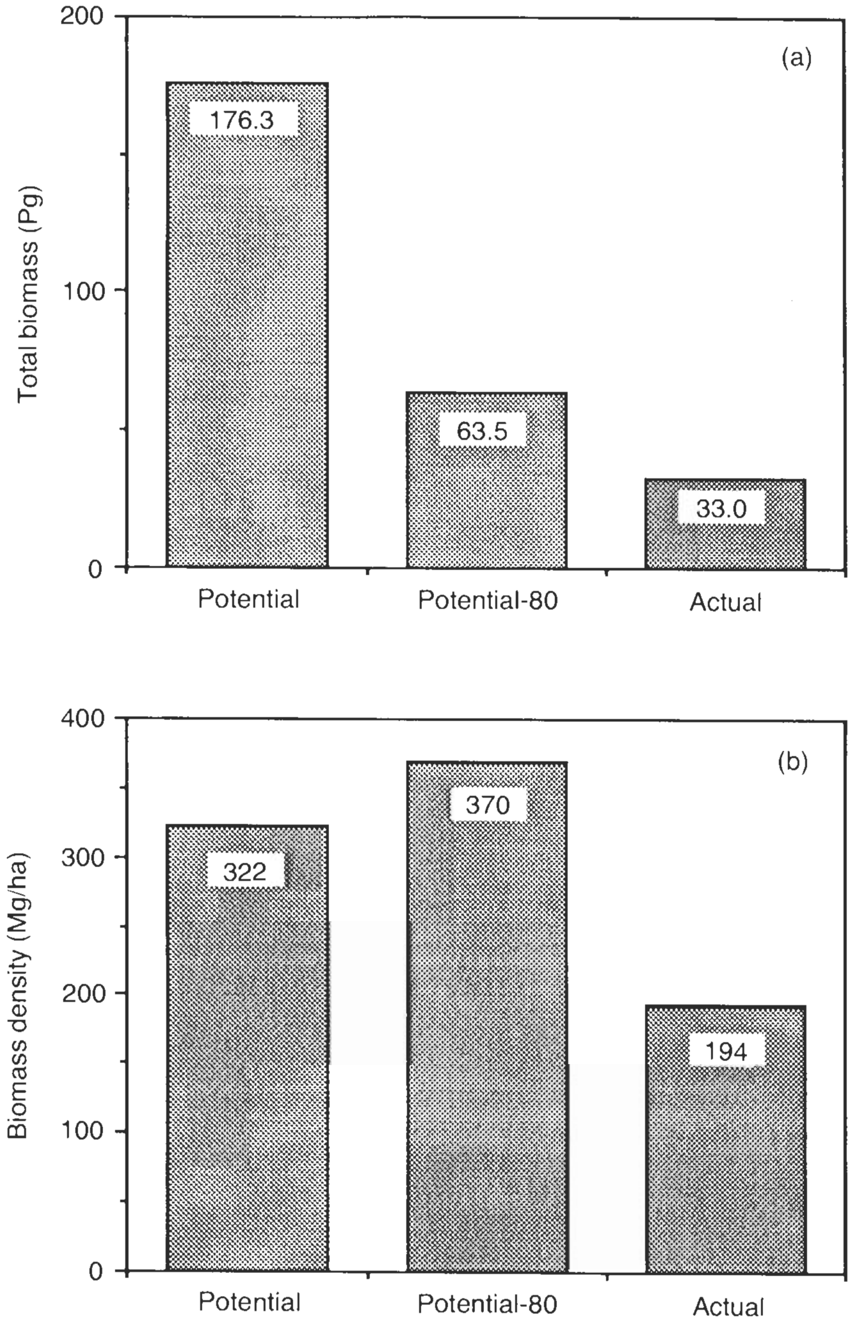

Figure 13. (a) Total biomass and (b) biomass density for potential biomass, potential biomass as of 1980 , and actual biomass as of 1980.

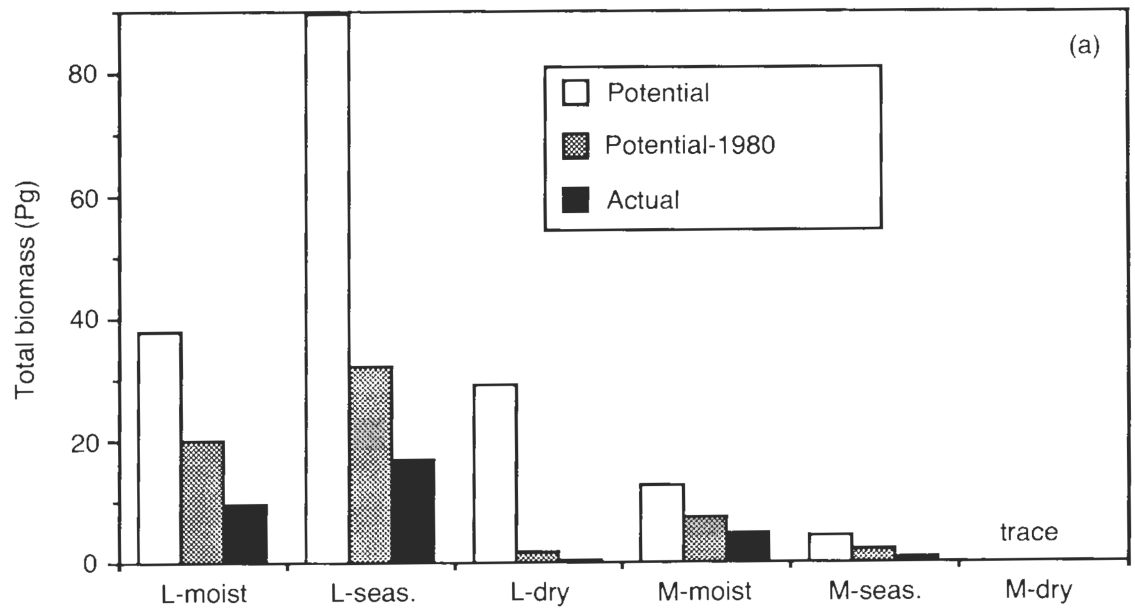

Figure 14a. Total Biomass for Each Reclassified Ecofloristic Zone (REFZ) in Continental South and Southeast Asia.

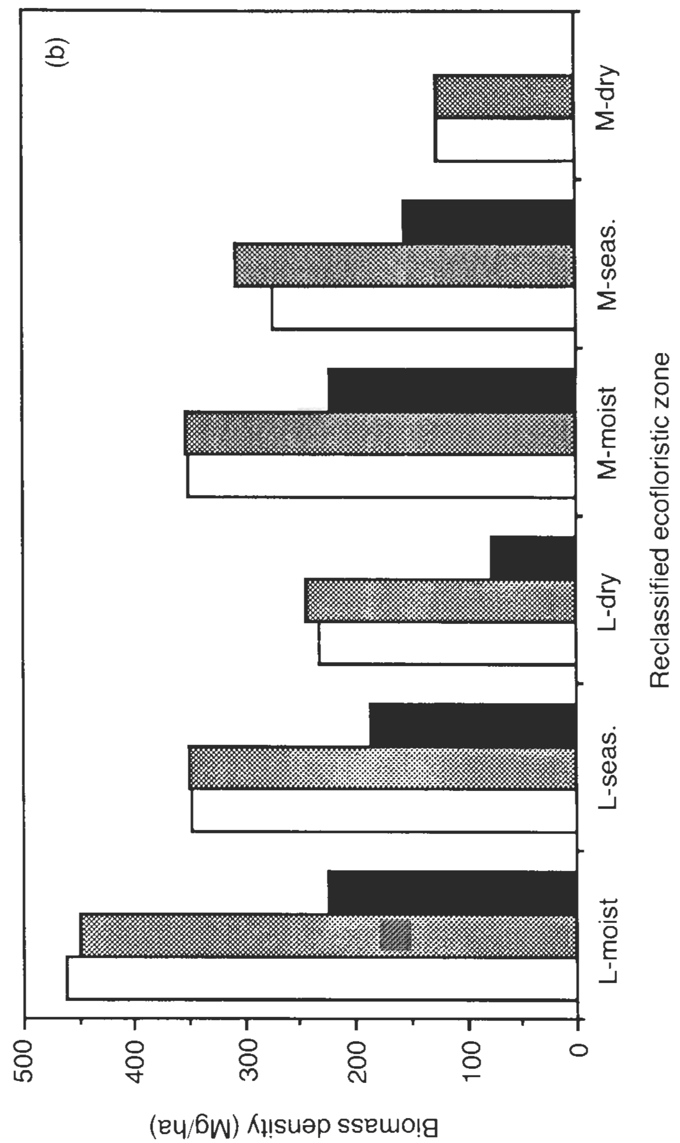

Figure 14b. Biomass Density for Each Reclassified Ecofloristic Zone (REFZ) in Continental South and Southeast Asia.

tane moist forests had a ratio of ABD to PBD-80 of 0.63, compared to a ratio of 0.50 for lowland moist. This trend is indicative of the greater inaccessibility, and thus less human degradation, of the montane forests.

Changes by 1980 Vegetation Classes

An overlay of vegetation classes with the PBD-80 and ABD maps was also performed to further understand the dynamics of forest biomass in the region. Closed forests accounted for the largest proportion of total biomass, 45 and 48% of total potential biomass in 1980 and total actual biomass, respectively (Fig. 15a). Shifting cultivation and open forests were approximately of equal importance to the region with respect to total biomass, each contributing about 20 and 23% to total potential and actual biomass, respectively. Secondary forests and forest mosaics contributed the least amount of total biomass.

In general, only small differences were exhibited with respect to PBD-80 and ABD among the vegetation classes (Fig. 15b). As expected, the lowest ABD values were obtained for the open-forest class (Fig. 15b). The consistent PBD-80 values for closed secondary and mosaic forests is expected because these latter two land uses likely originated from closed forests. However, the higher ABD value for secondary forests relative to closed forests was somewhat surprising. The secondary-forest average was calculated to be only 3.7 million ha compared to 79.8 million ha of closed forests. Those few secondary forests are largely found in highly productive moist environments whereas the closed forests are found throughout, including the drier, low-productivity forests of India.

Changes by Country

Total biomass and biomass density, when examined by country, show dramatic changes in PBD, PBD-80, and ABD (Fig. 16). India had, by far, the greatest total potential biomass and still has the most total actual biomass within its borders (Fig. 16a). This attribute is due strictly to its large size, however, because its PBD and ABD were the lowest of all countries (Fig. 16b). Therefore, when one considers carbon flux to the atmosphere because of land-use change, India is clearly a very important player for the region.

Next to India, Myanmar has the greatest amount of potential and actual biomass contained within its borders. Myanmar's forests had an average ABD of 231 Mg/ha, fourth after Cambodia (300 Mg/ha), Laos (272 Mg/ha), and Vietnam (261 Mg/ha) (Fig. 16b).

Distribution of biomass classes, according to the three estimates of biomass, provides a means of showing biomass shifts with time and by country (Fig. 17). For example, the Indian total PBD varied widely, from less than 100 to about 600 Mg/ha (Fig. 17a). Deforestation in the centuries up to 1980 (comparison of PBD to PBD-80) tended to increase the average biomass density as the drier, lower-biomass forests were proportionally converted at a higher rate. Degradation of those 1980 forests (comparison of PBD-80 to ABD), however, dramatically shifted the biomass classes down because of population pressure. For Peninsular Malaysia, the PBD was very high, even after de-

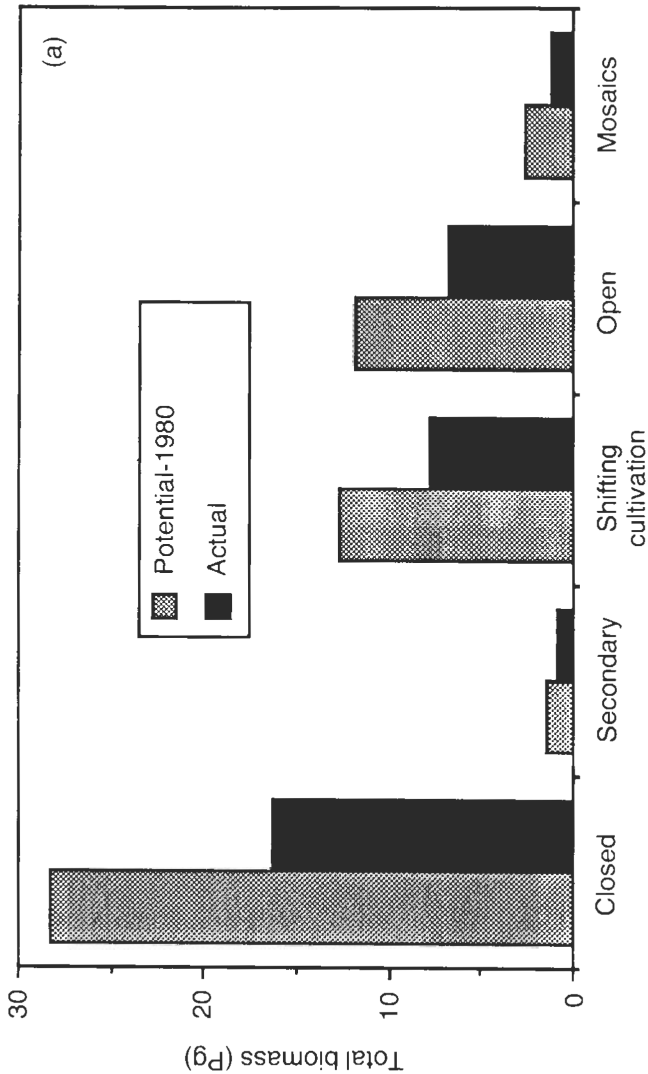

Figure 15a. Total Biomass by Vegetation Classes in Continental South and Southeast Asia.

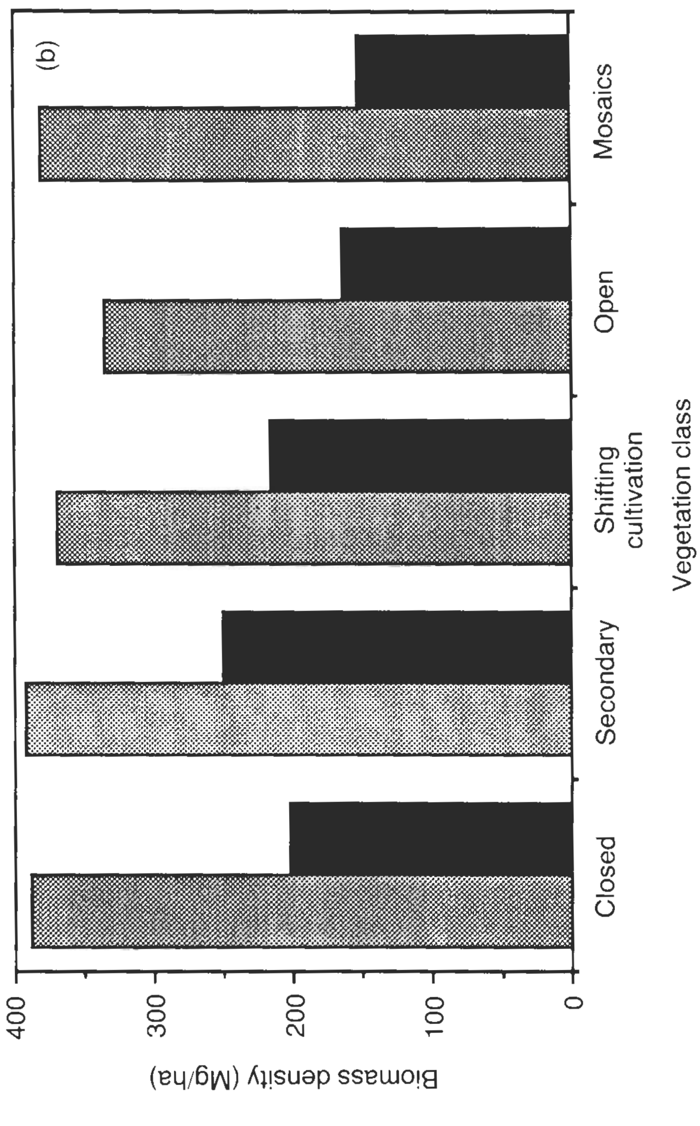

Figure 15b. Biomass Density by Vegetation Classes in Continental South and Southeast Asia.

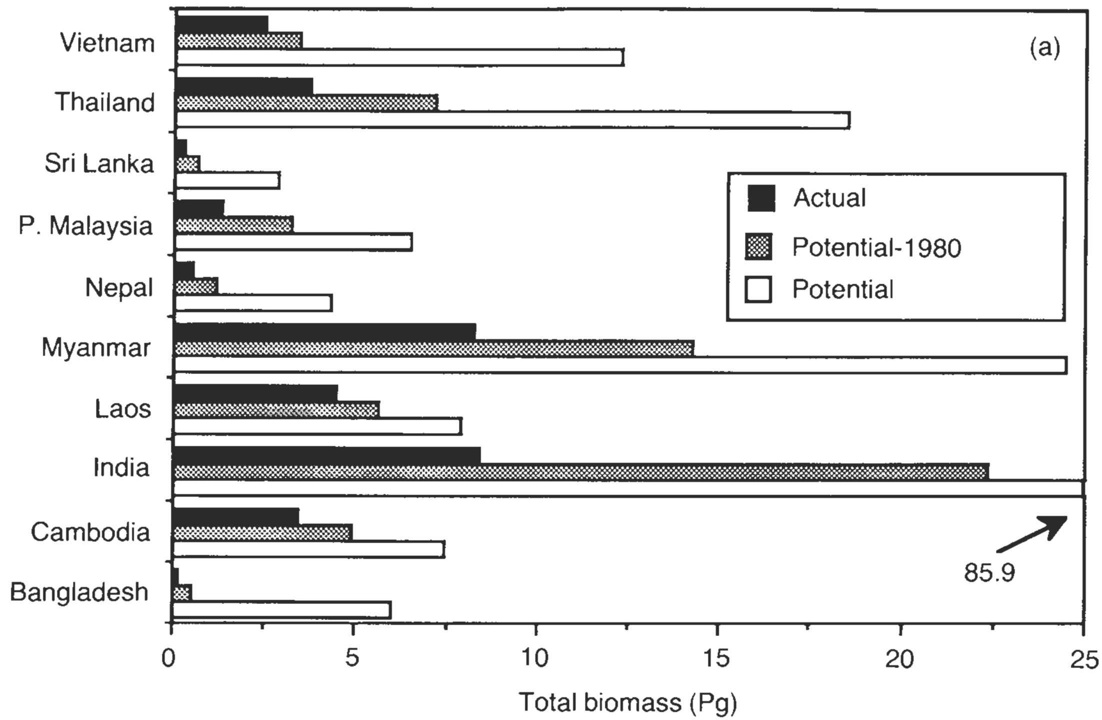

Figure 16a. Total Biomass for Each Country in South and Southeast Asia.

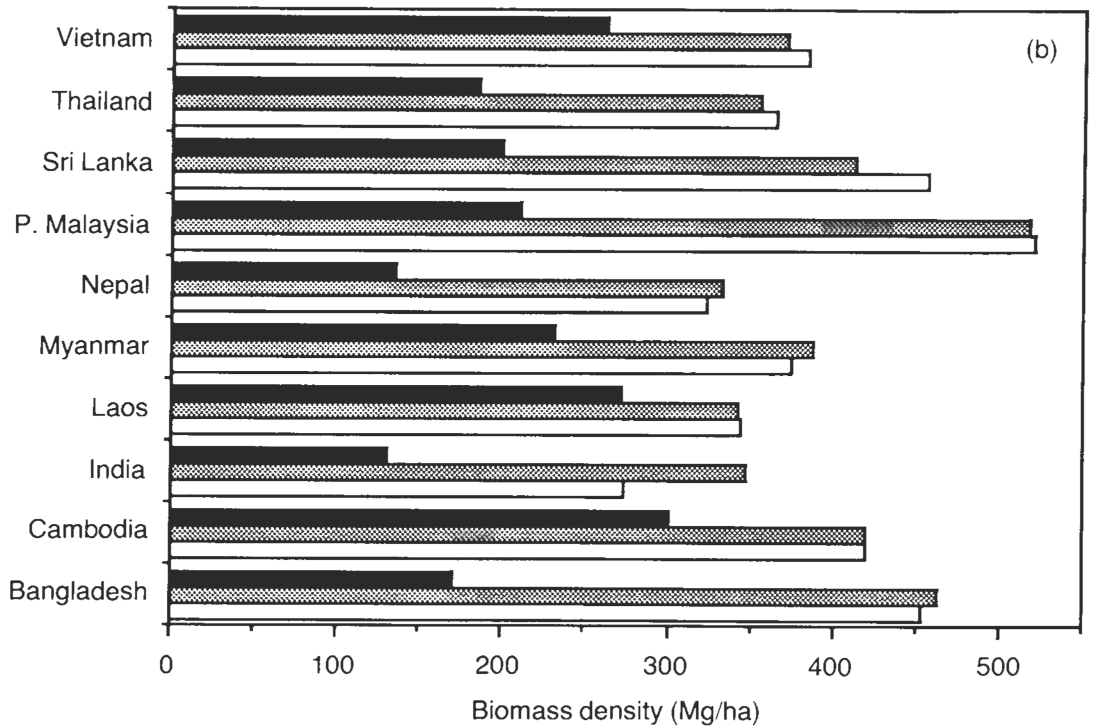

Figure 16b. Biomass Density for Each Country in South and Southeast Asia.

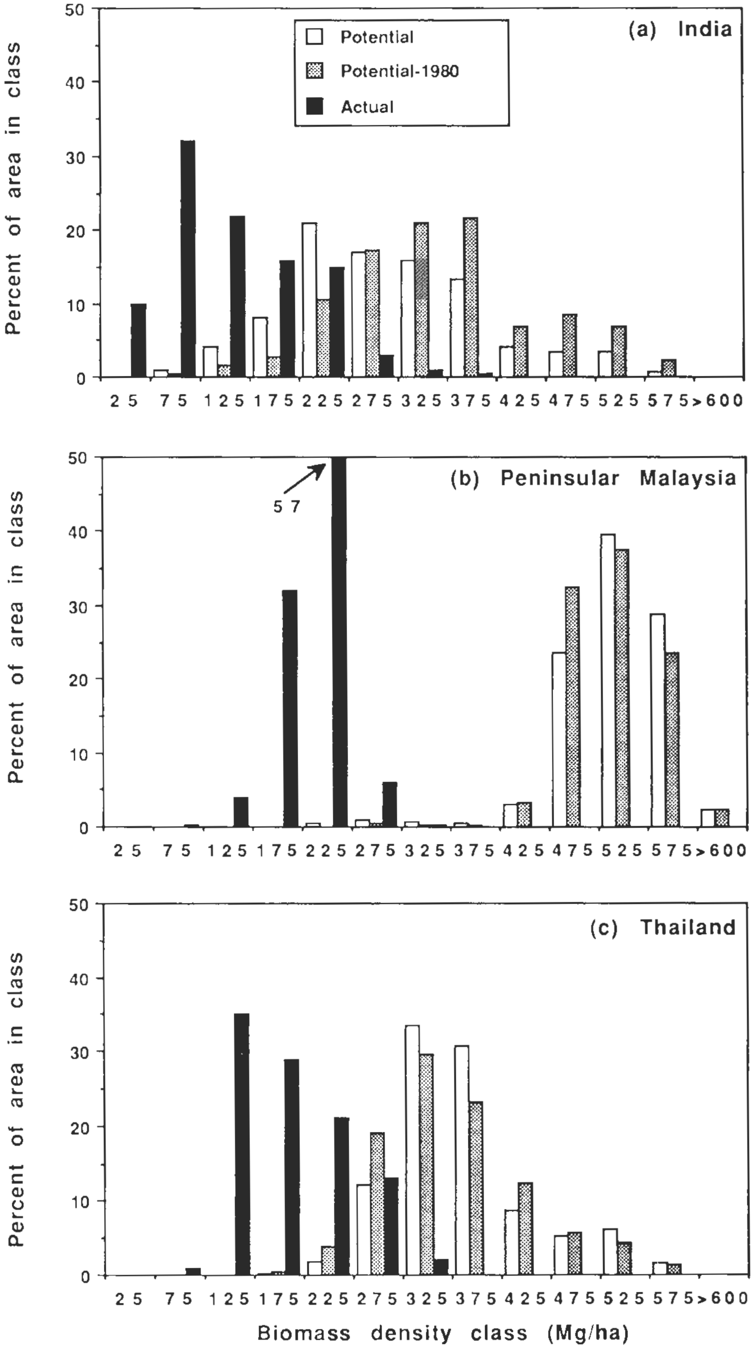

Figure 17. Percentage distribution of forest area by biomass-density (PBD, PBD-80, and ABD) classes for (a) India, (b) Peninsular Malaysia, and (c) Thailand. Bars are plotted at the midpoints of 50-Mg/ha classes.

forestation (PBD-80, Fig. 17b). The degradation effect then is shown by a downward shift of nearly 300 Mg/ha. The results for Thailand show a pattern similar to that in Peninsular Malaysia, only the biomass classes were lower from the start (Fig. 17c).

Conclusions

1. The use of GIS permitted us to spatially extrapolate our local and subregional understanding and data concerning the effects of climate, topography, soil, population pressure, and land use to estimate biomass-density changes for the entire region of continental South and Southeast Asia. The extrapolation based on biophysical and human factors provide an improvement in the estimates over those previously achieved.
2. Total potential biomass was estimated to be 176 Pg (176 x 10^{15} g) for all of South and Southeast Asia, and total potential biomass for areas still in forest in 1980 was 64 Pg. Therefore, total biomass decreased by 64% in the region because of deforestation, or conversion of forestland to nonforest.
3. Total actual biomass was estimated at 33 Pg for the region, a loss of 48% of the total potential biomass in 1980 because of degradation (reduction of biomass within forests).
4. The ecofloristic zone containing the most total biomass was the lowland seasonal forests; roughly half of the total potential or actual biomass was found in this zone. However, lowland and montane moist forests contained the highest biomass densities, followed closely by lowland seasonal forests.
5. Closed forests had the highest total potential and actual biomass because this class covers 41% of the forest area for South and Southeast Asia. Closed forests averaged an ABD of 202 Mg/ha over 79.8 million hectares. Open forests, found on a quarter of the forested area in 1980, had low biomass-density values (ABD of 164 Mg/ha) and contained an estimated 7 Pg of biomass across the continent. Forests in shifting cultivation were also very important and contained 8 Pg of biomass in 1980.
6. Total biomass and biomass density were estimated for each of ten South and Southeast Asian countries. India had the highest total biomass, simply a function of its large size; however, it had the lowest ABD. Cambodia, followed by Laos, Vietnam, Myanmar, and Peninsular Malaysia, had forests with the highest biomass densities, presently estimated at 300, 272, 261, 231, and 210 Mg/ha, respectively.
7. An implication for global carbon cycling is the widespread degradation that is another mechanism (besides deforestation) that reduces biomass and thus carbon pools in tropical forests. This mechanism needs to be addressed in all further carbon-budget analyses.

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Note

[1]The biomass data for the 93 ecological zones within the 13 countries studied are available in geographically referenced export files from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tenn., 37831-6335; telephone 615-574-0390.

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